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# HYDROGEN INDUSTRY OUTLOOK 2026

## Transforming Energy for a Sustainable Future

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## India's Hydrogen Moment: From Vision to Industrial Scale

As India advances towards its goals of energy security, decarbonisation, and global industrial competitiveness, green hydrogen is moving decisively from long-term promise to near-term reality. By 2026, hydrogen has emerged as a strategic pillar of India's clean energy transition—offering a viable pathway to decarbonise hard-to-abate sectors while strengthening domestic manufacturing and energy resilience.

The National Green Hydrogen Mission has provided clarity of direction and intent. With defined targets, incentive frameworks, and pilot programmes, India has shifted from policy vision to early execution. The focus now is on scale—where hydrogen production, demand creation, infrastructure development, and financing must progress in parallel to unlock meaningful impact.

Unlike earlier energy transitions, hydrogen's success in India will be driven largely by industrial adoption. Sectors such as refining, fertilisers, steel, chemicals, and heavy mobility are actively exploring hydrogen integration to reduce emissions, manage long-term energy risk, and remain competitive in a world of tightening carbon regulations and emerging border adjustment mechanisms. Beyond decarbonisation, hydrogen presents a significant opportunity to build domestic manufacturing ecosystems. Electrolysers, power electronics, storage solutions, advanced materials, and balance-of-plant equipment can become high-growth segments, reducing import dependence and creating skilled employment across the value chain.

Despite growing momentum, several challenges will define the next phase of growth. Cost competitiveness remains the most critical factor, requiring continued declines in renewable energy prices, electrolyser costs, and access to affordable long-term capital. Infrastructure—covering storage, pipelines, ports, and refuelling networks—must be developed at scale and in coordination with demand centres.

Equally important are standards, certification, and offtake visibility, which are essential for bankable projects and future hydrogen trade. Building talent and innovation ecosystems will also be vital as technologies evolve rapidly and deployment accelerates. The hydrogen economy cannot be built in silos. Success will depend on coordinated action among policymakers, industry leaders, technology providers, financiers, research institutions, and state governments. India's ability to orchestrate scale—leveraging its renewable energy leadership, engineering strengths, and large domestic demand—offers a distinct global advantage. Strategic partnerships, both domestic and international, will play a key role in accelerating learning curves, de-risking investments, and positioning India as a credible global hydrogen hub.

The years leading to 2030 will determine India's place in the global hydrogen landscape. The decisions taken today will shape not only emissions outcomes, but also industrial competitiveness and energy security for decades.

The Hydrogen Industry Outlook 2026 captures this pivotal moment—bringing together perspectives from across the hydrogen ecosystem. As India enters this decisive decade, the question is no longer whether hydrogen will matter, but how quickly and effectively it can be scaled to power the nation's next phase of industrial growth.

Looking forward to your valuable feedback!

Happy Reading!

**Pravin Prashant**
**Executive Editor**
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Government of India
Ministry of New and Renewable Energy

## Foreword

India is advancing toward a clean, secure, and sustainable energy future. Our national commitments—achieving 500 GW of non-fossil fuel-based electricity capacity by 2030 and net-zero emissions by 2070—reflect a long-term vision for growth that is both environmentally responsible and economically resilient. At the centre of this transition is the National Green Hydrogen Mission (NGHM), launched in January 2023, which seeks to position India as a global hub for the production, utilisation, and export of green hydrogen and its derivatives.

Green hydrogen represents a transformative opportunity for the country. It offers a pathway to decarbonise hard-to-abate sectors, reduce dependence on imported fossil fuels, and build high-value manufacturing and technology ecosystems. Through the Mission, we are creating an enabling environment that supports investment-ready projects, innovation-driven enterprises, and world-class infrastructure across the value chain—from electrolysers and renewable-powered hydrogen production to storage, mobility, industrial applications, and emerging export opportunities.

Significant progress has already been achieved. Incentives have been awarded for 3,000 MW per annum of electrolyser manufacturing capacity and for 8.62 lakh tonnes per annum of green hydrogen production. Price discovery has been completed for 7.24 lakh tonnes per annum of green ammonia, and public sector undertakings have initiated procurement for refinery applications. Pilot projects are underway in the steel, shipping, and transport sectors, including the deployment of hydrogen-fuelled vehicles and the development of hydrogen refuelling infrastructure across multiple routes. The enabling ecosystem is being strengthened through the notification of the Green Hydrogen Standard, the launch of the national certification scheme, support for R&D across 23 projects, and steady progress in skill development, with thousands of trainees already trained.

As India moves from pilot demonstrations to scalable commercial deployment, our collective priority must be to mobilise capital, deepen innovation, build skills, and develop resilient markets that deliver economic growth alongside climate responsibility. With rising investor interest and strengthening industrial capabilities, India is well-positioned to emerge as a trusted and competitive participant in global hydrogen supply chains.

I commend Indian Chemical News for bringing out the Hydrogen Industry Outlook 2026. This compendium will serve as a valuable reference for policymakers, industry leaders, investors, researchers, and international partners working to advance India's green hydrogen ecosystem.

**(Santosh Sarangi)**

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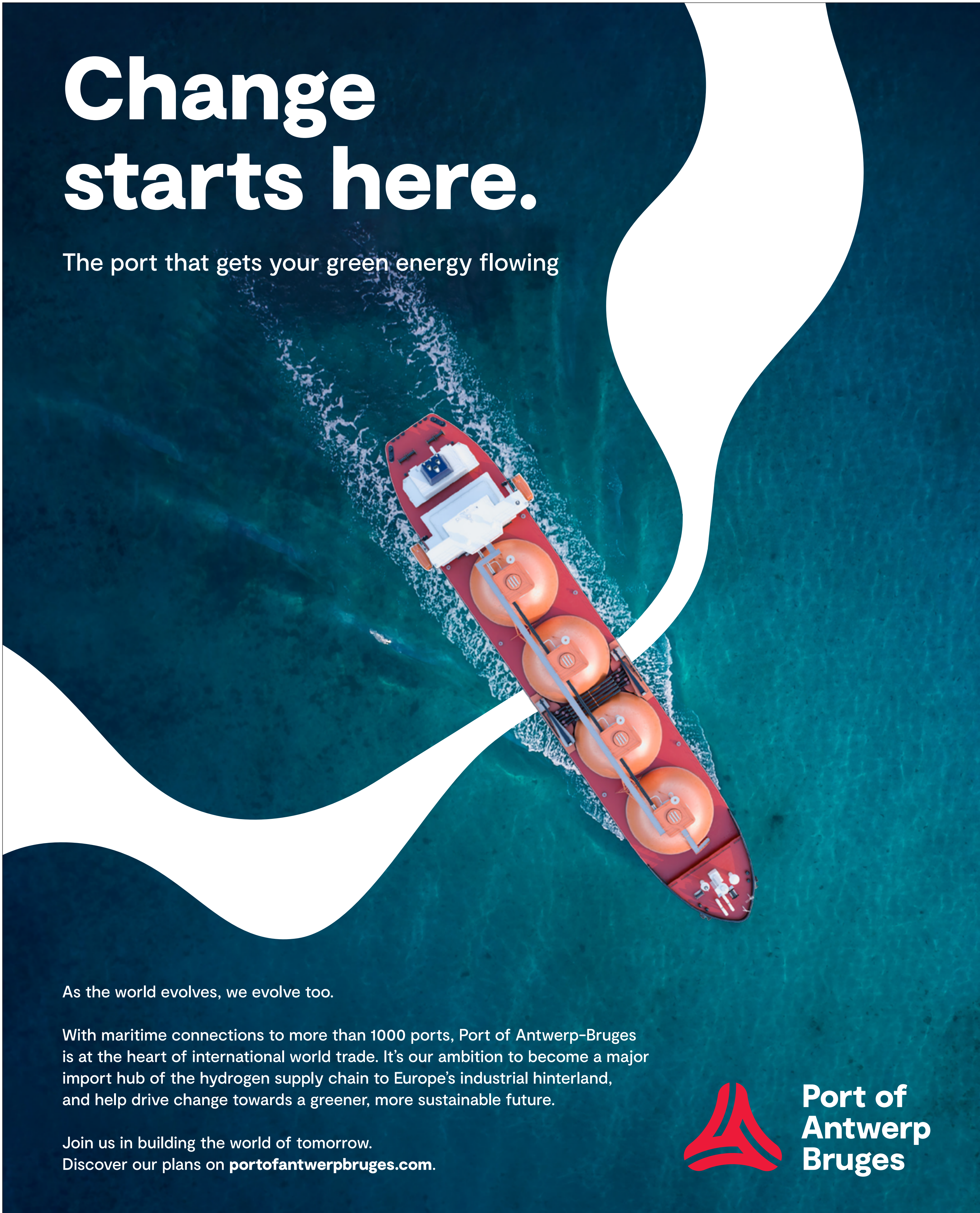
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HYDROGEN ASSOCIATION OF INDIA

## FOREWORD

The global energy transition is entering a decisive phase, and green hydrogen has emerged as one of its most transformative pillars — enabling deep decarbonisation, advancing industrial competitiveness, and opening new pathways for innovation-led economic growth.

Around the world, governments, investors, technology leaders, and industry pioneers are converging to build the foundations of a resilient and scalable hydrogen ecosystem. India is proud to be a part of this momentum — not only as a fast-growing market, but as a future contributor to global hydrogen supply chains, technology development, and manufacturing leadership.

As an industry community, our collective focus is on accelerating investments, strengthening domestic capabilities, and nurturing partnerships that connect policy ambition with commercially viable outcomes. The road ahead will require coordinated progress in infrastructure, standards, financing models, workforce development, and technology maturity — supported by trust, collaboration, and knowledge exchange across stakeholders.

The **Hydrogen Industry Outlook 2026** arrives at a timely moment for our sector. It offers valuable perspective on market evolution, emerging applications, investor confidence, innovation trends, and ecosystem readiness — helping industry leaders, policymakers, and financiers navigate the transition from pilots to large-scale deployment. Insights such as these play a crucial role in shaping informed decision-making and advancing a shared vision for sustainable growth.

As we move forward, the Hydrogen Association of India remains committed to advocating industry priorities, fostering collaboration, and enabling an environment where enterprises, innovators, and investors can thrive.

I commend the contributors of the Hydrogen Industry Outlook 2026 for advancing constructive dialogue in this strategic domain, and I invite all stakeholders to work together in building a competitive, inclusive, and future-ready green hydrogen economy for India and the world.

**Dr. R. K. Malhotra**
President
Hydrogen Association of India

RECYCLABLE PAPER

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## FOREWORD

The evolution of the green hydrogen sector is driven by innovation, policy vision, and collaborative ecosystem development. As economies accelerate toward net-zero pathways, green hydrogen is no longer an emerging concept — it is rapidly becoming a strategic industrial technology platform with the potential to decarbonise core sectors, enable new manufacturing capabilities, and reshape global energy architecture.

Our priority as an industry community is to advance technological maturity and commercialization, for which policy alignment and regulatory clarity is essential. Breakthroughs in electrolyser efficiency, renewable-integrated production, storage systems, and hydrogen derivatives have to be matched with standards, certification frameworks, grid integration mechanisms, and market-creation policies that enable scale, bankability, and cross-border interoperability. This is where industry-government-research collaboration becomes essential.

The Hydrogen Industry Outlook 2026 contributes meaningfully to this agenda. It provides evidence-based insight on technology trajectories, R&D priorities, cost-reduction pathways, pilot-to-commercial transition models, and enabling policy instruments that will guide the next phase of sectoral growth. Such knowledge platforms help stakeholders align innovation efforts with real-world deployment and long-term ecosystem resilience.

As we look ahead, the IH2A remains committed to advocating progressive policy frameworks, fostering innovation partnerships, strengthening standards and safety practices, and building talent and research capabilities across the value chain. By working together, we can ensure that the green hydrogen eco-system matures, offering a clear pathway to Net Zero. It combines clean-energy technology approach to decarbonize industry, demonstrate climate leadership and help achieve blue skies in our cities

**Amrit Singh Deo**
IH2A Secretariat


H2

# GREEN HYDROGEN

## Decarbonizing Industry

# GREEN HYDROGEN: INDIA TO SHAPE THE WORLD'S CLEAN ENERGY FUTURE

Not just another clean energy option but a once-in-a-generation strategic opportunity

TEAM ICN

India stands at a pivotal moment in the global energy transition. With abundant solar and wind resources, ambitious policy backing, private-sector muscle and an export-oriented outlook, the country is positioning itself not merely as a growing market, but as a potential global hub for green hydrogen production and innovation.

The advantage lies not in outspending competitors, but in executing differently. India already consumes hydrogen at scale, more than six million tonnes annually, primarily in oil refining and fertiliser production. Today, this hydrogen is grey, carbon-intensive and tied to volatile fossil fuel prices. Converting even a portion of this demand to green hydrogen is not just an environmental move; it is an economic and strategic correction.

Green hydrogen offers multiple advantages. It can enhance energy independence by reducing fossil fuel imports that cost over Rs. 1 lakh crore annually. It supports India's climate and net-zero commitments by enabling deep decarbonisation across hard-to-abate sectors. And it opens export opportunities, positioning India as a reliable supplier to markets such as the EU, Japan and South Korea.



## The Global Context

Globally, green hydrogen is moving from ambition to execution, though progress remains uneven. More than a thousand hydrogen projects have been announced worldwide, spanning Europe, the Middle East, Asia and Australia, with hundreds of billions of dollars in planned investment, even as only a fraction has reached final investment decisions. Europe is driving demand through subsidies and industrial decarbonisation mandates, while countries like Germany, the Netherlands and France are building large electrolyser and hydrogen infrastructure projects. The Middle East, led by Saudi Arabia and the UAE, is leveraging low-cost renewables, capital and export infrastructure to position itself as a major supplier of green hydrogen and green ammonia, exemplified by mega-projects such as NEOM. Japan and South Korea are focusing on long-term offtake contracts, hydrogen mobility and import supply chains, including liquefied hydrogen shipping. Australia is betting on scale and exports but has also seen project delays and cancellations, highlighting cost and demand risks.

Together, these developments show that the race is shifting from announcements to bankable projects, cost reduction and secure markets, a transition that will define winners in the coming decade.

## Government Policy: A Mission-Driven Push

India's green hydrogen strategy is anchored in the National Green Hydrogen Mission (NGHM), launched in January 2023, with a target of producing 5 million metric tonnes annually by 2030. The mission positions green hydrogen not just as an alternative fuel, but as a pillar of long-term energy transition and industrial decarbonisation.

To accelerate scale and competitiveness, the government introduced the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, allocating nearly Rs. 17,490 crore to support domestic electrolyser manufacturing and hydrogen production. Regulatory support includes waivers of inter-state transmission charges for renewable power used in hydrogen projects commissioned before 2030, significantly improving project economics.

This policy thrust is reinforced by

### A Reality Check

Green hydrogen has entered the difficult phase where ideas are tested against industrial reality. Costs remain high, projects are complex and timelines are slipping. Critics argue the hydrogen economy was oversold. But this moment represents not failure, but a test of seriousness, and for India, the stakes are unusually high.


Production Linked Incentive (PLI) schemes aimed at building a globally competitive domestic electrolyser industry. The financial ecosystem is also evolving, with climate finance taxonomies, emissions-based targets and the gradual development of carbon markets expected to channel capital into hydrogen and allied clean-energy ventures.

At the state level, Gujarat, Rajasthan, Andhra Pradesh and Karnataka have announced hydrogen policies focused on regional hubs, export clusters and integrated industrial ecosystems aligned with national goals. Importantly, the government's emphasis is on building a full-stack ecosystem, spanning manufacturing, renewable power, infrastructure, assured demand and alignment with global standards, to ensure India becomes a credible and competitive global player.

## Industry Dynamics: From Intent to Execution

Corporate India has responded with urgency and scale, translating policy intent into on-ground capacity across the hydrogen value chain. Large conglomerates, clean-energy developers and specialist startups are collectively turning green hydrogen into an active business frontier.

Reliance Industries is among the most aggressive movers, placing green hydrogen at the centre of its energy transition strategy. Through Reliance Green Hydrogen and Green Chemicals, the company plans to produce around 90,000 tonnes annually and has secured 300 MW of alkaline electrolyzer manufacturing capacity under the SIGHT scheme. The Adani Group has focused on infrastructure-led innovation. Its clean-energy arm, Adani New Industries Ltd, commissioned India's first off-grid 5 MW green hydrogen pilot in Kutch, powered entirely by solar energy and battery storage.

Beyond large conglomerates, companies such as AM Green, Welspun New Energy etc, are developing multi-metric-tonne hydrogen and green ammonia capacities in partnership with state governments. Under the NGHM, at least nine domestic firms, including Reliance, L&T and Waaree, have received approvals to set up hydrogen production facilities. Equally notable is the rise of specialised players like Hygenco, which claims to be supplying green hydrogen at prices competitive with grey hydrogen. INOX Air Products has already commissioned India's first commercial green hydrogen plant for industrial use, while GAIL has operationalised a megawatt-scale green hydrogen facility at Vijaipur in partnership with Tecnimont and NEXTCHEM. Renewable-focused firms such as Green Infra (Sembcorp), Welspun-linked entities, Oriana Power, Insolare and GH2 Solar are developing green hydrogen and green ammonia capacities aligned with export ambitions.

## Technology Trends Driving Competitiveness

India's current installations are dominated by alkaline electrolysis due to lower costs and proven performance. However, Proton

Exchange Membrane (PEM) electrolyzers are gaining momentum for their higher efficiency and better compatibility with intermittent renewables, and are expected to capture a growing share as manufacturing scales. The companies like Ohmium International and GreenH Electrolysis are scaling PEM and multi-technology electrolyzer manufacturing to support domestic demand and reduce import dependence.

India's rapid expansion of solar and wind capacity, with tens of gigawatts added annually, provides a structural advantage by lowering electricity costs, the single largest input to hydrogen production. Co-located renewable-hydrogen projects and off-grid models are becoming increasingly viable.

Infrastructure innovation is also underway. Studies suggest existing gas pipelines could safely accommodate limited hydrogen blending, enabling early distribution without waiting for entirely new networks. While modest, this approach helps build demand and operational experience.

Hydrogen's role is expanding beyond industry into mobility and transport. Hydrogen buses and heavy trucks are under deployment, Indian Railways is preparing to operate its first hydrogen-powered train, and a hydrogen-powered passenger vessel has been launched for inland waterways. These developments signal hydrogen's transition from niche fuel to versatile energy carrier.

### India's Race to $2 Green Hydrogen

With renewable power prices falling and electrolyzer manufacturing scaling up, green hydrogen costs in India are projected to drop to $1.50–$2 per kg by 2030, narrowing the gap with fossil-based hydrogen. The race is now about who reaches cost parity first, and at scale.

## Challenges Ahead

Despite momentum, challenges remain. One of the most pressing constraints is capital intensity. Green hydrogen projects require substantial upfront investment across the value chain, from renewable power generation and electrolyser manufacturing to storage, transport and end-use infrastructure. Equally important are infrastructure gaps. Establishing a robust, internationally accepted system for certifying green hydrogen, covering lifecycle emissions, traceability and sustainability benchmarks, is essential to ensure credibility and market access in regions with stringent carbon accounting norms. Without clear standards, Indian exporters could face barriers despite competitive production economics. Certification and standards pose another hurdle, particularly for exports. India also trails global leaders in electrolyser efficiency and durability, underscoring the need for sustained R&D and technology partnerships.

Yet, despite these constraints, industry analysts and policymakers remain cautiously optimistic. The consensus is that regulatory continuity, innovation and international collaboration can address these constraints over time.

## The Road to Leadership

By 2030, India is aiming to move decisively from hydrogen ambition to hydrogen authority, not merely by achieving its target of producing 5 million metric tonnes of green hydrogen annually, but by influencing global standards, shaping export markets and driving clean-technology innovation. If execution matches intent, India could emerge not only as a large producer, but as a global leader in sustainable energy technology and a major exporter of green fuels, shaping the contours of the future low-carbon economy.

If the 20th century was shaped by oil, the 21st will be shaped by clean molecules. Green hydrogen sits at the centre of that transformation. India has the scale, the talent, and the industrial base to lead. The next five to seven years will determine whether it emerges as a hydrogen heavyweight or a hydrogen consumer. What it needs now is speed, clarity, and the courage to move before certainty arrives

# KAKINADA PROJECT WILL BE INDIA'S FIRST COMMERCIAL-SCALE GREEN AMMONIA & GREEN HYDROGEN FACILITY

AM Green has already secured a strong export-oriented offtake pipeline. This includes a binding offtake agreement with Uniper, Germany for upto 500 KTPA starting Q2 2028. A Memorandum of Understanding (MoU) with RWE for approximately 300 KTPA is already in place. Further, 100 KTPA for BASF, 100 KTPA for Keppel, and a host of other players are in the offing

**Dr. S.S.V. Ramakumar**
**Chief Technology Officer and Executive Vice President**
AM Green

**Q How is AM Green's green-ammonia project progressing? What technology and design parameters have been finalized for electrolysers?**

AM Green is currently executing 1 million tonne per annum (MTPA) green ammonia complex at Kakinada, Andhra Pradesh. The site is the erstwhile Nagarjuna Fertilizers facility which was acquired and being repurposed as AM Green Ammonia Pvt. Ltd. The complex is coming up on 495 acres of land with an overall 3,000 tonnes of capacity per day for producing green ammonia. The project has achieved Final Investment Decision (FID) in August 2024 and construction is progressing rapidly and is expected to be completed in 37 months i.e. September-October, 2027.

The plant is based on 1.28 GW advanced pressurised alkaline electrolyser capacity supplied by John Cockerill, Belgium, under a long-term strategic partnership. The electrolysers are configured in 5 MW stacks, with each stack producing approximately 100 Nm$^3$ per hour of hydrogen equivalent to around 90 kg of green hydrogen. In the first phase of 0.5 MTPA, 128 stacks will be deployed, aggregating to about 640 MW electrolyser capacity.

**Q What is the timeline for deployment of two phases of 640 MW electrolyser installation? Dates for commissioning and expected hydrogen and ammonia production ramp-up curve post-start-up in 2027?**

From the point of FID, the project follows a 37-month execution timeline, with mechanical completion targeted for September-October 2027. The first 20 MW electrolyser block is expected to be commissioned by Q1 2027. Full Phase 1 capacity of 0.5 million tonnes of green ammonia is scheduled to be achieved by October 2027. Phase 2, which mirrors the scale and configuration of Phase 1 is planned for commissioning around 2028. Once both phases are operational, the cumulative electrolyser capacity will reach approximately 1.28 GW producing around 545 tonnes of green hydrogen per day for downstream ammonia synthesis.

**Q What is the CAPEX committed for the Kakinada project? What is the expected levelized cost of hydrogen at full scale?**

It is a multi-billion dollar investment and all financial commitments are already in place and disbursements have also commenced.

From a cost perspective, recent public tenders in India indicate green hydrogen prices in the range of Rs. 320–330 per kg as per Indian standards and the same may be expected to be 25-30% more for RFNBO standards. AM Green expects to be highly competitive and potentially the cost will be below this range which is driven by large-scale renewable integration, pumped storage,


> **AM Green's Kakinada project is designed to produce deep green ammonia with a carbon footprint of approximately 0.05 kg $CO_2$ per kg of product**

and economies of scale. Globally, green ammonia prices vary depending on carbon intensity and certification. Grey ammonia trades at around US $500 per tonne today while highest standard green ammonia compliant with EU RED III or RFNBO standards is priced at upwards of US $800 per tonne. Intermediate grades typically trade between US $600-$800 per tonne. Final pricing will ultimately depend on certification standards, which are currently under revision in India.

The Ministry of New and Renewable Energy (MNRE) and the Office of the Principal Scientific Adviser (PSA) to the Government of India have constituted a committee to revise India's green ammonia standards and incentive framework where I am serving as convener of the committee. The committee has submitted its report to the government and until these standards are formally notified, cost comparisons need to be interpreted carefully as the term 'green ammonia' represent very different levels of carbon intensity.

AM Green's Kakinada project is designed to produce deep green ammonia with a carbon footprint of approximately 0.05 kg $CO_2$ per kg of product (at gate), which significantly exceeds the EU RED III requirement of 0.5 kg $CO_2$ per kg (including shipping, storage and cracking,if any). Kakinada project will be India's first commercial-scale green ammonia and green hydrogen facility. It is already among the first few globally to receive pre-project EU RFNBO certification based entirely on its design, configuration, and power sourcing architecture.

**Q AM Green has set a target to reach 5 million tonnes per annum (MTPA) of green ammonia by 2030 equivalent roughly to about 1 MTPA of green hydrogen. What are the intermediate capacity milestones for hydrogen/ ammonia production and which other sites beyond Kakinada are planned for expansion?**

AM Green has a clear and structured roadmap to reach 5 million tonnes of green ammonia capacity by 2030, equivalent to roughly one million tonnes of green hydrogen annually. At Kakinada, the capacity can be expanded to 2 million tonnes with land and resources already secured. Land parcels have also been secured at Tuticorin and Kandla Port for an additional two million tonnes. One more site is currently under evaluation for the remaining one million tonnes. This provides visibility on four million tonnes with the final location to be announced.

**Q Given the massive scale, how many electrolyser manufacturing units or supply-chain facilities are planned? What is their expected commissioning schedule?**

In parallel with project development, AM Green is setting up India's first electrolyser assembly facility at Kakinada with a nameplate capacity of 2 GW in partnership with John Cockerill. The initial Kakinada ammonia project will use imported electrolysers but future projects will increasingly rely on domestic assembly.

Pressurised alkaline electrolyser was selected due to its proven maturity, scalability, and reliability at the megawatt scale. In contrast, PEM and AEM technologies are still largely limited to kilowatt-scale deployments or pilot projects.

**Q Confirmed offtake partners or customers for the green ammonia/ hydrogen? What volumes and contract durations have been secured till date?**

AM Green has already secured a strong export-oriented offtake pipeline. This includes a binding offtake agreement with Uniper, Germany for upto 500 KTPA starting Q2 2028. A Memorandum of Understanding (MoU) with RWE for approximately 300 KTPA is already in place. Further, 100 KTPA for BASF, 100 KTPA for Keppel, and a host of other players are in the offing. This positions AM Green as the first Indian company to finalise green ammonia supply arrangements with European buyers.

**Q Does AM Green foresee supplying green hydrogen or derivatives to domestic industrial users? Have any MoUs or negotiations been initiated for domestic supply?**

AM Green is a niche player as we operate in premium quality green ammonia. For the time being, the Indian specifications do not envisage high quality ammonia. Being the convenor of the committee, I will vouch that Indian green ammonia standards will be tightened up and will be at par with the European standards. Whenever the Indian standards measure up to the global standards, we will definitely participate.

Our green ammonia exports will be routed through Kakinada Port with Rotterdam serving as the primary import hub. DP World has been appointed as the logistics partner. AM Green has agreements in place with both Kakinada Port and Rotterdam Port and has also signed an MoU with the Govt. of Andhra Pradesh to participate in the development of a new greenfield port located near the manufacturing site.

**Q How is renewable power secured for round-the-clock operations?**

The project has been designed to comply with EU requirements on additionality, temporal matching, and traceability, including hourly reconciliation of power consumption. Renewable power sources include a 650 MW power purchase agreement with Gentari, solar assets from Gentari, a 2 GW pumped storage project operated by Greenko, and tie-ups with NTPC Vizag. Water requirements will be met through Godavari-based reservoirs, using existing allocations transferred from the legacy fertilizer facility.

**Q Beyond green ammonia, does AM Green plan to produce or supply other green molecules including green hydrogen-based chemicals? What is the roadmap for these molecules?**

AM Green is developing a diversified green molecule portfolio. This includes second-generation ethanol through its

> **Our endeavour in the next 5-6 years is to convert the green electron into all kinds of green molecules**

acquisition of Chempolis in Finland. The Assam Bio Refinery with a capacity of 300 KTPA inaugurated by the Prime Minister in Assam is based on Chempolis technology. We are planning Napier grass-based biorefineries of 250 KTPA each. The company is also targeting downstream products such as green acetic acid, furfural, lignin-based chemicals, and Sustainable Aviation Fuel. Overall, AM Green plans to set up five biorefineries across Andhra Pradesh, Karnataka, Madhya Pradesh, and Assam with cumulative investments exceeding Rs. 10,000 crore. Further, we are also in advanced stage of planning to set up commercial scale green methanol production units synthesized from captured biogenic $CO_2$ from paper & pulp industry and CBG plants.

**Q What is AM Green's long-term vision for India? Does it aim to position India as a global export hub for green molecules to Europe/Asia and also foster a strong domestic hydrogen economy?**

AM Green's vision is to decarbonise the hard-to-abate sectors and we have the advantage of one of the most cost efficient green electrons. Our endeavour in the next 5-6 years is to convert the green electron into all kinds of green molecules. For us, there are no boundaries as we are ready to cater to demands for low intensity green ammonia in India as well as globally.

**Q How does AM Green plan to scale up, in terms of capacity, geography, and product-mix over the next 5–10 years to adapt to evolving demand, policy changes, and technological developments?**

With a mission of producing 5 MTPA of green ammonia by 2030, we have already secured the land and other resources for our four units. Similarly, on the biomolecule front, we have envisioned building five biorefineries using lignocellulosic biomass, cultivated by us on marginalised lands. At least three bio-refineries will be in Andhra Pradesh and two will be located in Assam, Madhya Pradesh and Karnataka for setting up bio-refineries. On both the bio-refineries and ammonia front we will be a formidable player by 2030.

**Q What is the biggest missing piece today for green hydrogen and ammonia adoption in India?**

The most critical gap is the absence of a robust carbon trading mechanism and market-based pricing for low-carbon products. A transparent and credible carbon market, similar to what exists in Europe, is essential to appropriately value decarbonisation and accelerate adoption across hard-to-abate sectors. Government support and carbon trading are the need of the hour.

**Q How do you see green hydrogen adoption evolving in mobility and industry?**

As electrolyser manufacturing localises and costs continue to decline, green hydrogen is expected to reach parity with grey hydrogen within the next five years. Once that threshold is crossed, adoption across fuel-cell buses, mobility, cement, steel, and chemical industries will scale rapidly. The total cost of ownership for hydrogen-based mobility will become competitive with diesel, making India's net-zero ambitions both technically and economically viable ICN

# PLANNED RS. 12,000 CRORE FOR RENEWABLE INFRA AND RS. 28,000 CR FOR GH2 INFRA TILL 2040

BPCL has a long-term renewable energy goal of 10 GW by 2035 and around 60-70% of this will be required for green hydrogen production

**How does BPCL's hydrogen roadmap align with the National Green Hydrogen Mission and India's broader decarbonization targets?**

BPCL's strategy is fully aligned with the Government of India's vision under the National Green Hydrogen Mission (NGHM). We are working closely with the Ministry of Petroleum and Natural Gas, Ministry of New and Renewable Energy, and Centre for High Technology to ensure synergy with national objectives. Our commitment is clear and we aim to achieve net zero for Scope I & II emissions by 2040.

Bharat Petroleum Corporation Limited (BPCL) has taken pioneering steps in this direction. We were the first recipient of subsidy under Mode 1 Bucket II for producing green hydrogen through biomass-based pathways. Compressed Bio Gas (CBG) based green hydrogen project at Kochi is under commissioning. We have commissioned a 5 MW alkaline water electrolyser based green hydrogen plant at Bina Refinery, the largest plant amongst any Indian refinery.

To promote green hydrogen as mobility fuel, we have put up a fuelling station at Kochi city with assistance from CIAL (Cochin International Airport Ltd.) which is under commissioning and has the biggest indigenous electrolyser using BARC technology. Next phase Under the SIGHT 2B scheme, we have awarded a tender for a 5 KTPA Build-Own-Operate green hydrogen plant by 2030. We have plan to scale this further up to 25 KTPA.

**BPCL has commissioned a 5 MW green hydrogen plant at its Bina Refinery in Madhya Pradesh. Kindly share the current production data, actual versus planned output (tonnes/day, annual)? Will hydrogen be used for refinery operations, internal energy needs, or sale/export?**

**Sanjay Khanna**
**Director (Refineries) with Additional Charge of Chairman & Managing Director**
BPCL

The Bina Green Hydrogen plant is a milestone for BPCL and for India's refining sector. We commissioned it in a record time of 15 months setting a benchmark for speed and execution. Current production capacity is 2.2 tonnes per day. Annually, this translates to 0.72 KTPA of green hydrogen, reducing 9 KTPA of $CO_2$ emissions.

The plant has best in class electrolyser operational specific energy consumption of 47.75 kwh/kg-H2 vs design of 50.75 Kwh/Kg-H2. The unit is powered by in-house 18 MW solar power and the hydrogen produced will be used for refining processes, replacing grey hydrogen. This is a critical step toward decarbonizing our operations.

**What is the expected scale-up trajectory from 5 MW to bigger capacity within 3–5 years and what production volumes are targeted?**

Our roadmap is ambitious yet practical. Under the BOO model, a 5 KTPA electrolysis-based plant at Bina will become operational by April 2028, requiring about 55–60 MW of electrolyzers. By 2030, BPCL plans to have 20 KTPA additional capacity taking total green hydrogen production to 25-30 KTPA.

**The Bina plant is reportedly to supply hydrogen for refining processes. What proportion of refinery hydrogen demand does the green hydrogen output aim to meet now and in future?**

Presently, green hydrogen is 0.9 % of production and is scheduled to increase to 5% by 2028. We are aiming to achieve 10% of hydrogen share as significant a step toward decarbonization by 2030.

**What are the next planned green hydrogen facilities (locations, capacities, commissioning timelines) beyond Bina?**

we have setup biomass-based compressed biogas plant at Kochi and Bina which will


add 2 KTPA green Hydrogen. The BOO plant for green H2 at Bina will add 5 KTPA by 2028 and by 2030 we have plans of 25-30 KTPA green hydrogen production for our refineries.

**BPCL has unveiled India's first indigenous alkaline electrolyser in collaboration with Bhabha Atomic Research Centre (BARC). What is the expected production capacity of these electrolysers, and by when does BPCL envision commercial-scale deployment? How do you plan to integrate this electrolyser into a broader green hydrogen roadmap?**

A 0.5 MW electrolyser has been installed near the Cochin International Airport (CIAL) with a green hydrogen production capacity of approximately 200 kg per day, earmarked for vehicle mobility. Future decisions regarding the expansion of this initiative to include waterways mobility will be based on the performance of these electrolysers and the overall demand for green hydrogen.

**What is BPCL's long-term target for renewable energy capacity and what portion is earmarked for hydrogen production?**

BPCL has a long-term renewable energy goal of 10 GW by 2035 and around 60-70% of this will be required for green hydrogen production. However, it must be noted that green hydrogen production technologies are evolving and may take a while to stabilise. Also, Carbon Capture, Utilisation, and Storage (CCUS) technology which consumes green hydrogen is in the development phase. These factors will largely decide future renewable energy capacity for hydrogen production.

**BPCL has also partnered with KPIT Technologies to promote hydrogen-based mobility. Plans for hydrogen refuelling stations (HRS) and pilot fuel-cell-bus projects in Kerala (between Kochi and Trivandrum)? What is the planned timeline and scale for hydrogen-based mobility deployment in Kerala or other regions?**

BPCL has also partnered with KPIT Technologies to promote hydrogen-based mobility. It is planned to conduct a pilot by deploying FCEV (Fuel Cell Electric Vehicle) hydrogen bus between BPCL-HRS at CIAL to Aluva Metro Station, Kochi. Furthermore, BPCL has bagged MNRE funding under Hydrogen Mobility Scheme - Phase 1 to set up HRS at Trivandrum by

> **With renewable costs declining and electrolyser efficiencies improving, capacities increasing, green hydrogen costs are expected to reduce significantly over the next 5–7 years**


> **By 2030, BPCL plans to have 20 KTPA additional capacity taking total green hydrogen production to 25-30 KTPA**

December 2026 at the land provided by the Kerala State Government to establish hydrogen mobility across the state. On similar lines, BPCL is working with EKA mobility-KPIT consortium to fuel their FCEV vehicles on routes across Madhya Pradesh under MNRE Hydrogen Mobility Scheme-2 in central India.

**Is BPCL evaluating hydrogen use beyond buses, i.e. aviation, shipping (bunkering), petrochemical feedstock, or heavy-duty vehicles?**

Beyond buses, BPCL is also planning for heavy duty truck movement as part of its Kerala mobility plan. Discussions are on to explore Hydrogen for mobility for waterways at Kerala.

**What is BPCL's total planned investment (or allocation) for hydrogen, renewables, and associated infrastructure over the next 5–10 years?**

We have planned Rs. 12,000 crore for renewable infrastructure and Rs. 28,000 crore for GH2 infrastructure till 2040 for achieving Scope 1 and Scope 2 targets.

**What challenges does BPCL foresee in scaling hydrogen mobility and refuelling infrastructure across India, and what are the key risks in expanding green hydrogen production at refinery scale?**

BPCL, with decades of experience in handling hydrogen for refinery operations, is now preparing for a transformative shift toward hydrogen mobility and large-scale green hydrogen production. This transition brings significant operational, safety, technical, economic, and regulatory challenges. For hydrogen mobility, we need to upskill required manpower for operating and maintaining hydrogen refuelling stations and develop expertise among engineering and construction partners. Safety concerns include the scarcity of high-pressure components and the need for stringent storage and handling protocols, while regulatory hurdles persist due to low awareness among local authorities and evolving frameworks for hydrogen transport and public use.

At the refinery scale, technical risks include development of large-scale electrolyser technology, requirements for renewable power, and the non-availability of grid infrastructure upgrades to handle gigawatt-scale transmission. Economically, green hydrogen costs significantly more than grey hydrogen due to high capital expenditure and renewable power costs, compounded by GST on hydrogen projects and supply chain constraints.

BPCL considers the speed and extent of green hydrogen adoption in refineries to be shaped mainly by technology readiness and cost competitiveness

# PANIPAT GREEN HYDROGEN UNIT ON TRACK FOR DECEMBER 2027 COMPLETION

IndianOil's hydrogen strategy is a phased, indigenous transition that integrates technology readiness, cost-effectiveness, and safety

**How does IndianOil's hydrogen transition plan align with NGHM and India's broader net-zero or clean-energy commitments?**

IndianOil's hydrogen transition strategy is closely aligned with the National Green Hydrogen Mission (NGHM) and India's long-term decarbonization and net-zero commitments. The company is advancing green hydrogen production, refuelling infrastructure, hydrogen mobility, and industrial decarbonization in parallel, creating an integrated hydrogen ecosystem.

A key milestone is the establishment of India's largest green hydrogen plant at Panipat (10 KTPA), which directly supports NGHM objectives of demand creation, cost reduction, and domestic manufacturing. IndianOil is also deploying renewable powered hydrogen refuelling stations, developing indigenous electrolyser technologies (PEM and AEM), and demonstrating hydrogen fuel cell mobility.

Simultaneously, its roadmap prioritizes replacement of grey hydrogen in refining and petrochemical operations, reduction of emissions from hard-to-abate sectors, and enhancement of energy security. Collectively, these initiatives position IndianOil as a key implementing agency translating national hydrogen policy into on-ground outcomes aligned with India's 2030 NDCs and net zero vision.

**Long term strategy and CAPEX planned by IndianOil to roll out green hydrogen?**

IndianOil's long term strategy follows a phased and market responsive approach. The company is implementing its first large-scale project at Panipat (10,000 TPA) under a Build-Own-Operate (BOO) model, aligned with its broader target by 2030. Since Panipat project is BOO based, no upfront CAPEX is being incurred by IndianOil, and green hydrogen will be procured at a fixed discovered price over a 25 year term. The operational performance, technology maturity, cost trajectory of renewable power and electrolysers, and policy evolution will guide future capacity expansion and determine whether subsequent projects adopt BOO or conventional CAPEX led models.

**IndianOil is setting up a green hydrogen unit at Panipat Refinery & Petrochemical Complex with a capacity of 10,000 TPA. Current status and expected commissioning date? Targeted output once fully operational?**

The contract was awarded in June 2025 at a discovered price of Rs. 397 per Kg (including GST) through open tender for a 25 year term. Green hydrogen purchase agreement and contract agreement between L&T Energy GreenTech and IndianOil have been executed in July 2025. Pilot plan coordinates have been finalized and land lease agreement has been executed between L&T Energy GreenTech and IndianOil in September 2025. Design & Engineering activities at L&T are in progress. Expected completion of the Panipat project is December 2027.

**Dr. Alok Sharma**
**Director (R&D)**
IOCL

**Levelized cost of hydrogen (LCoH) estimated by IndianOil for the Panipat plant and its comparison to current grey-hydrogen costs?**

The Panipat project has secured a Levelized Cost of Hydrogen of Rs. 397/kg (inclusive of GST) over a 25-year term, the second lowest discovered price through competitive bidding in India to date. In comparison, grey hydrogen produced from natural gas currently costs approximately Rs. 180-200/kg (excluding GST).

While green hydrogen remains costlier at present, the cost gap is expected to narrow over time due to declining renewable energy tariffs, improvements in electrolyser efficiency, scaling up of domestic electrolyser manufacturing, and supportive policy incentives under NGHM.


**Q Recent public announcement mentions enlistment of a contractor at Panipat under a build-own-operate (BOO) model. Which electrolyser technology will be used and electrolyser supplier?**

As I said before, green hydrogen at Panipat will be produced by the BOO contractor, L&T Energy GreenTech, using high-pressure alkaline electrolysers manufactured by L&T Electrolysers Ltd. at its state-of-the-art facility in Hazira, Gujarat.

> **IndianOil will develop two new hydrogen refueling stations along the Mumbai-Pune corridor and the Jamshedpur-Balasore corridor**

**Q Which refinery processes or Petrochemical units will the green hydrogen feed? Will it fully substitute grey hydrogen or only partially?**

The first 10,000 TPA green hydrogen plant at Panipat will partially substitute grey hydrogen, meeting around 10% of the refinery's total hydrogen demand. Full substitution will be achieved progressively through phased capacity additions.

**Q Does the company also have plans on hydrogen fuel mobility and initial pilot geographies or partnerships?**

Yes, IndianOil is actively advancing hydrogen mobility pilots in collaboration with leading OEMs and government agencies. This includes India's first hydrogen fuel cell bus demonstration with Tata Motors with partial funding from Centre for High Technology (CHT), Ministry of Petroleum and Natural Gas, Government of India.

This exercise targets to collectively

complete over 3,00,000 kilometers across Delhi-NCR, Vadodara, and defence deployments.

Under NGHM, IndianOil, and Tata Motors proposed to join the development of hydrogen refueling stations (HRS) for hydrogen mobility trials. As part of this initiative, sixteen hydrogen-powered vehicles to be developed by Tata Motors shall undergo trials across four highways. To support this, IndianOil will develop two new hydrogen refueling stations along the Mumbai-Pune corridor and the Jamshedpur-Balasore corridor.

Additionally, existing hydrogen refueling stations at Faridabad and Gujarat will be used for operations along the Delhi-Sahibabad corridor and the Ahmedabad-Surat corridor. These pilots aim to establish operational readiness for national-scale deployment.


**Will you be deploying green hydrogen fuel dispensing pumps beyond internal refinery use? What is the planned scale and timeline for roll out?**

Yes, IndianOil's strategy includes public hydrogen dispensing infrastructure. The company has already commissioned India's first green hydrogen refuelling station at its R&D Centre at Faridabad and followed at Vadodara, Gujarat.

IndianOil will develop two new hydrogen refueling stations along the Mumbai-Pune corridor and the Jamshedpur-Balasore corridor. In the initial phase, stations will be deployed along pilot corridors including Delhi–NCR, Ahmedabad-Surat, Mumbai–Pune, and Jamshedpur–Kalinganagar.

Between 2028 and 2030, IndianOil plans to scale this into a nationwide network integrated with refinery-based hydrogen production hubs. These efforts are complemented by partnerships with Tata Motors, Hyundai, and the Indian Army, and Indian Navy to accelerate adoption of hydrogen fuel cell and hydrogen internal combustion engine (H2ICE) vehicles.

**How is IndianOil planning to build supply-chain infrastructure for hydrogen fuel (storage, compression/ transport, safety, and logistics)?**

IndianOil is adopting a phased supply chain development approach, beginning with large scale production at Panipat and controlled deployment at refineries. Pilot hydrogen dispensing stations at its R&D Centre and Gujarat Refinery are being used to establish best practices in compression, storage, dispensing, logistics, and safety.

As deployment expands, IndianOil will leverage its extensive fuel distribution network while ensuring strict compliance with PESO regulations and global hydrogen safety standards.

**Major technical or operational risks envisaged in switching from grey to green hydrogen in terms of power supply, water availability, electrolyser efficiency, storage, and safety?**

Key risks include intermittency of renewable power, which can affect electrolyser utilization; water availability, as electrolysis requires around 9 litres of demineralized water per kg of hydrogen; electrolyser efficiency and degradation over time; and challenges related to storage, compression, and material embrittlement.

Safety is a critical consideration due to hydrogen's flammability, necessitating advanced leak detection, emergency response systems, and stringent regulatory compliance. These risks are being mitigated through pilot projects, phased scaling, and robust safety frameworks.

**Q IndianOil's long-term target for hydrogen production capacity? Hydrogen share in total fuel/energy mix and renewable energy portfolio size?**

To achieve its net-zero target by 2046, IndianOil plans a progressive transition to full substitution of grey hydrogen across refineries, supported by large-scale renewable energy integration and advancements in electrolyser technology. Capacity expansion will be phased and market driven, aligned with cost reductions and policy evolution.

**Q IndianOil is also exploring green-fuel or alternate-energy initiatives like CBG, SAF, and biofuels in parallel to hydrogen? How will these complement the hydrogen roadmap?**

IndianOil is pursuing a diversified clean-energy portfolio. Under SATAT, it is investing around Rs. 1,200 crore in CBG plants through joint ventures with EverEnviro and GPS Renewables.

In SAF, IndianOil has achieved ISCC-CORSIA certification and is planning a 30,000 TPA SAF plant at Panipat, targeting 1–2% blending by FY 2027-28.

Biofuel initiatives include 2G ethanol, biodiesel, bio-bitumen, and indigenous SAF trials. These fuels complement hydrogen by addressing multiple sectors and accelerating emissions reduction.

**Q Does IndianOil foresee hydrogen becoming a significant revenue/business unit (beyond just replacing grey hydrogen) e.g. in hydrogen retail, exports, mobility, chemicals, or allied sectors?**

Yes, beyond replacing grey hydrogen, IndianOil envisions hydrogen as a commercial business vertical, encompassing hydrogen retail, mobility, infrastructure services, and allied sectors.

Public refuelling networks, corridor based deployments, and in partnerships with Tata Motors, Hyundai, and Indian Army will support the gradual scale up towards commercial hydrogen mobility and fuel markets. As far as hydrogen mobility is concerned, Japan and China are leading globally.


> **The first 10,000 TPA green hydrogen plant at Panipat will partially substitute grey hydrogen, meeting around 10% of the refinery's total hydrogen demand**

Toyota Mirai launched in Japan provides a mileage of 150 km/kg of hydrogen. China is ramping up its efforts towards augmentation of hydrogen refuelling stations.

In India, IndianOil is undertaking demonstration trials on 15 buses with the arrangement of refueling from two of its locations – one at Faridabad and other at Vadodara. Widespread hydrogen use in India will depend on cost effective hydrogen transport and storage solutions.

**Q Anything you would like to add from your side**

IndianOil's hydrogen strategy represents a systemic, phased, and indigenous transition that balances technology readiness, cost competitiveness, safety, and policy alignment. By integrating green hydrogen with refining, mobility, renewables, and alternative fuels, IndianOil is positioning itself as a central pillar of India's clean energy and net-zero journey

# REFINERY: WHEN WILL FUEL SWITCHING TO HYDROGEN MAKE ECONOMIC SENSE

While oil refining is the second-largest consumer of hydrogen globally, the transition to green hydrogen remains in its early stages due to significant technological and cost challenges

S. Bharathan
**Director – Refineries**
HPCL

Hydrogen, the universe's most abundant element, has transitioned from a celestial building block to a vital energy carrier. In 1874, Jules Verne prophetically envisioned water as an inexhaustible fuel source when decomposed by electricity in the novel "The mysterious island". Today, that vision is a reality, as the modern world harnesses hydrogen and oxygen to provide a sustainable foundation for heat and light.

## Global Oil Demand Dynamics: India as the Epicenter of Future Refining Growth

Oil refineries are a fundamental part of global energy systems, transforming crude oil into essential fuels and chemical feedstocks used every day across all economic sectors. International Energy Agency (IEA) estimates that in the Current Policy Scenario (CPS), oil demand rises from 100 mb/d currently to 105 mb/d in 2035 and to 113 mb/d in 2050. Further, IEA estimates that around 9 mb/d of new refining capacity comes online between 2024 and 2035. Asia sees a net increase of around 3 mb/d in refining capacity between 2024 and 2035, led by increases in India.

## Decarbonizing the Core: The Refinery-Hydrogen Integration

Hydrogen plays a key role in refining operations, primarily utilized for desulfurization and hydrocracking to upgrade heavy oils. While refining consumes 43 million tons of hydrogen annually, nearly all current production stems from unabated fossil fuels, with low-emission hydrogen accounting for a mere 250 ktpa—mostly via CCUS.

However, a shift is underway. The IEA projects low-emission hydrogen use will exceed 0.5 Mt by 2030, with electrolysis gaining a 15% share of all low emission hydrogen pool. Remarkably, refining is the sector with the largest share of projects that have reached final investment decision (FID) among announced projects, with one-third of potential production already at FID stage.

## From Pilot to Parity: Assessing the strategic levers and foundational architecture for cost-competitive green hydrogen in refining

To understand the strategic imperative of this transition, we will explore the critical intersections of technology, economics, and infrastructure. This overview evaluates the strategic levers that are currently reshaping how refineries will produce and utilize hydrogen in a net-zero economy.

### Narrowing the cost gap

The primary obstacle to widespread green hydrogen adoption is the 2x–3x price disparity compared to fossil-fuel methods. While low-cost natural gas keeps this gap wider in the U.S. and Middle East, recent tender price discoveries suggest the margin will narrow significantly in the medium term.

With an expected price decline for both electrolysers and renewables, the cost of green hydrogen can fall to approximately $1.60/kg by 2030 and $0.70/kg by 2050. Additional factors such as a potential

*Scaled-up Short-Stack under testing at HPGRDC*


*SOEC facility at HPGRDC*

> **A 24 KTPA CO2 capture demonstration plant is currently being commissioned at the Visakhapatnam refinery, marking a major leap in compact, industrial-scale decarbonization**

carbon price on fossil fuels could also aid in the cost-competitiveness of green hydrogen (Reference: NITI Aayog/RMI-Harnessing green hydrogen).

### 24/7 green hydrogen: Bridging the intermittency gap for India's refining sector

Refineries require a continuous hydrogen supply to maintain steady-state processes; interruptions risk multimillion-dollar shutdowns, and permanent catalyst damage. While fossil sources provide stability Hydrogen supply, transitioning to green hydrogen requires reconciling renewable intermittency with industrial demand. India addresses this through a unified national grid and strategic transmission waivers, seamlessly transporting renewable energy to Hydrogen generation hubs. Combined with battery storage, this framework ensures the stable, 24/7 electricity essential for domestic production.

### Scaling green hydrogen: Global project milestones and manufacturing trends

Global electrolysis capacity is surging, anchored by massive projects like Saudi Arabia's 2 GW NEOM plant and China's off-grid developments such as Envision Energy's 500 MW project. With electrolyser manufacturing capacity jumping 40% to 38 GW/yr, the industry is benefiting from learning curve effects that are projected to slash costs by 40%. This maturation is shifting green hydrogen from pilot phases to a competitive industrial ecosystem. To secure supply, global majors like TotalEnergies are utilizing large-scale merchant tenders. Similarly, Indian public sector oil companies are adopting Build-Own-Operate models, targeting over 40 ktpa of merchant green hydrogen by 2030 to decarbonize their refining operations.

**Next-Gen electrolysers: Driving down the cost of high-volume hydrogen for refineries**

The economic viability of green hydrogen depends heavily on the evolution of electrolyser efficiency and cost. Innovations like the Solid Oxide Electrolyser Cell (SOEC) are particularly promising, as they consume 20% to 30% less energy than standard Proton Exchange Membrane (PEM) or alkaline systems. Research centers are currently scaling up these technologies, including Anion Exchange Membrane (AEM) electrolysers, to reach industrial capacities that can reliably supply the massive hydrogen volumes required by global refining operations.

**Regulatory catalysts: Creating a guaranteed market for green hydrogen**

Strategic policies now drive the Green Hydrogen transition rather than market prices alone. Global mandates like RED and ReFuelEU Aviation create guaranteed demand for green hydrogen as a feedstock for Sustainable Aviation Fuel creating a high-value, guaranteed market. In India, the Carbon Credit Trading Scheme (CCTS), operational by 2026, will nudge industrial decarbonization by penalizing high emissions. By replacing grey hydrogen with green variants, refineries can earn tradable credits, offsetting initial costs and aligning with global standards.

**Government incentives and funding**

Under the National Green Hydrogen Mission, the Rs.17,490 crore SIGHT programme catalyzes India's energy independence. By providing direct financial incentives for domestic electrolyzer manufacturing and green hydrogen production, SIGHT lowers costs, builds a self-reliant ecosystem, and ensures a steady clean fuel supply for heavy industries like refining and steel.

> **With an expected price decline for both electrolysers and renewables, the cost of green hydrogen can fall to approximately $1.60/kg by 2030 and $0.70/kg by 2050**

*370 TPA Green Hydrogen unit at its Visakhapatnam refinery*

**The Role of green hydrogen and refineries in the circular carbon economy**

Beyond direct refining, green hydrogen is pivotal for industrial decarbonization via Carbon Capture, Utilization, and Storage (CCUS). By combining captured CO2 with green hydrogen, refineries can produce e-fuels like e-methanol and e-kerosene—"drop-in" replacements for aviation and shipping. This synergy, alongside waste-to-hydrogen technologies, transforms waste into sustainable feedstocks, enabling refineries to evolve from emission sources into hubs for active carbon recycling.

## HPCL's Pioneering Deployment of Green Hydrogen Technologies

HPCL is pioneering India's sustainable refining transition through strategic infrastructure and cutting-edge R&D. In July 2024, the company marked a historic

*$CO_2$ capture demonstration plant using HP-HiGAS Technology*

milestone by operationalizing a 370 TPA unit at its Visakhapatnam facility—the first green hydrogen plant ever integrated into any Indian refinery.

HP Green R&D Centre (HPGRDC), in Bengaluru is HPCL's primary nucleus for green hydrogen research. Since 2020, this DSIR-recognized center has integrated green hydrogen across its activities, achieving several national milestones. Key innovations include commissioning India's first Solid Oxide Electrolyser-reducing energy consumption by 30%-, and scaling Anion Exchange Membrane (AEM) technology to 1 MW cell sizes. By developing domestic 25 kW electrolyzers and fuel cell prototypes with BARC and ARCI respectively, alongside a new hydrogen fueling station near Visakhapatnam, HPCL is securing the entire value chain from production to mobility.

Additionally, the center is pioneering "Blue Hydrogen" via proprietary HP-HiGAS (A Rotating Packed Bed based absorption process technology). Major advantage of this technology is size reduction of tall absorption columns by 10 times. A 24 KTPA $CO_2$ capture demonstration plant is currently being commissioned at the Visakhapatnam refinery, marking a major leap in compact, industrial-scale decarbonization.

Commercially, HPCL is de-risking the market with a 5 KTPA contract at a benchmark price of Rs. 328/kg. These advancements in technology, procurement, and mobility pilots anchor HPCL's leadership toward its 2040 net-zero target.

## Conclusion: The Green Hydrogen Horizon:

## Architecting the Future of Sustainable Refining

Successfully integrating green hydrogen into refining requires a synchronized evolution of technology, infrastructure, and policy. While green hydrogen currently remains two to three times more expensive than fossil-based alternatives, the rapid expansion of global manufacturing capacity is driving significant economies of scale. This industrial maturation, paired with standardized facility designs, is projected to reduce system costs and accelerate the adoption of green hydrogen. As indigenous technology and infrastructure converge, green hydrogen will evolve from an experimental alternative into the cornerstone of a decarbonized, self-reliant refining sector

# VOC PORT TARGETS 2029 FOR FIRST PHASE OF GREEN HYDROGEN PRODUCTION

Based on projections and shipping decarbonisation trends, the port is expected to handle green methanol demand of around 1 million metric tonnes per annum (MMTPA) in 2030

**Susanta Kumar Purohit**
**Chairperson**
V.O.C Port Authority

**Q VOC Port has inaugurated India's first port-based green hydrogen pilot project with a 10 $Nm^3/hr$ production facility that powers port streetlights and an EV charging station. What are the key learnings from this pilot, and how do you plan to scale green hydrogen production at the port?**

The green hydrogen pilot plant at V.O. Chidambaranar Port Authority has provided several critical learnings. First, it validated the technical feasibility of plant at port for green hydrogen production, with stable operations using renewable power. Second, it demonstrated production, storage, and application in powering port streetlights and an EV charging station without grid dependency.

Importantly, it enabled the port to understand and address end-to-end challenges across the project lifecycle, creating a clear institutional roadmap for faster and smoother scale-up. These learnings form the foundation for modular scale-up, where capacity can be expanded in phases to MW scale in near future.

**Q What are the next phases planned following the green hydrogen pilot, in terms of capacity enhancement ($Nm^3/hr$ to tonnes per day) and integration with larger port operations?**

For technology demonstration, VOCPA went ahead with green hydrogen plant in pilot scale. Simultaneously, port being declared as green hydrogen hub, it allotted land to the reputed firms for production of green hydrogen and its derivatives. Apart from the above VOCPA intends to scale up pilot plant to 10 MW which will be used for green mobility like deployment for hydrogen powered trucks for port operations.

**Q Can you explain the anticipated timeline and readiness plan for transitioning from the pilot project to a full-fledged commercial green hydrogen facility at VOC Port?**

The transition from pilot to commercial-scale green hydrogen at V.O. Chidambaranar Port Authority is being implemented through a phased and preparedness-driven approach. As part of its role as one of India's emerging green hydrogen hubs, the port has already allotted 206 acres of land to Green Infra, ReNew, and Gentari for the establishment of commercial green hydrogen production facilities, significantly advancing project readiness beyond the pilot stage. First stage of green hydrogen production is expected in 2029. In the near term, the focus is on scaling up pilot green hydrogen plant in phased manner.

**Q VOC Port has earmarked over Rs. 41,860 crore in land allocation for green hydrogen and green ammonia manufacturing and storage, involving multiple investors. How is port coordinating investments and partnerships to realise this green hydrogen hub vision?**

V.O. Chidambaranar Port Authority is playing a proactive role as an enabler and infrastructure provider for facilitating large-scale green hydrogen projects. The port has earmarked and allotted dedicated land parcels to investors for green hydrogen, green ammonia manufacturing, and storage facilities, ensuring zoning clarity and long-term scalability. VOC Port is planning to develop common user infrastructure to optimise capital costs and enable faster project execution. The port will ensure pipeline connectivity within the port estate and up to designated export berths, facilitating seamless movement of hydrogen derivatives from production units to storage and shipping points. Port also plays a key role,

> **VOC Port Authority has already allotted 206 acres of land to Green Infra, ReNew, and Gentari for the establishment of commercial green hydrogen production facilities**

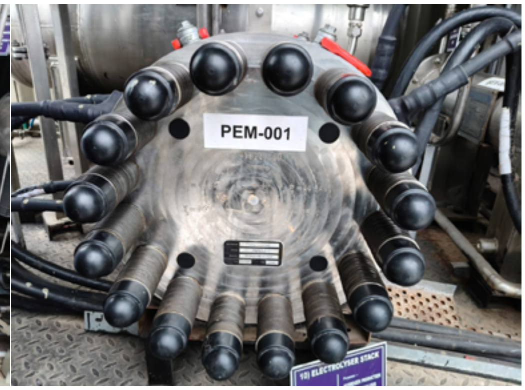
regularly convening stakeholders through platforms such as the Green Conference conducted in August 2025, which brought together policymakers, industry leaders, and global experts to shape the green hydrogen and green shipping ecosystem. This integrated approach allows multiple large investors to operate efficiently within a cohesive hydrogen hub ecosystem, rather than in isolated project silos.

**Q What strategic advantages does VOC Port believe its location and connectivity (road, rail, and maritime) provide in positioning itself as a national green hydrogen-ammonia hub of India?**

The port is an all-weather port, offers excellent multimodal connectivity, with direct access to national highways, dedicated rail links, and deep-draft maritime infrastructure enabling efficient domestic movement and international exports. It is located in a region endowed with abundant renewable energy resources, particularly high solar irradiation and strong wind potential, ensuring reliable and cost-effective green power for hydrogen production. Strategically, VOC Port lies along the international sea route and emerging Rotterdam-Singapore Green Shipping Corridor, placing it at the centre of future low-carbon fuel trade routes and enhancing its attractiveness as a bunkering and export hub for green hydrogen derivatives.

**Q VOC Port recently signed MoUs worth over Rs. 42,000 crore with major energy players (including Green Infra, ACME Green Hydrogen, and CGS Energy) for green hydrogen and green ammonia projects. How do these partnerships fit into the port's hydrogen roadmap, and what are the expected timelines for project delivery?**

To ensure a structured and future-ready approach, V.O. Chidambaranar Port Authority has onboarded a reputed consulting agency - BCG to support the preparation of a comprehensive long-term roadmap for green hydrogen and its derivatives. This roadmap is being developed in alignment with national objectives under the National Green




Hydrogen Mission (NGHM) and global maritime decarbonisation pathways under IMO roadmaps, ensuring policy coherence and international relevance. The MoUs signed with major energy players are being strategically aligned within this framework, so that investments in green hydrogen, green ammonia, and bunkering infrastructure progress in a phased, coordinated, and globally competitive manner.

**How does the port engage with central ministries and state authorities to secure policy support, incentives, and approvals essential for hydrogen hub development?**

At this nascent stage of green hydrogen development, ports require targeted financial and policy support to build enabling infrastructure.

In general, ports require financial assistance for two critical areas: power intake and development of common user infrastructure such as pipelines, storage interfaces, safety systems, and utility corridors. In this context, the Ministry of Ports, Shipping and Waterways (MoPSW) has declared V.O. Chidambaranar Port Authority as a green hydrogen hub, and the port engages regularly with central ministries and state authorities to seek support, align policies, and facilitate timely approvals. VOC Port is also actively coordinating with state agencies to address region-specific issues related to power availability, water supply, land development, and connectivity, ensuring that foundational infrastructure is created ahead of large-scale private investments.

**VOC Port has announced plans for a green methanol bunkering and refuelling facility with a 750 m$^3$ capacity? What role will this facility play in supporting clean shipping corridors, and what is the expected commissioning date?**

The proposed green methanol bunkering and refuelling facility at V.O. Chidambaranar Port Authority is planned to cater specifically to the bunkering requirements of green methanol-powered vessels, which are expected to increase significantly in the coming years. Situated along the Rotterdam-Singapore Green Shipping Corridor, VOC Port is strategically positioned to serve as a key refuelling point for low-carbon vessels operating on this route. Based on projections and shipping decarbonisation trends, the port is expected to handle green methanol demand of around 1 million metric tonnes per annum (MMTPA) in 2030. The green methanol bunkering facility, with a planned capacity of 750 m$^3$, is targeted for commissioning on 17th March 2026, aligning with the global rollout of methanol-fuelled vessels. This facility will play a crucial role in supporting clean shipping corridors and India's maritime decarbonisation goals.

**What hydrogen storage, compression, and distribution infrastructure is being planned at VOC Port to serve industrial, maritime, and potential mobility sectors?**

The port is undertaking fuel-specific feasibility assessments to determine appropriate storage technologies, safety systems, compression requirements, and distribution modes for each fuel. VOC Port is in active discussions with industry players and technology providers to align infrastructure development with project timelines, operational needs, and international safety standards.

**Is the port exploring hydrogen bunkering for marine vessels or other industrial applications, and if so, what technology standards and safety protocols are being adopted?**

At present, V.O. Chidambaranar Port Authority is primarily focused on green methanol bunkering, considering its higher level of technological maturity and vessel readiness. In parallel, the port is actively exploring green hydrogen bunkering for future maritime and industrial applications.

As part of this exploration, VOC Port is planning to tie up with reputed domestic and international organisations for specialised safety training, capacity building, and knowledge transfer related to hydrogen handling. Safety frameworks under consideration include compliance with OISD standards such as OISD-117 and OISD-118, along with applicable tank design norms, hazard zoning, emergency response systems, and global best practices.

**How is VOC Port integrating renewable energy sources with green hydrogen production strategy to ensure round-the-clock low- carbon power supply?**

The green hydrogen pilot plant is presently producing green hydrogen and utilising it for internal applications, demonstrating the effectiveness of renewable-powered hydrogen generation. To further strengthen this integration, VOC Port is in the process of establishing a Battery Energy Storage System (BESS), which will enable seamless coupling of renewable energy power with the green hydrogen facility. The BESS will help manage intermittency, ensure power stability, and support continuous and reliable operation of the green hydrogen plant, while also catering to future increases in hydrogen production demand.

**What sustainability performance metrics including lifecycle emissions, water usage, quality improvements, will the port track as part of its hydrogen and clean-energy**


> **VOC Port lies along the international sea route and emerging Rotterdam–Singapore Green Shipping Corridor, placing it at the centre of future low-carbon fuel trade routes and enhancing its attractiveness as a bunkering and export hub for green hydrogen derivatives**

**initiatives?**
As per the Harit Sagar Guidelines, V.O. Chidambaranar Port Authority is in the process of developing its own comprehensive sustainability performance matrix for green hydrogen and clean-energy initiatives. This matrix will cover renewable energy mix, source-to-offtake traceability, lifecycle emissions, operational efficiency, and water usage, ensuring alignment with national port decarbonisation frameworks. The port's customised monitoring framework is currently under preparation and is expected to be finalised and operational within the next six months, enabling structured tracking, reporting, and continuous improvement.

**Q What are the estimated CAPEX and operating cost projections for scaling VOC Port's hydrogen hub projects from pilot to full commercial operations?**
At V.O. Chidambaranar Port Authority, the port's approach to capital and operating expenditure is structured around its role as a facilitator and ecosystem enabler. VOC Port primarily supports projects by providing land, developing common user infrastructure, and ensuring access to utilities such as renewable energy, water, and connectivity, rather than directly investing in large-scale commercial plants. Large commercial green hydrogen and derivative fuel projects are expected to be developed and operated largely under PPP models, with the port extending full facilitation support to private developers. Direct port investment is currently focused on pilot and demonstration projects, which help de-risk technologies, build operational experience, and create confidence for subsequent commercial-scale investments.

**Q What role does VOC Port expect to play in India's broader hydrogen ecosystem as a major bunkering and export hub for green ammonia/hydrogen, or primarily as a regional industrial supply node?**
Tuticorin is strategically located close to major international sea routes, unlike many other green hydrogen hubs that are inland or require long-distance logistics to reach export markets. This gives VOC Port a natural advantage for direct bunkering and export of green ammonia and green hydrogen derivatives. Leveraging its position along the Rotterdam–Singapore Green Shipping Corridor, deep-draft berths, and extensive experience in handling bulk chemicals, the port aims to emerge as a major bunkering and export hub for green fuels. At the same time, VOC Port will function as a regional industrial supply node, supporting nearby industries with green hydrogen and derivative fuels for decarbonisation. By combining proximity to international shipping lanes, strong hinterland connectivity, and an integrated hydrogen ecosystem, VOC Port is uniquely positioned to act as a gateway linking India's green hydrogen production with global markets and domestic demand.

**Q How does the port plan to address supply-chain constraints such as electrolyser availability, storage equipment, skilled workforce when scaling hydrogen production and distribution?**
Predominantly facilitation for establishment green hydrogen derivatives is a part of the broad plan of the government. Individual developers are well in place to source the technology and its implementation. However, if there is a supply chain issue in major components port will intervene in consultation with relevant ministries. In parallel, the port is


focusing on training and skill development, including tie-ups with domestic and international institutions, to ensure availability of a skilled workforce for hydrogen production, handling, safety, and operations as the ecosystem scales up.

**How is VOC Port aligning its hydrogen initiatives with national targets such as ports having hydrogen/ ammonia bunkering infrastructure by 2035 and what milestones has the port set towards 2030/35?**

VOC Port has initiated India's first port-based green hydrogen pilot, planned for commissioning of a green methanol bunkering facility by March 17, 2026, and has allotted land for commercial green hydrogen projects—laying essential early infrastructure and operational experience. The port is progressing towards establishing green hydrogen and its derivatives bunkering infrastructure, bulk storage, and export capability as part of its broader hydrogen hub vision. This includes developing pipelines, storage systems, integration with renewable energy, and multi-fuel bunkering facilities that support national decarbonisation pathways.

**How is VOCPA positioning itself from green fuel perspective?**

V.O. Chidambaranar Port Authority is positioning itself not only as a green hydrogen hub, but also as an emerging offshore wind hub, placing the port at the forefront of decarbonisation in the Indian port sector. By combining green hydrogen, green ammonia, green methanol, offshore wind, renewable energy integration, and clean bunkering initiatives, VOC Port is adopting a holistic approach to port-led energy transition, setting benchmarks for other ports in the country.

The port actively encourages innovation and pilot projects and extends full facilitation support to firms, startups, technology providers, and research institutions interested in demonstrating green and clean-energy solutions within the port ecosystem. VOC Port remains open and accessible to all stakeholders willing to partner in this journey, and interested organisations are encouraged to engage directly with the port to explore pilot projects and collaborative opportunities that advance decarbonisation of the maritime and port sector.

**The chemical industry is increasingly discussing green and sustainable chemistry. From a port perspective, how do you see this transition?**

The transition to green chemistry is often discussed in terms of technology or policy, but from our perspective, the real constraint is infrastructure readiness. The ports are fully capable of handling green fuels unlock large scale green hubs in the surrounding encouraging supply to pick up momentum. This will have multi-order effect downstream and upstream with port led ecosystem and industrialisation taking shape rapidly. Lack of ready ports will increase cost of value chain multifold.

At VOCPA, we are already among the pioneers in handling green molecules. Our already operational green hydrogen plant, our proven handling of green ammonia cargo serve as testament to our capabilities. We are now fully scaling and gearing up for large scale volume movements from India to both East and West emerging as a noe for Green Energy for India.

**What do chemical manufacturers typically look for in a port when planning future-facing investments, especially in emerging segments like green chemicals?**

What the industry values most is predictability. In emerging segments such as green chemicals, margins are still stabilising and supply chains are evolving. In that environment, incentives matter far less than operational certainty. Manufacturers want confidence that cargo will move safely, on time, and within clearly defined systems. At VOCPA, our strength lies in institutional stability and operational discipline. We are not in a reactive mode. The port is already efficient and profitable, which allows us to focus on supporting future cargo streams with clarity and consistency. For green chemical manufacturers, that predictability reduces risk. And when risk reduces, investment decisions become easier

# PORT OF ANTWERP-BRUGES EYES INDIA AS STRATEGIC HUB FOR GREEN HYDROGEN IMPORTS

Port of Antwerp-Bruges is hosting the world's first operational ammonia cracker and is actively constructing its hydrogen pipeline network, with strong connectivity ambitions towards Germany by 2030

**Tom Hautekiet**
**Chief Business Development and Transition Officer**
Port of Antwerp-Bruges and
**Chairman**
Belgium Hydrogen Council

**Port of Antwerp-Bruges recently reinforced ties with India during the 2025 Belgian Economic Mission and supported a MoU involving Flanders Investment & Trade, Green H2 India, and Belgian Hydrogen Council to promote renewable hydrogen worldwide. How does the port plan to translate this India-focused MoU into concrete hydrogen initiatives or projects?**

The first year of the MoU has already demonstrated its practical value. We focused on building mutual understanding and trust. This included several webinars on hydrogen strategies and project pipelines, participation in the EU Hydrogen Week, and several site visits to Port of Antwerp-Bruges. For instance, there was a visit to the world's first operational ammonia cracking installation in Antwerp. We were also honoured to welcome India's MNRE Secretary to the Port House which further strengthened the dialogue at policy and industry level.

Looking ahead, the focus shifts clearly to project-oriented cooperation. This includes a visit to India to engage directly with developers such as AM Green in Kakinada, participation in the GH2 Symposium, discussions around potential ammonia import-export corridors, and port infrastructure partnerships. In parallel, Port of Antwerp-Bruges recently has joined GH2's Green Shipping & Ports Network to work closely with Indian developers, ports, and shipping lines on concrete trade flows.

**The MoU signed with Green H2 India and other partners aims to boost renewable hydrogen production and alternative energy collaboration. What specific areas of knowledge exchange, technology transfer or joint project development does Port of Antwerp-Bruges envision with Indian stakeholders?**

The MoU provides a framework for cooperation. We see strong value in structured exchanges through webinars, expert missions, roadshows, and port visits. On the technology side, Belgium has a strong hydrogen technology ecosystem. Several Belgian technology suppliers are already active in India, including membrane suppliers and electrolyser manufacturers involved in flagship Indian projects. Through the MoU, we aim to deepen these connections and stimulate additional technology partnerships, pilot projects, and joint innovation between Belgian and Indian companies across hydrogen value chain.

**Port of Antwerp-Bruges has supported training and consultancy efforts with Jawaharlal Nehru Port Authority. How important is workforce capacity building in hydrogen supply chains for India?**

Workforce development is a critical, and sometimes underestimated, success factor in building hydrogen supply chains. Hydrogen and its carriers are not new to ports like Antwerp-Bruges, but scaling them safely and efficiently requires specialised operational, regulatory, and logistics expertise. Through decades of experience Port of Antwerp-Bruges can share best practices in port management, safety frameworks, logistics optimisation, and training models. Our subsidiaries Port of Antwerp-Bruges International and APEC/Flanders Port Training Center can offer tailor made programs and offerings.

**Port of Antwerp-Bruges is positioning itself as a major import hub for green hydrogen and hydrogen carriers such as ammonia and methanol from regions with abundant renewable**


> **Belgium's ambition is to become a major import hub for green molecules in Northwest Europe aligns perfectly with India's ambition to become a global production and export hub**

**energy. How does the port see this import infrastructure aligning with India's ambitions to become a hydrogen exporter or supply partner for European hydrogen markets?**

Belgium's ambition is to become a major import hub for green molecules in Northwest Europe aligns perfectly with India's ambition to become a global production and export hub. Belgium has limited domestic renewable potential, making imports essential for industrial decarbonisation. In Port of Antwerp-Bruges, multiple large-scale ammonia storage and cracking projects are under development with partners such as Air Products, Vopak, Advario, Fluxys, and VTTI. Several of these projects have entered FEED phases and permitting procedures, with 2 FID's expected hopefully soon and commissioning targeted towards 2029–2030. This timeline aligns well with India's flagship hydrogen production projects. Port of Antwerp-Bruges is hosting the world's first operational ammonia cracker and is actively constructing its hydrogen pipeline network, with strong connectivity ambitions towards Germany by 2030.

**Q The port is planning large-scale terminals for ammonia and hydrogen carrier imports by 2027–2028. What role could India play as an export source of green molecules to Antwerp-Bruges and broader European market?**

India is emerging as a key long-term partner for Europe's green molecule supply. The momentum created by the 2025 Belgian Economic Mission, the BHC-GH2 MoU and recent high-level visits is already translating into concrete commercial discussions. We see increasing interest from Indian producers to connect with European offtakers clustered in and around Port of Antwerp-Bruges. The port's role is to provide reliable, open-access infrastructure and transparent market conditions that enable these long-distance supply chains to move from concept to reality.

**Q Port of Antwerp-Bruges is active in international coalitions and is a founding member of H2Global Foundation to promote hydrogen trade and market expansion. India, with its focus on building green hydrogen and export capacity, benefit from deeper participation in such global market mechanisms?**

H2Global is the leading market creation mechanism in the hydrogen market.

With it's double sided auction, it provides transparency and competition on both producing and off taking side. If we could set up a trilateral window in H2Global India-Belgium-Germany, we could aggregate demand and create benefits of scale.

**Given the port's development of hydrogen infrastructure, how does Port of Antwerp-Bruges envisage integrating or collaborating with Indian ports that are building hydrogen or hydrogen-carrier ecosystems?**
Through its subsidiary Port of Antwerp-Bruges International, the port actively explores advisory, investment, and partnership opportunities worldwide. POABI brings expertise in port development, energy infrastructure, governance models, and operational excellence. Globally, we expect new bunkering hubs for low-carbon fuels to emerge along major shipping routes due to lower energy densities and increased refueling needs. India is strategically positioned to become one of these key hubs. Therefore we are keen to explore collaboration opportunities with Indian ports developing hydrogen and hydrogen-carrier ecosystems.

**The port supports innovation projects such as NextGen District and the HyBex hub project for hydrogen trading and balancing. What learnings or models from these initiatives could be relevant for Indian hydrogen hub development?**
While not directly transferable, initiatives like NextGen District (our circular economy hub for start and scale ups) demonstrate how ports can create space for industrial-scale innovation, circular economy projects and energy transition technologies. They showcase how regulatory flexibility, infrastructure access, and industrial clustering can accelerate deployment.

**Port of Antwerp-Bruges is working with cutting-edge industrial partners on hydrogen value-chain infrastructure with Fluxys, Air Liquide, VOPAK, and VTTI. How might these partnerships translate into India-focused collaborations, including technology transfer, joint ventures or pilot projects?**
Our partnerships with companies such as Fluxys, Air Liquide, Vopak, and VTTI create strong bridges to India. Vopak, for example, already operates in India, opening opportunities to link Indian and European terminal developments. Fluxys' international experience with pipeline joint ventures could be relevant in an Indian context as hydrogen backbone infrastructure develops. Combined with POABI's capabilities, these partnerships can support joint ventures, pilot projects, and targeted infrastructure development.

**In the context of India's NGHM and export ambitions for green hydrogen and derivatives, what policy frameworks or bilateral agreements would Port of Antwerp-Bruges like to see developed between India and EU?**
Concluding a comprehensive EU-India

trade framework with hydrogen and energy as a core pillar is essential. Reducing or removing trade barriers for green molecules will be critical for viable import-export corridors. At bilateral level, a dedicated Belgium–India hydrogen MoU could further accelerate cooperation. A joint H2Global window would complement these policy frameworks.

**What strategic incentives does Port of Antwerp-Bruges consider essential for streamlining India-Europe hydrogen supply chains?**

Key incentives include long-term offtake certainty, transparent pricing mechanisms, aligned certification schemes, and streamlined permitting. Public support instruments should focus on de-risking projects and bridging initial cost gaps until scale effects reduce prices.

**Port of Antwerp-Bruges aims to be climate neutral by 2050 and is building a hydrogen economy that supports industrial decarbonisation. How partnerships with Indian ports and industries contribute to shared sustainability outcomes and emissions reduction goals?**

Partnerships between Indian producers and European consumers enable optimal allocation of renewable resources globally. India's strong production potential combined with Europe's concentrated industrial demand creates a natural production–consumption synergy that maximizes emissions reduction per euro invested.

**Key logistical, regulatory, and commercial challenges Port of Antwerp-Bruges has faced in scaling hydrogen and hydrogen carrier infrastructure? How these insights will help Indian ports and policymakers accelerate hydrogen adoption?**

Logistically, handling ammonia and methanol is not new for Antwerp-Bruges. These products have moved through the port safely for decades. The challenge lies mainly in scaling volumes. Regulatorily, EU hydrogen legislation is being translated into Belgian law, guided by principles of transparency, non-discrimination, and open access. Adoption is expected in 2026. Commercially, long-term binding offtake agreements remain key. India's highly competitive production costs are a strong advantage in this respect.

**As hydrogen supply chains mature globally through 2025 and beyond, how does Port of Antwerp-Bruges plan to balance domestic European hydrogen demand, imported volumes and collaboration with emerging markets like India?**

Belgium has limited domestic hydrogen production potential, making imports indispensable. At the same time, diversification is essential to avoid overdependence. Alongside India, we are exploring supply routes from Namibia, Oman, Brazil, and others.

> **India's strong production potential combined with Europe's concentrated industrial demand creates a natural production–consumption synergy that maximizes emissions reduction per euro invested**

**Port of Antwerp-Bruges and Port of Rotterdam are both positioning themselves as major European hydrogen and hydrogen-carrier (ammonia/methanol) hubs. How does Antwerp-Bruges differentiate its value proposition with Port of Rotterdam?**

In this respect, European ports are rather complementary and not purely competitive. For Indian partners, the most important factors are infrastructure readiness, regulatory clarity, industrial demand, and logistics connectivity. These are all areas where Port of Antwerp-Bruges offers a very strong value proposition.

**Port of Rotterdam has invested heavily in hydrogen infrastructure, pipeline networks and bunkering. How is Antwerp-Bruges tailoring its port infrastructure and service offerings to compete effectively for Indian green hydrogen/ammonia volumes?**

In Antwerp-Bruges, multiple large-scale ammonia storage and cracking projects are under development with partners such as Air Products, Vopak, Advario, Fluxys, and VTTI. Several of these projects have entered FEED phases and permitting procedures, with 2 FID's expected soon and commissioning targeted towards 2029–2030. All these projects are among the most advanced in Europe.

**Looking ahead to 2030, what shared benchmarks or project milestones would Port of Antwerp-Bruges like to achieve with Indian counterparts?**

By 2028–2030, we aim to see the first fully operational hydrogen and ammonia import corridors. This marks the transition from strategy papers to real molecules flowing, from ambition to execution

# TRANSFORMING ENERGY FOR A SUSTAINABLE FUTURE

As the nodal agency, SRM University–AP facilitates collaboration among stakeholders, supports translational research, and anchors workforce development initiatives

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India's pursuit of green hydrogen marks a decisive shift in how the country thinks about energy, industry, and development. India's clean energy transition has entered a decisive phase, with the Union Cabinet's approval of National Green Hydrogen Mission (NGHM). The national aspiration to achieve 5 million tonnes per annum of green hydrogen production by 2030, under NGHM, is not simply a quantitative target; it is a qualitative reimagining of India's energy future. Green hydrogen sits at the convergence of climate responsibility, energy security, and industrial competitiveness, offering India a pathway to decarbonise hard-to-abate sectors while simultaneously building indigenous technological and manufacturing capabilities.

NGHM aims to attract investments of over Rs. 8 lakh crore, create more than 6 lakh jobs and cut fossil fuel imports by at least Rs. 1 lakh crore. These numbers indicate that hydrogen is central to India's economic vision.

Green Hydrogen has emerged as one of the promising energy sources to decarbonise core industries, enhancing energy security and open new global markets.

Technology and policy alone will not be able to deliver this transition. At its core, the green hydrogen economy is a human enterprise. Its success depends on whether India can develop a workforce that is scientifically competent, technologically agile, safety-conscious, and industry-ready, innovative applications of hydrogen

> **The pace and complexity of the hydrogen transition demand a rethinking of traditional industry–academia relationships**

in energy intensive sectors, such as railways, aviation, data centers etc. As India transforms its energy systems, it must also transform its education, training, R&D, and institutional frameworks to ensure that skills evolve in step with ambition.

## Green Hydrogen as a Systemic Energy Transition

Green hydrogen is produced by splitting water using renewable electricity, resulting in a clean energy carrier that emits no carbon from end to end. While the concept is well understood, its deployment at scale introduces significant complexity. Hydrogen production requires high-performance electrolysers, stable and quality renewable power supply, reliable water management, and robust balance-of-plant systems. Storage and transportation add further layers of challenge due to hydrogen's low volumetric energy density, necessitating solutions such as high-pressure compression, liquefaction, or advanced material-based storage.

What distinguishes green hydrogen from earlier energy transitions is its systemic nature. It does not replace a single fuel in a single sector. Instead, it connects renewable electrical energy with industry, transport, chemicals, and power generation. This interconnectedness means that the workforce supporting green hydrogen must be interdisciplinary—combining knowledge of electrochemistry, materials science, electrical engineering, mechanical systems, digital control, and environmental assessment.

## Applications Driving Demand for Skills

Hydrogen's versatility explains why it has emerged as a cornerstone of long-term decarbonisation strategies. In transportation, fuel cell electric vehicles are gaining attention for applications where batteries struggle, particularly heavy-duty trucks, buses, and long-distance mobility. In industrial processes, hydrogen offers a route to deep decarbonisation in steelmaking, refining, and high-temperature manufacturing, where fossil fuels have traditionally been indispensable.

The fertiliser and chemical sectors stand to benefit through the production of green ammonia, reducing dependence on imported feedstocks and lowering lifecycle emissions. Hydrogen also enables long-duration energy storage, complementing solar and wind power by addressing intermittency. Emerging applications—such as backup and prime power for telecom infrastructure, data centres, and even aviation—highlight hydrogen's potential to penetrate new domains as technologies mature.

Ministry of Railways has developed a hydrogen powered fuel cell base passenger train and will be demonstrated soon. The Indian Railways is undertaking a transformation with a few global parallels.

Each application introduces distinct technical and operational requirements. A hydrogen-based steel plant demands metallurgical expertise and process integration skills, while hydrogen-powered buses require competencies in fuel cells, power electronics, and refuelling infrastructure. Data centres, increasingly energy-intensive due to digitalisation and artificial intelligence, require professionals who understand both hydrogen systems and mission-critical power reliability. The breadth of applications therefore translates directly into a wide spectrum of workforce needs.

## National Vision and the Role of Human Capital

The National Green Hydrogen Mission, announced by the Prime Minister, Narendra Modi, positions India as a future global supplier of green hydrogen and its derivatives. The Mission's emphasis on domestic manufacturing, cost reduction, research and development, and employment creation reflects a strategic understanding: leadership in green hydrogen will be determined not only by natural resources or capital investment, but by capabilities embedded in people and institutions.

India's demographic advantage amplifies this opportunity. A young workforce, if appropriately trained, can become a competitive asset in a global hydrogen market that will increasingly value skills in system design, safety management, and large-scale operations. Conversely, without targeted skilling initiatives, the same demographic advantage could become a bottleneck, slowing deployment and increasing reliance on imported expertise.

## Andhra Pradesh and the Green Hydrogen Valley Vision

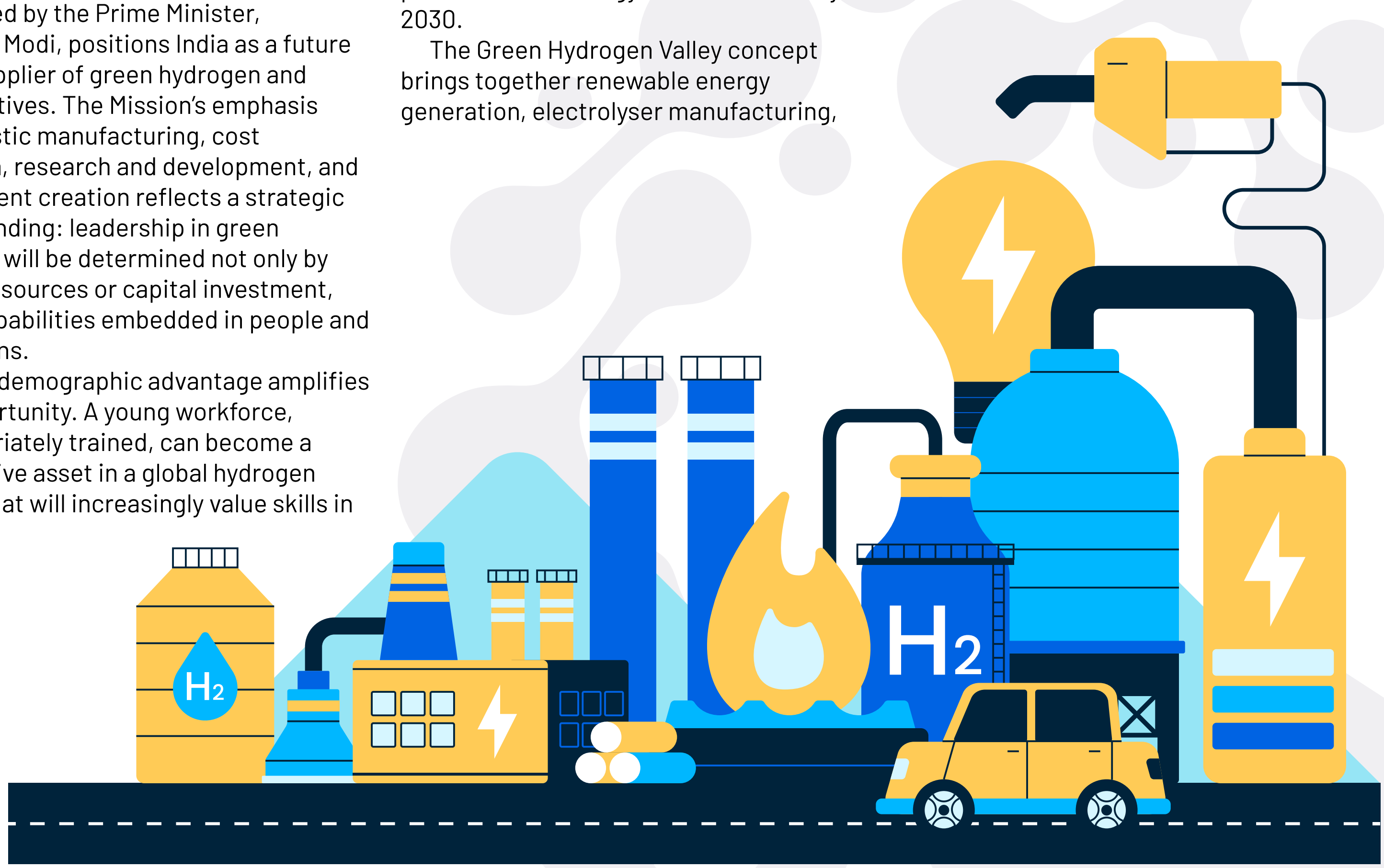
Within this national context, Andhra Pradesh has articulated a particularly ambitious and integrated approach. The declaration of the Green Hydrogen Valley – Andhra Pradesh signals the state's intention and commitment to move beyond isolated pilot projects and towards an ecosystem-based model of development. The vision is to establish Andhra Pradesh as India's largest green hydrogen hub and a global reference point for clean energy transformation by 2030.

The Green Hydrogen Valley concept brings together renewable energy generation, electrolyser manufacturing, hydrogen production, end-use applications, and skill development within a single strategic framework. Targets such as large-scale hydrogen production capacity, local manufacturing of electrolysers and storage systems, and the creation of dedicated green energy corridors reflect a commitment to scale and integration. Equally important is the focus on demand creation through hydrogen-powered transport, industrial clusters, and decentralised energy solutions.

What sets this approach apart is the recognition that infrastructure and incentives must be matched by institutional leadership and workforce preparedness.

## SRM University–AP as the Nodal Institution

Recognizing the need for coordinated institutional leadership, SRM




University-AP has been designated as the State Nodal Agency for the Green Hydrogen Valley. This role places the university at the intersection of policy, industry, research, and skill development.

As the nodal agency, SRM University-AP facilitates collaboration among stakeholders, supports translational research, and anchors workforce development initiatives. Its mandate extends beyond academic instruction to include technology validation, start-up incubation, and continuous dialogue between government and industry. By situating the hydrogen ecosystem within an academic institution, the state ensures that learning, innovation, and deployment progress together rather than in isolation.

A particularly significant aspect of this role is the emphasis on creating an integrated green hydrogen skilling ecosystem. Such an ecosystem recognises that hydrogen-related jobs will span multiple qualification levels—from researchers and design engineers to technicians, safety officers, and plant operators. Training programs must therefore be modular, interdisciplinary, and closely aligned with industry needs.

## Industry–Academia Partnership as a Cornerstone

The pace and complexity of the hydrogen transition demand a rethinking of traditional industry-academia relationships. Static curricula and isolated research efforts are insufficient in a domain where technologies, standards, and economics are evolving rapidly. Instead, continuous engagement is required, with industry shaping research questions and academia responding with solutions that are not only innovative but also scalable and commercially relevant.

Such partnerships are particularly critical for workforce development. Students trained in hydrogen technologies must be familiar with real-world operating conditions, safety protocols, and industrial constraints. Similarly, professionals already in the workforce require opportunities for reskilling and upskilling as hydrogen systems are integrated into existing industries.

A Centre of Excellence in Hydrogen focusing on production, storage, and utilisation keeping the industry standards on place. The centre is being established at SRM University - AP, in association with industry and the objectives are

- Indigenous development of electrolysers for hydrogen production at industrial scale
- Large scale and novel solid-state storage of Hydrogen using $NaBH_4$
- Direct sea water electrolysis to produce Hydrogen using a low-cost electrocatalyst: A combination of precious metals and mixed metal oxides (Synergized Precious Group Metal Catalysts)

## Workforce Development across the Value Chain

A future-ready hydrogen workforce must be developed across the entire value chain. At the upstream end, researchers and engineers are needed to improve electrolyser performance, reduce reliance on critical materials, and develop safer and more compact storage solutions. In manufacturing, skills in precision fabrication, quality assurance, and systems integration are essential to localise production and reduce costs.

At the deployment and operations stage, technicians trained in installation, maintenance, and safety management become critical. Hydrogen's unique properties require rigorous adherence to codes and standards, making specialised training indispensable. Beyond technical roles, the hydrogen economy also demands professionals in project management, policy analysis, environmental assessment, and finance—underscoring the need for multidisciplinary education.

## Platforms for Knowledge Exchange and Collaboration

> **The Green Hydrogen Valley concept brings together renewable energy generation, electrolyser manufacturing, hydrogen production, end-use applications, and skill development within a single strategic framework**

Sustaining momentum in workforce development requires regular platforms for knowledge exchange. Events such as the Green Hydrogen Summit – 2025 are designed to bring together industry leaders, researchers, policymakers, start-ups, and students to share insights and align priorities. Such forums play a vital role in translating policy goals into actionable strategies, while exposing the next generation of professionals to emerging challenges and opportunities.

More importantly, these platforms help build a shared narrative around green hydrogen—as a long-term national mission rather than a short-term technological trend. This narrative is essential for attracting talent, investment, and sustained public support.

## Conclusion: People at the Centre of the Hydrogen Transition

India's green hydrogen ambition is bold, timely, and necessary. Yet its realisation will depend on the country's ability to place people and skills at the centre of the transition. Technologies can be imported and infrastructure can be financed, but the capacity to innovate, adapt, and operate at scale must be cultivated domestically.

The Green Hydrogen Valley initiative in Andhra Pradesh, supported by strong industry–academia partnerships and institutional leadership from SRM University–AP, offers a compelling blueprint. By aligning national ambition with regional execution and workforce development, it demonstrates how India can transform energy systems while simultaneously building human capital. In doing so, green hydrogen becomes not only a pathway to decarbonisation, but also a vehicle for inclusive, sustainable, and future-ready growth

# WHAT IT WILL TAKE TO BUILD A SCALABLE GREEN HYDROGEN TECHNOLOGY ECOSYSTEM IN INDIA

Building a resilient and competitive green hydrogen ecosystem in India will require deep coordination across policymakers, industry leaders, technology providers, financiers, and investors

**Bharat Goenka**
**Region Vice President - India**
NEXTCHEM (MAIRE group)

Developing a robust and scalable 'Green Hydrogen Technology Ecosystem' in India is emerging as a critical pillar in realising the world's fastest-growing economy's dream of achieving energy independence by 2047. But realising this vision requires a tightly coordinated, multi-stakeholder approach that brings together technology innovation, industrial strategy, infrastructure development, regulatory clarity, and capital markets into one shared national ambition.

## Ambitious Renewable Energy Push

As the world's fourth-largest economy aims to achieve the Net Zero Emission target by 2070, it is primarily betting on harnessing wind, solar, nuclear, and other renewable sources of energy to cut emissions. In the process, the country aims to increase the renewable power capacity to 500 GW by 2030, including 280 GW of solar and 100 GW of wind capacity.

To give a further push to its green economy, India has articulated one of the world's most ambitious targets of achieving five million tonnes of annual Green Hydrogen production capacity by 2030, supported by around 125 gigawatts (GW) of renewable energy.

The vision extends beyond domestic decarbonization to global leadership in green molecules hydrogen and ammonia by leveraging India's long coastline, a strengthening transmission network, abundant biomass potential, and a policy framework that encourages scale. Port-led hubs for green hydrogen and ammonia are designed to service export markets while anchoring local consumption in strategic sectors.

## Government's Green Energy Push

India is among few countries in the world where the government has announced production-linked incentive schemes and targeted subsidies to accelerate the adoption of green molecules in the country to achieve Energy independence and Net Zero Emissions goals. MAIRE subsidiary installed India's first 10 MW green H2 Plant

> **India is also among very few countries in the world where the government have announced production-linked incentive schemes and targeted subsidies to accelerate the adoption of green molecules in the country**

on EPC basis in India at GAIL Vijaipur.

To provide a strong policy impetus to the green economy and support the growth of the adoption of green hydrogen and ammonia, the world's most populous nation has launched the National Green Hydrogen Mission (NGHM) and Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, supported by targeted incentives, coastal infrastructure development, and waste-to-energy potential, with a combined budgetary outlay of $2.1 billion.

Besides providing cash incentives and tax benefits, the government has also identified key sectors including steel, fertilisers, refineries, transportation and energy storage for green hydrogen deployment and has sanctioned several pilot projects under the mission across the steel, mobility and maritime sectors.

## Challenges

Despite presenting tremendous opportunities, India's effort to develop a scalable green hydrogen technology ecosystem is not without its share of challenges, including high capital costs, limited infrastructure for storage and transportation, technology dependencies for critical electrolyser components, and water resource constraints in renewable-rich regions.

The cyclic nature of renewable energy remains the biggest bottleneck to scaling up green hydrogen production capacity in the country. India, over the past few years, has made significant investments in ramping up renewable power generation capacity, but grid constraints continue to limit the reliable and affordable power supply needed for large projects.

Going forward, India will need 60-80 GW of renewable power by 2030, yet transmission and connectivity timelines are already slipping beyond that horizon. To overcome the grid challenge, India needs to invest heavily in setting up a strong transmission network, enabling hydrogen plants to be developed anywhere in the country without being constrained by grid co-location.

## Opportunities: Unlocking India's Green Hydrogen Potential Through Waste-to-Energy

Harnessing waste-to-energy presents another unique opportunity for India to scale up the production of the green molecule, as the country produces nearly 62 million tonnes of municipal solid waste annually and has a surplus of around 230 million metric tonnes of agricultural biomass. If efficiently aggregated and organised at industrial scales, these resources can serve as a feedstock base to produce around 20 million tonnes of Green Hydrogen per year. Therefore, a thrust is required in waste aggregation and making availability for industry to attract investment.

NEXTCHEM, the Sustainable Technology Solutions business unit of MAIRE, has been a frontrunner in deploying industrial-scale waste-to-X (hydrogen/ Chemicals) technologies globally. Their experience in converting MSW and biomass into green molecules aligns closely with India's ambitions. Leveraging such proven technologies could help transform India's massive waste streams into a dependable, year-round feedstock for green hydrogen production

> **The cyclic nature of renewable energy remains the biggest bottleneck to scaling up green hydrogen production capacity in the country**

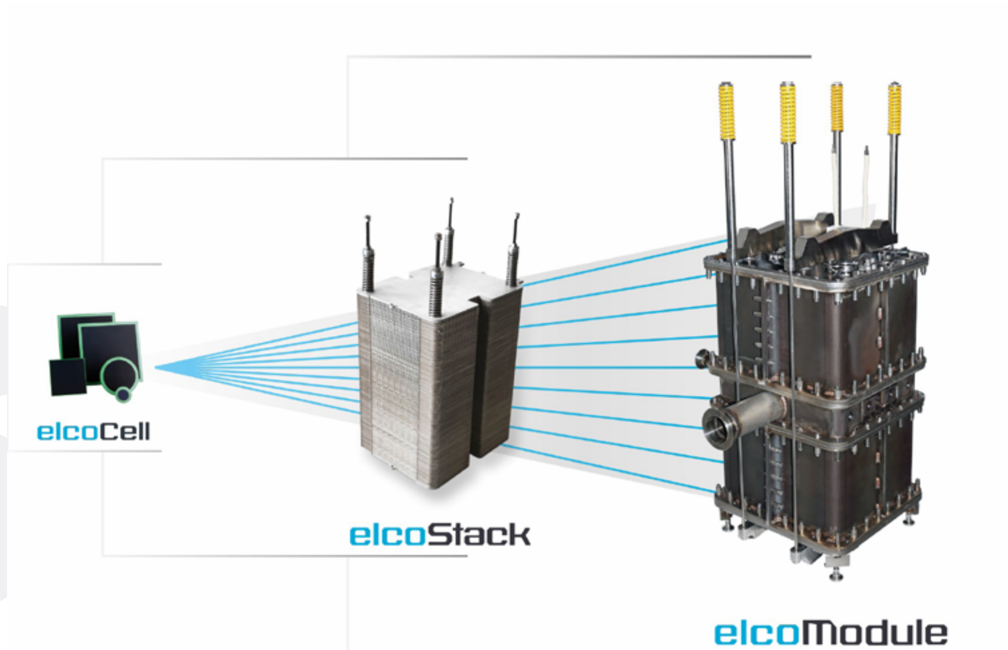
## Conclusion: The Path to a National Hydrogen Ecosystem

Building a resilient and competitive green hydrogen ecosystem in India will require deep coordination across policymakers, industry leaders, technology providers, financiers, and investors. If this alignment is achieved, green hydrogen can significantly strengthen India's climate ambition, enhance industrial competitiveness, and reinforce long term energy security

# ELCOGEN AND THE CASE FOR SOLID OXIDE TECHNOLOGY IN INDIA'S HYDROGEN FUTURE

Elcogen partners with clients across the entire project lifecycle, providing support from initial design and simulation to final commissioning and optimization

**Anil Srikar Pavuluri**
**Business Development Director India & APAC**
Elcogen




Amid India's accelerating transition towards a low-carbon economy, hydrogen has emerged at the centre of industrial and energy policy discussions. The National Green Hydrogen Mission, expanding renewable generation and the urgent need to decarbonise heavy industry are together shaping one of the most promising hydrogen markets in the world. For Indian stakeholders assessing global technology providers with proven industrial capability, Elcogen is a company that merits close attention.

Founded in 2001, Elcogen develops and supplies a proprietary solid oxide technology platform capable of operating in both fuel cell and electrolysis modes. This means the same underlying technology can be used either to generate clean electricity or to produce green hydrogen. The ability to switch between these functions offers a level of flexibility that is increasingly valuable as energy systems evolve. Reflecting both its technological maturity and global relevance, Elcogen was named one of TIME Magazine's World's Top Green Tech Companies of 2025.

Elcogen has its registered office in the UK, with headquarters in Tallinn, Estonia, and research and development centres in Estonia and Finland. From these bases, the company serves a growing global customer base. Its solid oxide cells, stacks and modules are integrated into third party systems across sectors where decarbonisation is essential, including Combined Heat and Power (CHP), steelmaking, e fuels, shipping, data centres and energy infrastructure.

## Moving Beyond Combustion-based Systems

The starting point for Elcogen's technology proposition is the recognition that combustion has reached its limits. Even with efficiency improvements, combustion-based processes continue to generate harmful emissions. Industries with high energy demand now require solutions that fundamentally change how



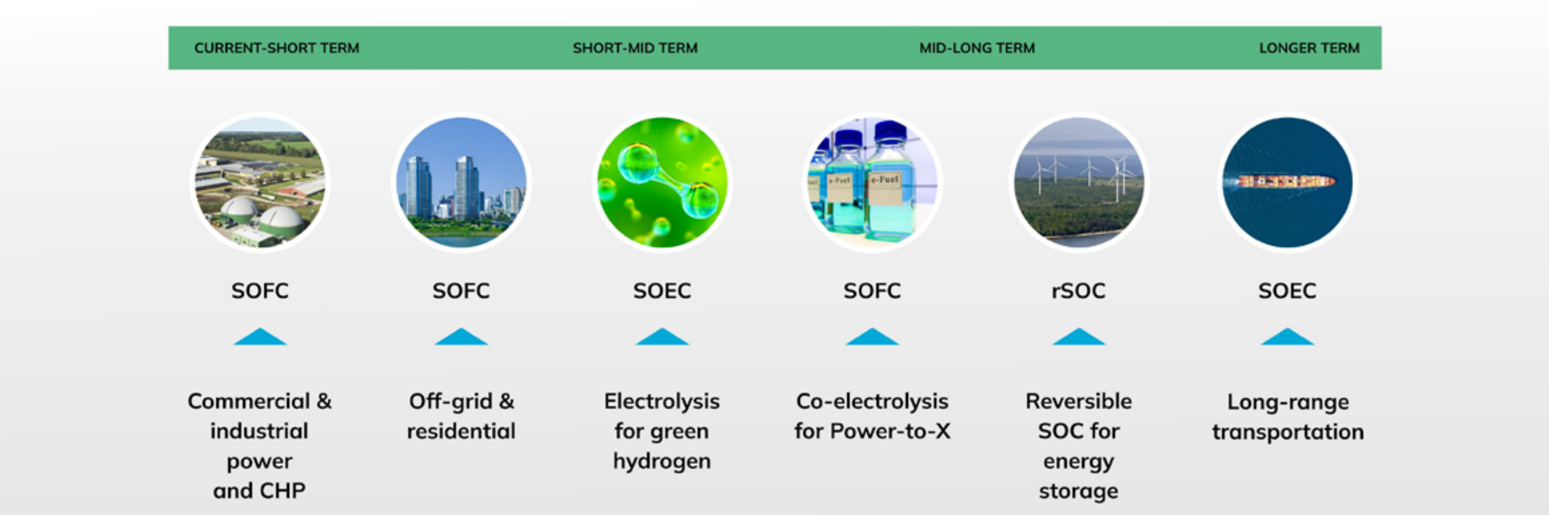
energy is produced and used.

Solid oxide technology enables hydrogen production through electrochemical conversion rather than combustion. Operating in electrolysis mode, solid oxide electrolysers use both electricity and heat to split water into hydrogen and oxygen, delivering significantly higher efficiency than conventional technologies. Elcogen's solid oxide components consume around 30 per cent less electricity than alkaline, PEM, and AEM electrolysers and produce hydrogen at approximately 33 to 40 kilowatt hours per kilogram, among the lowest energy consumption levels currently achievable at industrial scale. When renewable energy availability and cost are the key decisive factors in determining green hydrogen competitiveness, this efficiency advantage is particularly relevant, as lower electricity demand reduces the renewable power, land and capital required and accelerates progress towards cost competitive green hydrogen for sectors such as fertilisers, refining, steel and synthetic fuels.

## Designed for Flexibility and Localisation

Elcogen deliberately positions itself as a component manufacturer, thus

> **Elcogen's solid oxide technology consumes around 30% less electricity than Alkaline, PEM and AEM electrolysers, leading to reduction in renewable power, land, and capital requirements, which accelerates the progress towards cost competitive green hydrogen**



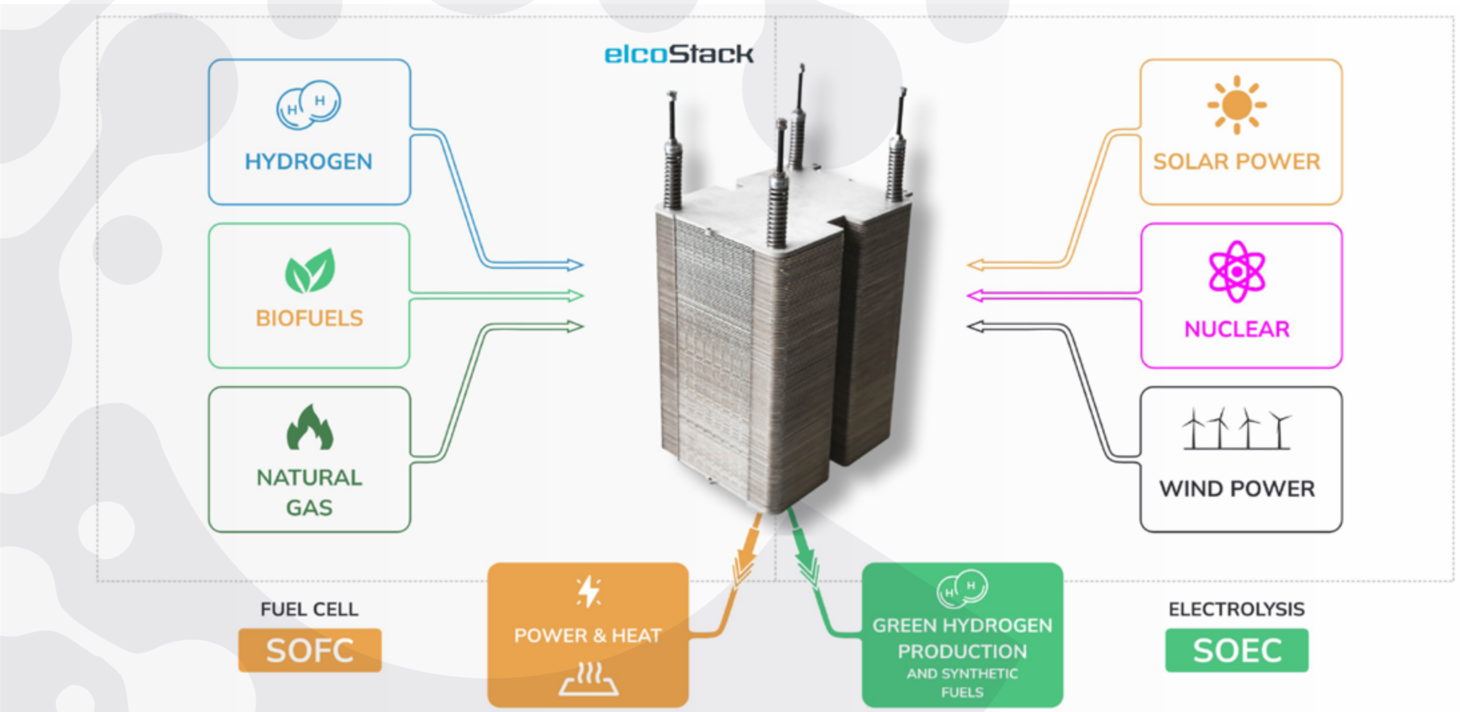

technology enabler, rather than a system owner. Its core products are cells, stacks and modules that form the heart of electrolysers and fuel cell systems developed by partners. This application-agnostic approach allows system integrators and industrial players to tailor solutions to specific market needs.

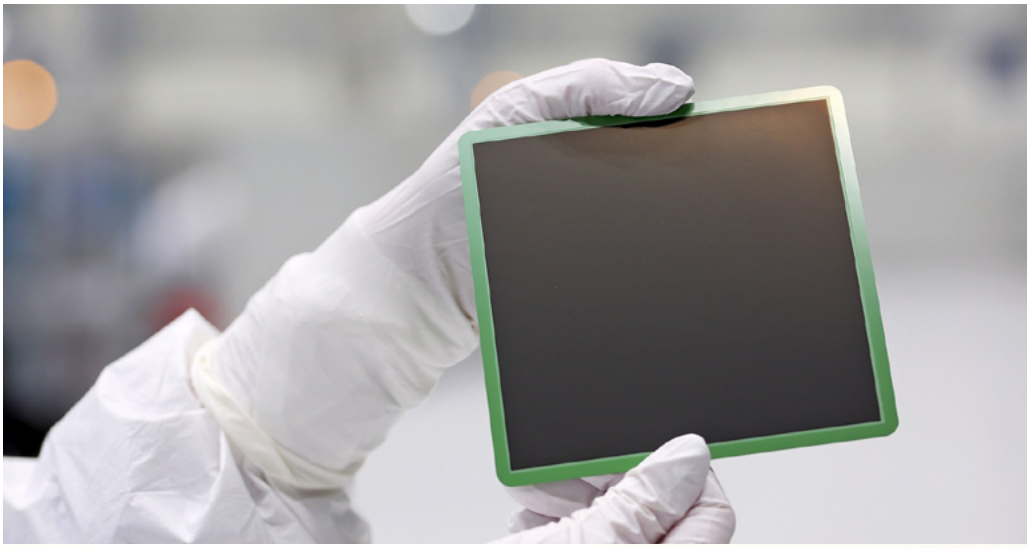
For India, this opens the door to localisation. Elcogen licenses its technology and manufacturing blueprint to support domestic production while maintaining intellectual property control and consistent performance. This model aligns well with India's industrial policy priorities, including local manufacturing, supply chain resilience and the development of domestic hydrogen ecosystems.

## Proven Performance across Real World

## Applications

Solid oxide technology has long been recognised for its potential, but Elcogen has demonstrated its viability in practical deployments. Its technology has been validated in combined heat and power systems, electric vehicle charging infrastructure and industrial hydrogen projects. The firm is currently involved in the Horizon Europe-funded SYRIUS project, aimed at nothing less





than demonstrating the world's largest 4.2+ MW Solid Oxide Electrolyser in a steel plant in Terni, Italy. Capable of producing 100 kg/h of green hydrogen, the integration is expected to cut $CO_2$ emissions by 5,600 tonnes per year.

A key advantage with Elcogen lies in reversibility. The same solid oxide platform supports both power-to-gas and gas-to-power operation. This enables systems that can produce hydrogen when renewable electricity is abundant and generate electricity when energy demand is high. In the context of India's evolving power system, with rising renewable penetration and growing demand for decentralised energy solutions, this flexibility is a significant asset. Elcogen's solid oxide fuel cell technology achieves electrical efficiencies of up to 75 per cent, rising to around 90 per cent when heat is recovered and used in cogeneration. High efficiency improves project economics while making better use of energy resources, which is critical in energy intensive industrial environments.

## Manufacturing at Industrial Scale

As hydrogen moves from demonstration projects to large scale deployment, manufacturing capacity has become a key differentiator. In 2025, Elcogen completed and opened ELCO I, a 14,000 square metre, state-of-the-art manufacturing facility in Tallinn, Estonia. This marked a decisive shift from limited production to true industrial scale manufacturing.

The production line is already operational and capable of producing up to 360MW. Factory construction was supported by strategic industrial investors including Baker Hughes and HD Hyundai, and funding from the EU Innovation Fund. Advanced automation, including roll-to-roll printing and continuous processing, is reducing production times from weeks to days while improving yield and consistency. For customers and partners, this scale and reliability of supply are critical as hydrogen projects grow in size and complexity.

> **Crucially, solid oxide technology avoids reliance on precious materials such as iridium and platinum, positioning it as a more resilient and future-proof solution as supply chains tighten and demand accelerates**

## Relevance for India's Hard to Abate Sectors

India's hardest to abate sectors share two defining characteristics. They are energy intensive and they generate significant amounts of heat. These conditions are particularly well suited to solid oxide electrolysers, which can integrate heat into hydrogen production to reduce overall energy costs.

At the same time, the rapid expansion of data centres, telecom infrastructure and remote industrial operations is driving demand for clean, reliable and efficient power generation beyond the grid. Solid oxide fuel cells running

on hydrogen or low carbon fuels offer a pathway to zero emission baseload and backup power without the noise and pollution associated with diesel generators.

The combination of industrial hydrogen demand and distributed power generation creates strong momentum for solid oxide technology, linking hydrogen production directly with high efficiency electricity generation.

Elcogen is actively exploring partnerships with numerous incumbent EPCs to broaden the reach of its SOEC tech. They recently inked an MoU with Casale, the global provider of technologies and integrated engineering solutions to produce base chemicals. This will enable the parties to collaborate on green ammonia and other Power-to-X projects. Ammonia production, which today relies primarily on hydrogen derived from natural gas, has traditionally been dependent on fossil fuels, making it a significant source of CO2 emissions. However, by coupling green hydrogen technology into ammonia production and leveraging renewable energy sources, the new process can significantly reduce emissions, offering a cleaner and more sustainable solution for the industry.

## A Collaborative Approach to Energy Transition

Elcogen's role in the hydrogen economy extends beyond supplying components. The company works closely with partners throughout the project lifecycle, from early-stage design and system simulation through to commissioning and optimisation. This reflects a recognition that successful hydrogen projects depend not only on technology, but on economic viability, system integration, operational performance and long-term reliability.

Economic value is paramount to the large-scale uptake of green hydrogen, and this is where solid oxide technology is becoming increasingly compelling. Solid oxide systems are on track to reach cost parity with alkaline and PEM technologies, and once achieved, are expected to deliver even greater value through a lower levelised cost of hydrogen, superior electrical efficiency and greater scalability. Crucially, solid oxide technology avoids reliance on precious materials such as iridium and platinum, positioning it as a more resilient and future-proof solution as supply chains tighten and demand accelerates.

Elcogen was founded in post-independence Estonia at a time when energy security and cost predictability were essential for economic survival, shaping the company's focus on efficiency, reliability and long-term performance.

Commenting on the relevance of this experience for India, Elcogen CEO Enn Õunpuu shares: "Elcogen was created in a market where energy security and cost predictability were critical from day one. That heritage matters for green hydrogen off-takers today. We inherently understand that industrial customers need green hydrogen and bankable technology that can deliver reliable volumes over decades. We deliver this through our patented high-efficiency SOEC technology, manufacturing at scale, and deep integration expertise that supports long-term, dependable hydrogen supply."

With more than two decades of experience in solid oxide development and a clear pathway to large-scale manufacturing, Elcogen enters the Indian market conversation at a moment of accelerating ambition. For policymakers, industrial leaders and project developers, it represents a mature and flexible technology platform capable of supporting both cost-competitive hydrogen production and clean power generation at scale

# 2.4 KTPA GREEN HYDROGEN PLANT SET FOR Q2 FY 26-27 COMMISSIONING

## Our goal for 2030 is to achieve 22–24 KTPA of green hydrogen equivalent capacity

**Bhaskar Jyoti Phukan**
**Managing Director**
Numaligarh Refinery

**How does NRL's hydrogen plan align with NGHM and mandatory obligations under green hydrogen consumption or renewable purchase obligations?**

As a refiner, hydrogen is already central to our processes. Currently, the majority of Indian refineries utilize grey hydrogen, which is typically synthesized from either natural gas or naphtha feedstocks. In alignment with India's National Green Hydrogen Mission, the nation has set an ambitious target to produce approximately 5 million tonnes of green hydrogen annually by 2030, with the refining and fertilizer sectors anticipated to be the primary drivers of this increased demand.

Although no strict mandate exists, the transition to green hydrogen is advancing through allocated targets and voluntary adoption. In support of this national vision, NRL has committed to progressively integrating green hydrogen into its energy portfolio.

We are actively advancing our green hydrogen initiatives. A 2.4 KTPA (Thousand Tonnes Per Annum) green hydrogen plant, featuring a 17 MW alkaline electrolyser, is currently under execution and scheduled for commissioning by Q2 of the next financial year. Concurrently, a tender has been issued for an additional 10 KTPA plant on a build-own-operate (BOO) basis, with subsequent phases planning for a further 10 KTPA expansion.

Additionally, our parent company, Oil India, is making significant investments in compressed biogas (CBG). The biogenic methane generated from CBG is recognized as a green molecule. By integrating these various green streams, we anticipate reaching a capacity of 2.4 KTPA by next year, followed by an expansion to approximately 12.4 KTPA the year after. Our goal for 2030 is to achieve 22–24 KTPA of green hydrogen equivalent capacity; further expansion will hinge primarily on affordability and supportive policy frameworks.

**Where does 2.4 KTPA green hydrogen and 17MW alkaline electrolyser project stand today?**

We have achieved over 50% physical progress on the project. This milestone was reached because most construction activities are finished and nearly all major equipment has been ordered. The facility's full hydrogen production will be utilized internally (in-house).

**What is the status of the 10 KTPA green hydrogen tender?**

We have issued a tender for 10 KTPA of green hydrogen, attracting ten participants. Bids will be opened shortly, and the contract will be awarded to the most competitive bidder. Project completion is anticipated within 18 months.

For subsequent 10 KTPA plants, we are assessing the potential green hydrogen equivalent available via Oil India's Compressed Biogas (CBG) investments. This evaluation will determine the size of the remaining capacity, which will likely be tendered out, potentially on a Build-Own-Operate (BOO) basis again. Given that power accounts for 70–80% of green hydrogen costs, many power producers are now entering the production market, enhancing overall competitiveness.

**How much investment has been made for these plants?**

The total investment for the 2.4 KTPA project is estimated at approximately Rs. 150 crore. This cost covers electrolyzers, the balance of the plant, and land allocation. The larger 10 KTPA project, however, will operate on a Build-Own-Operate (BOO) model, meaning NRL will avoid capital expenditures (CAPEX); instead, the output will be procured at the lowest discovered cost.

**What electrolyser technology is planned for 2.4 KTPA green hydrogen plant? What are the design specifications and target timeline for scaling hydrogen output from the initial 2.4 KTPA to mid- and long-term goals?**

The tender process was inclusive, welcoming proposals for various technologies such as alkaline, Polymer Electrolyte Membrane (PEM), or others. The chosen solution is an alkaline electrolyser, sourced via Greenko and manufactured by John Cockerill of Belgium. Commissioning is slated for Q2 of next year. The scaling up process


is expected to be straightforward, and full-scale operation should be achievable within one month of the system stabilizing.

**Given the requirement of around 18 MW of green electricity for the hydrogen plant, how does NRL plan to source this through new RE installations, PPAs, or procuring Renewable Energy Certificates (RECs)?**

We have invested Rs. 1,170 crore in a 220 kV substation, developed in collaboration with Assam Grid Corporation Limited (AGCL), to enable long-term green power procurement. The main hurdle is the intermittency of renewables, preventing guaranteed round-the-clock (RTC) availability. We are treating this as an industrial-scale pilot project and will assess the best strategies for managing RTC needs as the operation progresses.

> **We are assessing the potential green hydrogen equivalent available via Oil India's Compressed Biogas investments. This evaluation will determine the size of the remaining capacity, which will likely be tendered out, potentially on a Build-Own-Operate (BOO) basis**

**How much of NRL's total hydrogen demand (current and projected) will be met by this green hydrogen? What percentage substitution relative to grey hydrogen are you targeting?**

Initially, the 2.4 KTPA of green hydrogen production is projected to satisfy approximately 5% of our present hydrogen requirements. Following the refinery expansion, total demand for hydrogen is set to increase to about 138 KTPA. Within a two-year timeframe, green hydrogen output is expected to reach 12.4 KTPA, covering roughly 9% of that total future demand. Currently, all hydrogen produced is utilized internally within the refinery's hydroprocessing units. While there are no immediate

**While the mobility sector's transition may progress at a slower pace, industrial applications—particularly in refining, fertilizers, and steel production—are expected to spearhead the adoption once production costs decreases**

plans for external sales, we remain open to supplying surplus green hydrogen externally (e.g. for fuel cell vehicles) should a viable market and attractive pricing emerge in the future.

**How will the integration of green hydrogen affect NRL's overall carbon footprint in terms of emission reductions expected from Scope 1 and Scope 2?**

Each kilogram of grey hydrogen produced emits 9–10 kg of $CO_2$. Shifting some demand to green hydrogen substantially reduces Scope 1 and Scope 2 emissions. Annual emissions tracking results are published in our sustainability reports.

**Does NRL expect hydrogen production costs competitive with grey hydrogen? What is the target cost per kg of green hydrogen?**

Grey hydrogen currently costs approximately Rs. 100 per kg, produced using domestic natural gas. In contrast, green hydrogen is estimated to cost Rs. 300–350 per kg, making it two to three times more expensive at present. With policy interventions, reduction in cross-subsidy charges, and lower renewable tariffs, green hydrogen can become competitive.

**Are there plans to expand green hydrogen capabilities beyond the refinery campus for mobility (fuel-cell vehicles), export clusters, or supplying to other industries?**

Oil India is currently operating hydrogen-powered buses in Jorhat, utilizing a small, AM-based hydrogen plant.
However, the widespread implementation of large-scale hydrogen mobility hinges on the development of a complete ecosystem, including dispensing stations, storage facilities, and extensive infrastructure, which is a time-consuming process. Consequently, in the immediate future, the primary drivers of hydrogen adoption are expected to be the refinery and industrial sectors.

**What are the key challenges in executing the green hydrogen project (power availability, water supply, safety, regulatory approvals, capital cost)?**

The two main challenges are high electricity costs, driven by transmission charges, cross-subsidy, and interstate wheeling fees, and the need for round-the-clock renewable availability.
Hydrogen storage is not currently viable due to high costs, so production and consumption must remain closely aligned. Water availability is not a concern for us, as we operate in a water-surplus region. It is anticipated that electrolyser expenses will decrease as industrial-scale manufacturing becomes more widespread.

**What is NRL's long-term roadmap for hydrogen beyond the initial 2.4 KTPA. What capacity do you plan for 2030, 2035 and 2038 (net-zero target)?**

Our long-term strategy involves a phased transition from grey to green hydrogen, commencing with an initial replacement target of 48 KTPA. Following this initial phase, we will assess the optimal approach for integrating our existing and new infrastructure.
The widespread adoption of green hydrogen across key sectors like refining, fertilizers, and steel is poised to accelerate significantly if it becomes consistently affordable and available 24/7 at an electricity cost of just Rs. 3–4 per unit.

We maintain a strong conviction that green hydrogen will reach economic viability in the near future. While the mobility sector's transition may progress at a slower pace, industrial applications—particularly in refining, fertilizers, and steel production—are expected to spearhead the adoption once production costs decrease.

**What safety and environmental standards will be followed in hydrogen production, storage, and handling? How will these be integrated into the expanded refinery operations?**

We have been handling the hydrogen molecule for ages. We have our own safety standards within the refinery and process units.

**How does NRL plan to monitor and report the carbon-emission reductions and sustainability gains achieved through the hydrogen initiative?**

We already have a CO2 emission assessment every year. We publish a Business Responsibility and Sustainability Report (BRSR) report each year and one can see it for the details. We have accredited agencies to monitor the same

# FROM PROMISE TO PROOF: INDIA'S MOMENT IN THE GREEN HYDROGEN ECONOMY

## Green hydrogen and its derivatives represent a rare opportunity for India to shift from being a net importer of energy molecules to a competitive exporter of clean ones

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**Managing Director and Senior Partner**
Asia Pacific Leader, Climate & Sustainability
BCG

**Siddharth Jain**
**Managing Director and Partner**
BCG

2026 is shaping up to be a watershed year for green hydrogen ($GH_2$). After several years dominated by announcements, pilots, and memoranda of understanding, the sector is entering a more demanding phase. One defined by kilograms delivered, hours operated, and projects financed on terms that resemble infrastructure rather than experimentation. The industry is moving from promise to proof.

This shift is not accidental. Three cost curves - renewable electricity, battery storage, and electrolyzers - are bending in the right direction at the same time. When that happens, hydrogen stops being a niche decarbonization option and begins to look like a competitive commodity in global energy and molecules markets.

The clearest way to see this inflection is through the lens that ultimately matters: dollars per kilogram. Conventional grey hydrogen produced from natural gas typically costs around \$1.5-\$2.5/kg, depending on feedstock prices and plant economics. Blue hydrogen with carbon capture usually lands in the \$2.0-\$3.5/kg range under common assumptions. Green hydrogen, by contrast, remains a premium product in most markets (often \$3.5–\$6.0/kg) with India frequently cited around \$4/kg today.

These figures, however, are not destiny. They reflect an industry still climbing its learning curve. The strategic question for 2026 is whether green hydrogen can begin a credible march toward the \$2/kg frontier in the best locations. Once it does, green hydrogen (and its derivatives such as green ammonia, green methanol, and ultimately sustainable aviation fuels) starts competing on economics, not just policy support.

The first driver of cost reduction is renewable power, which today accounts for >60% of the cost of hydrogen. As storage economics improve and hybrid renewable configurations become more standardized, round-the-clock (RTC) power is gaining traction. Higher electrolyzer utilization materially reduces cost per kilogram by spreading fixed capital costs over greater output. Every 10% improvement in cost of renewable power brings down cost of GH2 by \$0.2-0.3/kg.

The second driver is electrolyzer scale and standardization. The sector is transitioning from bespoke, project-by-project engineering to manufactured systems. This shift matters as much for bankability as it does for headline capex. The largest driver here will be improvement in electrolyzer efficiency. Today at system level, we need 55-60kwH


of energy to generate 1kg of GH2. Most estimates suggest that this will come down to <50KwH of energy in the next 1-2 years. This will further bring down cost of GH2 by $0.5/kg.

The third driver which may define GH2 in 2026 is the "Asia factor". Chinese, Indian and broader Asian electrolyzer manufacturers are entering global deployments with cost structures that many Western suppliers struggle to match. If these systems demonstrate reliability at scale (across availability, degradation rates, efficiency under dynamic operation, and system integration) the impact will be structural rather than incremental. If Asian electrolyzers deliver on their promises, the global cost floor for green hydrogen will shift downward by atleast $0.5-0.7/kg. Further improvements in technology, yield will bridge the gap to $2/kg.

As GH2 economics improve, the global competitive map is coming into focus. Europe will continue to shape demand, standards, and incentives, but the fiercest competition on low-cost supply will come from regions that combine exceptional renewable resources, fast execution, and export-ready logistics. China's advantage lies in manufacturing depth and supply-chain integration. The Middle East benefits from high solar intensity, land availability, rapid infrastructure build-out, and long coastlines that simplify exports. Chile remains a benchmark for renewable quality and high utilization potential.

Against this backdrop, India enters 2026 with a strategic opening. Green hydrogen and its derivatives represent a rare opportunity for India to shift from being a net importer of energy molecules to a competitive exporter of clean ones. India's advantage sits at the intersection of scale and proximity: a large, flexible power system that allows flexible energy generation; a massive industrial base that provides domestic demand; and geographic closeness to fast-growing

**The strategic question for 2026 is whether green hydrogen can begin a credible march toward the $2/kg frontier in the best locations**

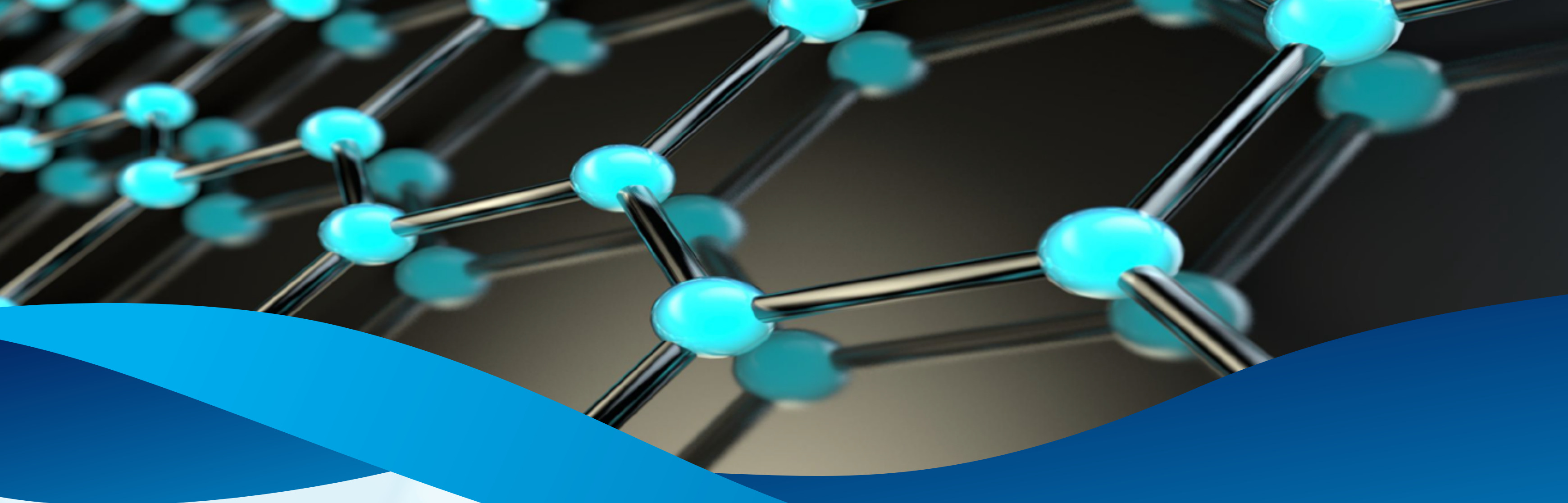
> **Europe will continue to shape demand, standards, and incentives, but the fiercest competition on low-cost supply will come from regions that combine exceptional renewable resources, fast execution, and export-ready logistics**

Asian demand corridors.

Winning, however, will require disciplined focus on four structural levers. The first is the delivered cost of clean power. India's grid scale and wheeling capability can be a competitive advantage allowing for flexible generation and transmission of renewable power (especially v/s markets like the Middle East with smaller grids) - provided policy frameworks keep power movement predictable and low-friction. The second lever is supply-chain pragmatism. While domestic electrolyzer manufacturing is strategically important, near-term competitiveness may depend on allowing imports of cost-competitive, bankable equipment, particularly if Asian systems prove reliable at scale. The third is land and execution speed. Land constraints affect renewables, electrolysis, storage, water systems, and export infrastructure; plug-and-play industrial zones and port-linked hydrogen hubs can materially shorten timelines and reduce delivered costs. The fourth lever is integration. India's industrial clusters can anchor demand, concentrated $CO_2$ point sources may support early e-fuels development and abundant bio-mass can offer blending opportunities with bio-fuels.

India's policy intent is already clear. The National Green Hydrogen Mission, with an initial outlay of Rs. 19,744 crore, including support through the SIGHT program and funding for pilots and R&D, has created a strong foundation. The prize is significant. If India delivers on a 5 MMT-scale vision and builds credible export capacity, potentially 3–3.5 MMT of export-oriented hydrogen or derivatives, it could materially strengthen the country's energy balance, improve the current account, and create a durable industrial position in global clean fuels.

The global race, however, is accelerating. India's right to win will not come from aspiration or announcements alone. It will come from structural advantages, execution speed, and relentless focus on cost. The winners of the hydrogen decade will be the ones that can deliver green hydrogen at a price the world will buy: dollars per kilogram, at scale ICN



# ECONOMICS OF GREEN HYDROGEN: WHEN AND HOW WILL IT BE COMPETITIVE?

Green hydrogen is still an evolving sector and will require strong, coordinated support across the ecosystem to become competitive at scale in India

**Sanchit Makhija**
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Green hydrogen is moved slowly from concept to centrepiece in global decarbonization strategies. Governments see it as essential for net-zero ambitions while industrial players view it as a pathway to decarbonize processes that electricity alone cannot reach. Yet, a central question remains unresolved: when, where, and how will green hydrogen become economically competitive?

The answer is nuanced. Green hydrogen will not become competitive everywhere at once, nor across all applications simultaneously. Instead, competitiveness will emerge first in specific geographies, sectors, and use cases—driven by a combination of renewable power economics, technology learning, policy design, and financing structures. This pattern is particularly evident in India, where structural advantages coexist with practical constraints. India is expected to play a structural role in green hydrogen global ecosystem. It has advantages of largest integrated grid in the world, backed by low cost of renewable energy potential and strong policy intent from the government to enhance energy security for the country. In addition, high cost of gas also makes gap lower vs. green hydrogen. However, multiple challenges exist which need to be addressed to define the economics for Green hydrogen in India going forward.

## Green Hydrogen: Cost Gap That Needs to be Addressed for India

Cost of green hydrogen is fundamentally determined by three key factors- price of clean electricity, electrolyser capital costs & its utilization rates and financing for the project. Together these determine the extent of cost gaps we see in India/ globally from conventional hydrogen/ alternate fuels.

### Electricity dominates the cost structure

Green hydrogen production is a power intensive process with requirement of 50-55 kWh of electricity per kilogram of hydrogen depending upon technology and efficiency. In India, renewables have been fairly competitive globally (ranging from Rs. 2.5-3.8/kWh depending upon the technology/ location). However, over the last 3 years, renewable tariffs have been rising consistently due to ALMM restrictions on the regulatory side, increase in equipment costs, cautious approach on CUFs by developers and lenders leading to higher cost of capital. In addition, co-location of renewables, access to banking and financing mechanisms, clear rules on grid supplied power in lines with global requirements critical to influence operating hours.


**Capital intensity of electrolysers and utilization are critical**
Electrolysers are capital intensive assets. In India, electrolyser domestic manufacturing is rising, however currently its exposed to global supply chains and currency risks. In future, backed by scaling, standardization, stack life improvements, electrolysers can have significantly lower costs. However, learning rates materialize only when deployment is sustained and supply chain mature. Stop start signals on policy can delay the cost reductions & keep "first of its kind" premiums high. In addition, in case electrolyzers run on low capacity factors on account of renewable power being intermittent or grid access being constrained, costs for the hydrogen rises further.

**Financing costs and structures need addressal**
Green Hydrogen is an emerging sector where risks on projects are not completely understood due to limited on-ground projects. By nature, these projects also involve large upfront investment, long payment periods and limited long term off taker agreements. Indian capital markets have been hesitant to fund such projects- thereby increasing costs and limited flexibility on structures for meeting project needs.

In addition to these challenges, it's also critical to address the overall supply chain costs- including compressors, storage, transport and conversion into derivatives such as ammonia/methanol. In India, where hydrogen infrastructure is limited, these downstream costs can rival productions costs especially for distributed/export oriented projects

## Path for Competitiveness in India

In our view, India can follow a four pronged approach for addressing the competitiveness of green hydrogen. This over the coming 3-5 years can enhance India's chances to reach 5 MMTPA targets for domestic production and 10 per cent of global green hydrogen demand. It's imperative that India progresses all these imperatives in parallel to meet the pace of global developments and needs for meeting its Net Zero targets.

**Building hub & valley infrastructure** to drive scale and reducing the costs of hydrogen production as supply chain mature. This would involve multiple activities including expediting plans on developing three to four 1-MMPTA+ eastern & western coast hubs, fast tracking 3-5

> **Indian companies should also track the NGHM's R&D and pilot schemes (including biomass based hydrogen pilots led by BIRAC) that diversify production pathways and hedge feedstock risk**


high priority ports anchored for GH2 exports with adequate ammonia/methanol storage, standardization of certifications (RFNBO/non RFNBO) early and aligning with global (European/US/Japanese) benchmarks. In addition, allocation of high CUF sites for wind and solar projects is critical for enabling the environment for hub development. Overall, country needs to plan hydrogen corridors/valleys for enabling scale in this area.

### Domestic demand certainty via mandates/standards/public procurement

Accelerate ammonia and GH2 demand aggregation opportunities across Indian refinery and fertilizer space. In addition, push on methanol based opportunities such as diesel blending in the Indian domestic market through similar routes. In addition, imported urea can be replaced by green urea via domestic GH2 route. These would demonstrate viabilities as well as get large private investors/ developers in the space which would create a virtuous cycle of interest in the space.

### GoI support for making GH2 competitive

This is a critical enabler for building the viability of Indian export oriented projects, especially in early days. Active engagement at G2G level for inclusion of Indian grid as a bidding zone in European standards, inclusion of carbon trading under bilateral Japanese /Korean agreements is key. State/central level support as capex subsidies, waivers on electricity duty in the target states, push on inter/intra state waivers on power transmission (charges & losses), push on production subsidies on domestic electrolyzer manufacturing can also enhance the viability of the green hydrogen product from India. In addition, existing provisions for SEZs for green hydrogen hubs and associated RE infrastructure can also help.

> **Typically, GH2 and its derivative projects would have 10-12 year offtake agreements. This would require innovative structures on green financing to fund the projects**

**Green financing push customized for green hydrogen projects** Typically, green hydrogen and its derivative projects would have 10-12 year offtake agreements. This would require innovative structures on green financing to fund the projects. Indian NBFCs can take a lead in mobilizing global capital for these area and build the ecosystem for accessing th real risks for such green hydrogen projects. In addition, evaluating mezzanine funds/short term arrangement for construction phase at competitive rates would also enable faster movement. Green hydrogen derivative linked bonds can also lead to active investor interest in this area.

In summary, green hydrogen is still an evolving sector and will require strong, coordinated support across the ecosystem to become competitive at scale in India. This includes sustained engagement from central and state governments, public and private developers, EPC contractors, electrolyser manufacturers, certification agencies, banks, and patient, long-term capital providers.

Financial institutions will need to adapt appraisal frameworks to reflect the unique risk profiles of $GH_2$ and derivative projects, while policy clarity and standardization will be essential to build investor confidence.

The next three to five years are critical for establishing hub infrastructure, supply chains, and market demand at scale. Timely and well-aligned interventions can create a virtuous cycle of scale, cost reduction, and investment. If executed effectively, India can emerge as a global leader in the green hydrogen ecosystem, while strengthening energy security and long-term industrial competitiveness

# GOPALPUR PROJECT FIRST PHASE ON TRACK FOR LATE 2028/EARLY 2029 COMMISSIONING

We are actively connecting with top academic and research entities, global OEMs, and technology startups to jointly develop and pilot next-generation solutions spanning the entire value chain

**Avaada has signed a MoU with Tata Steel SEZ in 2023 to set up a green hydrogen/ammonia manufacturing unit at Gopalpur Industrial Park, Odisha. Current status of the project and expected timeline for commissioning?**

The collaboration with Tata Steel SEZ at Gopalpur marks a significant milestone in Avaada Group's vision to establish an integrated green molecules ecosystem in eastern India.

Since the signing of the Memorandum of Understanding (MoU), the project has progressed steadily through the planning and pre-development phase. We've seen encouraging traction across key work streams, including land allocation, grid connectivity, and renewable integration, leading to significant advancement of key project milestones.

We are actively advancing discussions on technology partnerships, project structuring, and off-take alignment with reputable global and domestic players. The process for technology selection and engineering design is currently underway.

Due to the project's massive scale, we've adopted a carefully phased approach to maintain global competitiveness and future readiness. Our immediate goal is to establish a robust foundation—technically, financially, and environmentally—for a world-class green hydrogen and ammonia complex. This facility will significantly contribute to both Odisha's industrial ecosystem and India's broader green energy ambitions. Project plan is progressing for first phase to be commissioned around end 2028/early 2029, with capacity ramp-up thereafter.

**Given your recent renewable energy and storage investments (floating solar, pumped storage, and manufacturing) in Odisha, how will Avaada ensure dedicated, stable renewable power supply for hydrogen electrolysis?**

We are building a diversified renewable ecosystem in Odisha that includes large-scale solar, floating solar, and firm renewable energy solutions, all designed to ensure a continuous supply of clean power.

To ensure both cost optimization and supply resilience, our strategy combines intra-state renewable projects, which strengthen Odisha's local grid and industrial ecosystem, with inter-state renewable linkages, which provide access to high-resource zones and balance seasonal variations. This hybrid approach ensures that our green ammonia facility benefits from the most efficient and reliable power mix available nationwide.

By integrating round-the-clock renewable generation with energy/hydrogen storage and intelligent dispatch systems, we can deliver stable, reliable, and cost-competitive power to our green hydrogen/ammonia facilities. This approach minimizes intermittency risks and maximizes electrolyser utilization, a critical factor in reducing the overall cost of green hydrogen/ammonia.

**Prashant Choubey**
**President & Head – Green Hydrogen/Ammonia Business & New Initiatives**
Avaada Group

The first-of-its-kind energy banking facility secured in Odisha will provide crucial flexibility and play a pivotal role in ensuring operational reliability for our Gopalpur green ammonia Project.

**What synergies does Avaada foresee between its renewable-power generation business, electrolyser manufacturing arm, and hydrogen/ammonia plants, both technically and economically? Are there plans for backward or forward integration to ensure end-to-end control and cost efficiency?**

The synergies across Avaada's renewable power generation, manufacturing, and green hydrogen/ammonia operations are


> **Our Gopalpur Green Ammonia Project is strategically located on the eastern coast, offering direct access to port infrastructure for global exports while maintaining proximity to domestic industrial hubs**

both strategic and deeply transformative. We see this integration not as an incremental advantage, but as the core of our long-term vision to build a self-sustaining clean energy ecosystem that extends "from sand to molecule."

On the technical front, tight integration across renewable generation, storage, and hydrogen/ammonia production enables superior process optimization. For instance, by aligning our solar, wind, floating solar, and storage assets directly with electrolysers, we can ensure round-the-clock green power, minimize intermittency, and achieve higher electrolyser utilization factors — a key driver of lower hydrogen costs.

On the economic side, integration offers powerful cost and risk advantages. Captive renewable power provides insulation from market price volatility. Additionally, forward integration into green ammonia and derivative production helps us capture more value across the chain, while backward integration into manufacturing, ensures tighter quality control and higher efficiency.

Our goal is to develop a digitally integrated "Power-to-Molecule" platform that synchronizes renewable generation, storage, electrolysis, and ammonia synthesis into a single, optimized workflow. This unified approach minimizes the Levelized Cost of Hydrogen (LCOH) while strengthening resilience against global supply chain volatility.

**Q Newly signed MoU with GRIDCO and IIT-Bhubaneswar aims to set up a Centre of Excellence (CoE) for green hydrogen. What will be the focus areas? Will the CoE also look at localization of electrolyser manufacturing, hydrogen storage technologies, and green hydrogen safety norms adaptation for Indian conditions?**

The partnership with GRIDCO and IIT Bhubaneswar to establish a Centre of Excellence (CoE) for green hydrogen represents a significant step in advancing India's innovation ecosystem for clean energy.

The CoE will act as a collaborative innovation hub, structured around three core pillars:

### Technology Localization and Adaptation

Focuses on advancing research into indigenous electrolyzer components and hydrogen storage solutions that are specifically designed for India's unique climate and operating conditions.

### Safety, Standards, and Regulatory Alignment

Involves working with academic and policy institutions to develop green hydrogen safety protocols, material standards, and codes that align with Indian infrastructure and environmental realities.

### Skill Development and Innovation Incubation

Aims to nurture the next generation of scientists, engineers, and startups in the green hydrogen and ammonia sectors, thereby solidifying Odisha's role as a

**There is a pressing need to build a robust domestic demand framework — through instruments like GHPOs, refinery and fertilizer blending mandates, and incentives for steel, shipping, and mobility sectors**

national hub for clean energy innovation.

In addition, the CoE will play an important role in bridging academic research with industrial application, supporting pilot demonstrations, and fostering real-time technology validation for upcoming large-scale projects like our Gopalpur Green Ammonia facility.

**Q Does Avaada plan further collaborations with academic/ research institutes or other technology providers to develop advanced hydrogen technologies?**

Building India's clean energy future cannot happen in isolation; it is a shared endeavor propelled by science, technology, and strategic partnerships. We are actively connecting with top academic and research entities, global Original Equipment Manufacturers (OEMs), and technology startups to jointly develop and pilot next-generation solutions spanning the entire value chain.

These collaborations are not just about technology but about co-creation and adaptation — developing solutions that are optimized for Indian conditions, cost-competitive globally, and aligned with India's Make-in-India and energy-transition goals.

**Q Given the large scale and investment, does Avaada intend to target exports of green ammonia/ hydrogen derivatives (for global markets), or focus primarily on domestic demand?**

India is set to become a global leader in green hydrogen consumption over the coming decades, propelled by assertive government policies and a strong industry drive toward decarbonization. While domestic usage will eventually dominate, crucial early demand will come from export markets in Europe, Japan, and South Korea as local supply chains mature.

Our Gopalpur Green Ammonia Project is strategically located on the eastern coast, offering direct access to port infrastructure for global exports while maintaining proximity to domestic industrial hubs. This dual advantage allows us to serve both domestic and international demand seamlessly, ensuring flexibility and long-term market stability.

We truly appreciate the Government of India's leadership under the National Green Hydrogen Mission (NGHM) and the support from the Government of Odisha for creating an enabling environment for such investments.

However, as the ecosystem evolves, there is a pressing need to build a robust domestic demand framework – through instruments like green hydrogen purchase obligations (GHPOs), refinery and fertilizer blending mandates, and incentives for steel, shipping, and mobility sectors. This will ensure that India not only produces competitively but also creates a stable home market that complements its export ambitions.

**How does Avaada plan to manage logistics, storage, and transport for hydrogen/ammonia? Does it foresee building dedicated port, bunkering or shipping infrastructure?**

Gopalpur's strategic coastal location gives us a natural logistical advantage for developing an integrated green ammonia export ecosystem. From the very outset, we designed the project with port connectivity, storage, and maritime logistics as core enablers rather than afterthoughts.

We are closely working with the Gopalpur Port authorities and other state agencies towards dedicated ammonia storage and loading infrastructure. The focus is on creating and using an end-to-end logistics corridor along with storage to ensure seamless movement from production to shipment.

While Avaada does not intend to build or operate shipping fleets, we are actively exploring strategic partnerships with global ammonia carriers, bunkering companies, and port operators to establish long-term logistics solutions. These partnerships will not only serve our exports but also position Gopalpur as one of India's first green hydrogen and ammonia maritime hubs, capable of supporting future bunkering operations and hydrogen-based fuel adoption in shipping.

**Given that large-scale electrolysis and ammonia production are water- and energy-intensive, how does Avaada plan to ensure sustainability, water sourcing, zero minimal emissions, waste-management, and manage environmental/social impact in local communities?**

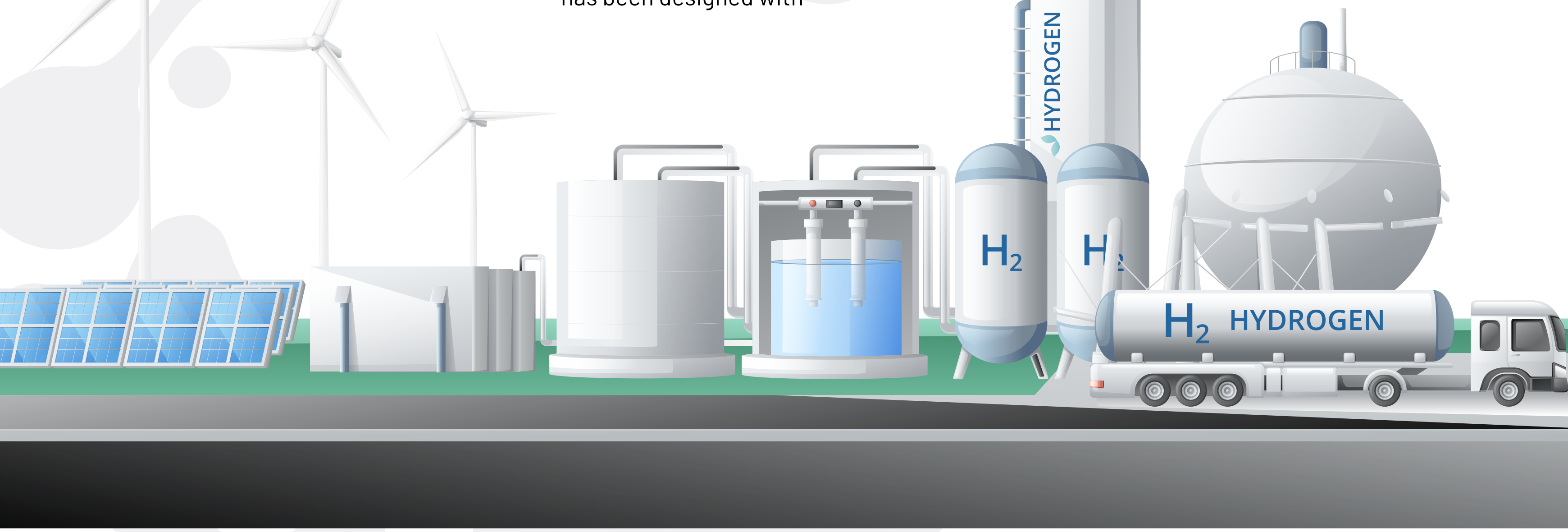
At Avaada, sustainability is not an add-on – it's the foundation of our green molecules business model. Every aspect of our Gopalpur project has been designed with a deep commitment to environmental stewardship, community well-being, and alignment with the UN Sustainable Development Goals (SDGs).

The Government of Odisha is working on to ensure water availability/allocation from sustainable sources such as regulated river systems and designated water bodies. In parallel, desalination-based water supply options are being explored to ensure long-term resilience and zero dependency on freshwater stress zones.

From a design standpoint, the project incorporates high-efficiency electrolysers, zero-liquid-discharge (ZLD) and closed-loop water recycling systems, state-of-the-art emission control, and renewable-powered auxiliary systems – ensuring that every tonne of green ammonia produced has a minimal environmental footprint.

Equally important is our social and community engagement strategy. Avaada's approach goes beyond compliance – we focus on local employment generation, skill development, and creating shared value for nearby communities. Our social impact initiatives ensures that the benefits of the green energy transition are inclusive and sustainable.

In essence, our Gopalpur project aims to become a benchmark for responsible industrial growth



# ACHIEVING INDIA'S AIM TO EXPORT GREEN HYDROGEN

The velocity of India's export growth is contingent upon navigating foreign regulatory frameworks and ensuring sufficient resource scalability

**Sehul Bhatt**
**Director**
Energy and Commodities
Crisil Intelligence

**Jaydeep Dattani**
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## Green Hydrogen takes Centre Stage in Global Energy Transition

As energy transition policies shift focus from the power sector to hard-to-abate end-use sectors, green hydrogen and green ammonia are increasingly emerging as essential decarbonisation vectors rather than optional alternatives.

The hard-to-abate sectors—steel, chemicals, refining, shipping and long-distance transport—together account for around 40 per cent of global greenhouse gas emissions and have limited electrification potential.

The shift, embedded in binding policy frameworks across major consuming economies, presents a significant opportunity for exporters.

The European Union, under REPowerEU and the RFNBO (Renewable Fuel of Non-Biological Origin) regime, aims for 20 MTPA of renewable hydrogen consumption by calendar year 2030, of which 10 MTPA is to be met through imports. Japan's Basic Hydrogen Strategy targets combined hydrogen and ammonia demand of ~3 MTPA by calendar year 2030 and ~12 MTPA by calendar year 2040, with imports forming the dominant share. South Korea's Clean Hydrogen Portfolio Standard under its Carbon Neutrality Act mandates progressive uptake of clean hydrogen in power generation and industry through the 2030s.

## Hydrogen Targets Anchoring Decarbonisation Pathways

| | Net Zero Targets | Target Green $H_2$ | Hydrogen strategy | Focus Sectors | Potential |
|---|---|---|---|---|---|
| US | 2050 | 10 MT | Inflation Reduction Act (IRA) National hydrogen strategy | Industry, Mobility, Power etc. | |
| India | 2070 | 5 MT | National Green Hydrogen Mission | Refining, Fertilizer, Steel, Mobility etc. | |
| European Union | 2050 | 10 MT (Imports) | EU Delegated Acts | Steel, Cement, Chemicals, Aviation, Shipping etc. | |
| South Korea | 2050 | 3.9 MT | Hydrogen Economy Roadmap Carbon Neutrality Act | Transportation, Power generation, Heavy Industry etc | |
| Japan | 2050 | 3 MT | Basic Hydrogen Strategy Hydrogen Society Promotion Act | Steel, Mobility, Shipping, Power etc. | |
| Australia | 2050 | 0.2-1.2 MT (Exports) | National Hydrogen Strategy | Steel, Ammonia, long haul transport, shipping etc. | |

Importer — Exporter

*Source: Government reports, Crisil Intelligence*
Note: Hydrogen targets mentioned are till calendar year 2030. Potential indicates whether a region's hydrogen volumes would be import- or export-driven (e.g., much of Japan's ~3 MT is expected to be import-driven).

However, domestic supply is structurally constrained in Europe and north-east Asia, since lower and variable renewable capacity factors, land & grid limitations, and persistently high power costs restrict the development of large-scale, low-cost, high-utilisation renewable-to-hydrogen systems. Even with accelerated policy support, producing certification-compliant green hydrogen is expected to be costlier in these regions than in renewable-rich geographies in the medium term.

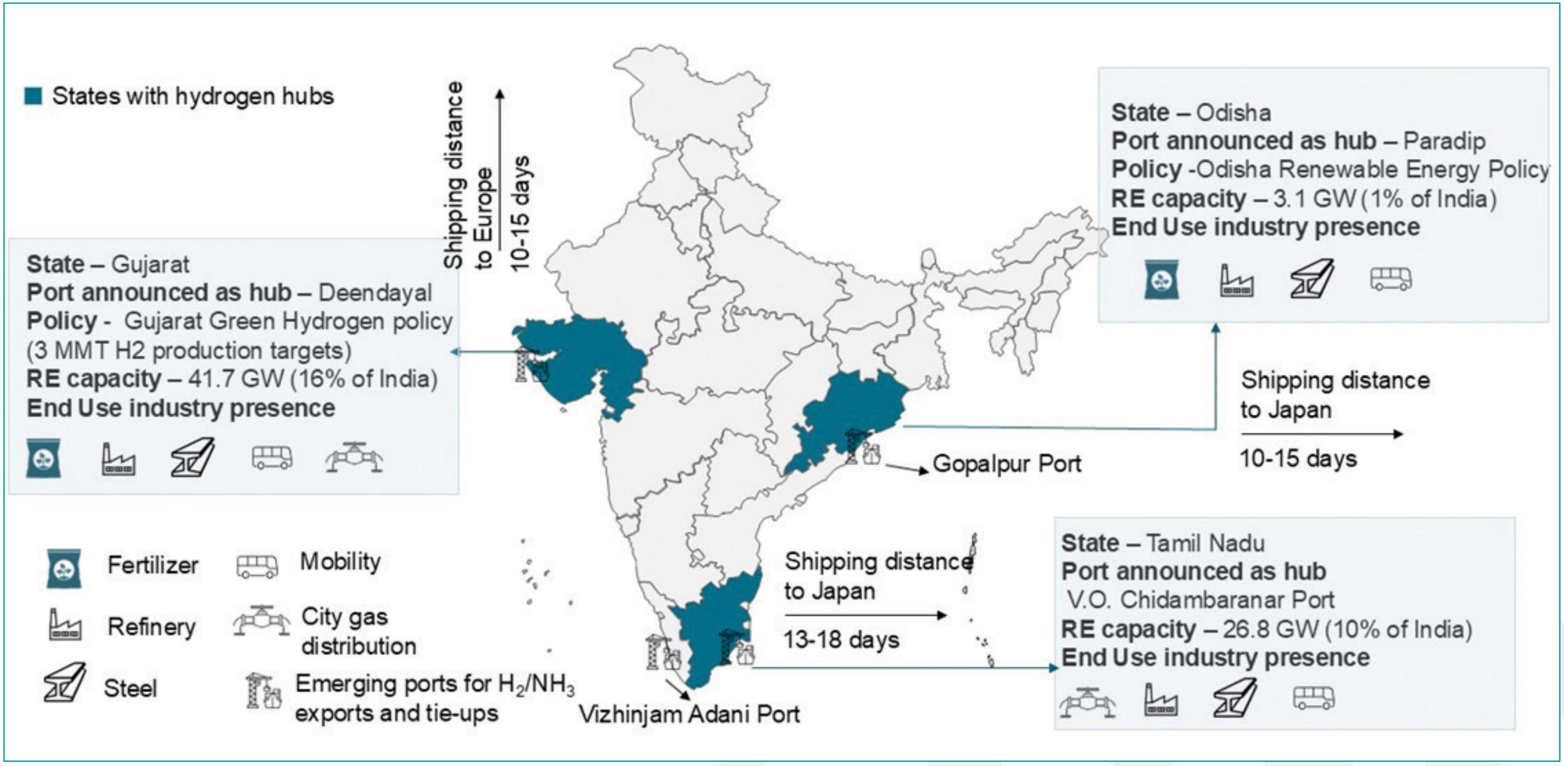
**The European Union, under REPowerEU and the RFNBO (Renewable Fuel of Non-Biological Origin) regime, aims for 20 MTPA of renewable hydrogen consumption by 2030, of which 10 MTPA is to be met through imports**

This demand-supply asymmetry points to an import-oriented structure for the hydrogen and ammonia market, similar to the early phase of the liquefied natural gas market development—where a small group of low-cost, infrastructure-ready countries accounted for the bulk of the global exports. Delivered cost, access to port-linked infrastructure, shipping distance to major demand centres and compliance with evolving certification regimes (such as RFNBO) are expected to result in supply being concentrated in a limited set of geographies that can combine scale, competitiveness and execution readiness.

## India's Positioning as a Serious Hydrogen Market Player

India is among the few geographies where the core elements required for participation in this emerging market are coming together at scale. By 2025, renewable energy accounted for over 50 per cent of installed power capacity. International benchmarks consistently place Indian utility-scale solar and onshore wind in the lower global cost quartile, comparable to the Middle East and below the US and most European markets. Given that electricity contributes more than half of the levelised cost of green hydrogen, India has a durable structural advantage on the production cost curve.

### Hydrogen hubs can act as integrated centres for production, consumption and export




*Source: Ministry of New and Renewable Energy, industry reports, Crisil Intelligence*

Resource quality strengthens this positioning. Solar and wind capacity factors in states such as Gujarat, Rajasthan, Tamil Nadu and Karnataka support high electrolyser utilisation, particularly in hybrid systems with storage. Several of these high-capacity utilisation factor (CUF) zones are located close to deep-water ports and are positioned to become hydrogen export clusters through state policies providing capital subsidies, land facilitation, transmission and duty waivers. Co-location of renewable power generation, electrolysis and ammonia synthesis with export terminals reduces transmission bottlenecks, lowers balance-of-plant costs and shortens inland logistics, directly improving delivered economics.

Geography further reinforces competitiveness. Sailing time from India's west coast to north-west Europe (10-15 days) and from the east coast to Japan and South Korea (8-12 days) is comparable to that from the Middle East and shorter than that from Australia or Chile. For ammonia-led trade, where shipping and storage can account for a meaningful share of cost, insurance and freight, shorter routes translate into lower freight, faster inventory turns and higher supply reliability.

This is also reflected in emerging bilateral and commercial corridors, including the India–Japan clean hydrogen and ammonia partnership, initial green ammonia offtake agreements with Japanese and European utilities, and port-linked agreements with Singapore and east Asian players, which provide early demand signals, standards alignment and port-to-port logistics pathways for future trade flows.

### Exports can anchor early scale for India

India's hydrogen ecosystem is characterised by a large prospective domestic market and a developing export opportunity. The country is the world's third-largest hydrogen consumer, with over 8 MTPA used in refining and fertiliser production—priority targets under the National Green Hydrogen Mission with initial tenders and policy instruments already underway. Capacity additions in steel, expansion of the city gas distribution network and early pilots in mobility and

> **India's Green Hydrogen Certification Scheme is anchored in an emissions-intensity threshold, whereas key importing regions—notably the European Union under the RFNBO framework—define eligibility through production-pathway and power-sourcing rules, including additionality, system boundaries, and traceability**

industrial heating are expected to broaden the domestic demand base for low-carbon hydrogen and derivatives in the medium term.

In the near term, stringent decarbonisation mandates, import targets and higher willingness to pay in overseas markets—Europe, Japan, and South Korea—are expected to provide the initial anchor for large, export-oriented projects. Export-linked offtake enables early scale-up of renewable and electrolyser capacity, supports higher utilisation and accelerates learning-curve effects in equipment and project execution. Over time, these scale effects and technology cost reductions are expected to lower the delivered cost of green hydrogen and ammonia to levels that allow wider adoption across domestic refining, fertilisers, steel and gas networks.

This interaction creates a complementary dynamic rather than a trade-off: export markets facilitate early scale and price discovery, while the domestic market provides long-term volume depth and demand stability. Few competing export hubs combine both attributes at comparable scale, giving India an inherent option value and resilience in the evolution of its hydrogen economy.

## Regulatory Alignment and Offtake Maturation will Shape Export Realisation

The pace at which India's export ambitions translate into sustained volumes will be governed by regulatory and commercial alignment in importing regions and the availability of scalable resources. These aspirations face the following bottlenecks:

### Evolving definitions and certification frameworks

There is no harmonised global definition of green hydrogen and its derivatives. India's Green Hydrogen Certification Scheme is anchored in an emissions-intensity threshold, whereas key importing regions—notably the European Union under the RFNBO framework—define eligibility through production-pathway and power-sourcing rules, including additionality, system boundaries and traceability. This divergence creates uncertainty around cross-recognition of certificates and the eligibility of source-country molecules under legally binding import mandates and support schemes.

### Scale of renewable capacity and availability

Export-oriented green hydrogen &


ammonia production and domestic consumption at scale will require large and time-bound additions of renewable capacity of ~125 GW, aligned with the National Green Hydrogen Mission's production targets, against the current installed base of ~254 GW as of Noember 2025. Mobilising such capacity will depend on the availability of suitable land, timely development of transmission and evacuation infrastructure, depth of domestic manufacturing in solar, wind and electrolyser supply chains and development of port-linked renewable corridors in coastal states. The ability to ensure stable availability of renewable power, through hybridisation, grid balancing and storage, will also be important to sustain electrolyser utilisation and competitive export economics.

### Long-term offtake and bankability

While import targets and policy mandates have been articulated, binding, long-tenure offtake has been slower, reflecting the phased roll-out and slippage of sectoral decarbonisation milestones, such as in maritime fuels and renewable deployment. A large share of engagements remain at the level of memorandums of understanding or pilot-scale procurement rather than long-term contracts. The availability of anchor buyers providing volume and price visibility over the asset life will be a key determinant of when large export-oriented projects move from development to financial closure.

### Price discovery and contract standardisation

Global green hydrogen and green ammonia trade is still in the early stages of price formation and contract structuring. While domestic tenders and overseas support mechanisms have indicated production and delivered cost ranges, there is no widely accepted benchmark price or standard contract format covering conversion, shipping, storage, carbon attributes and risk allocation. India's recent green ammonia tender provides a price signal, but the absence of large-scale, long-tenure and internationally benchmarked contracts limits price discovery and trade continues to be structured on a bespoke rather than liquid, standardised basis.

The coming years will determine how policy initiatives and project pipelines translate into sustained participation in global trade. Early progress through bilateral partnerships, industry collaborations and emerging corridors with demand centres provides a constructive foundation. How these evolve into scaled infrastructure, long-term offtake and stable trade frameworks will shape India's role in the global low-carbon molecule flows

# POLICY VOLATILITY AND INVESTMENT RISKS IN HYDROGEN EXPORTS PROFITABILITY

## The government projects Rs. 8 lakh crore of cumulative investment and 600,000 green jobs created across the value chain by 2030, with an explicit ambition to become a global export hub

India's National Green Hydrogen Mission (NGH), launched in January 2023, with an overarching objective to make India the global hub for production, usage and export of green hydrogen and its derivatives, is moving from vision to execution—and with it, a once in a generation opportunity to position Indian developers, ports, and financiers at the center of the hydrogen trade, given a global demand of over 100 MMT of green hydrogen and its derivatives like green ammonia expected to emerge by 2030.


However, export profitability is inseparable from policy volatility at home and abroad. European certification rules, border carbon pricing, and import auctions—and Japan's 15 year CfD subsidies—can swing margins more than equipment costs or renewable tariffs. The edge lies in structuring projects that fit multiple policy regimes while securing policy backed offtake.

India has signalled scale and intent: a 2030 target of 5 MMT/year of green hydrogen, incentives under Strategic Interventions for Green Hydrogen Transition (SIGHT), hub development, and a public R&D and standards framework.

The government projects Rs. 8 lakh crore of cumulative investment and 600,000 green jobs created across the value chain by 2030, with an explicit ambition to become a global export hub.

Recent tenders span green hydrogen hub Detailed Project Reports, transmission lines for Tuticorin and Kakinada, and cluster development calls—showing the enabling pieces are being assembled on the ground.

Solar Energy Corporation of India (SECI) has launched a call for proposals for Green Hydrogen Hubs, while specialized tenders target transmission systems for proposed green hydrogen/ammonia projects in Tuticorin (Tamil Nadu) and Kakinada (Andhra Pradesh). These corridors are the backbone for moving electrons to molecules and molecules to ships, synchronizing upstream renewables with downstream export logistics.

**Aashish Kasad**
**Senior Partner and National Leader for the Chemical and Agriculture Sector**
Ernst & Young LLP, India


> **Indian companies should also track the NGHM's R&D and pilot schemes (including biomass based hydrogen pilots led by BIRAC) that diversify production pathways and hedge feedstock risk**

## Why Policy Alignment is New Levelized Cost of Hydrogen (LCOH)

For an Indian exporter, "clean" is not a slogan—it's a passport.

In the EU, two Delegated Acts (Renewable Fuel of Non-Biological Origin ('RFNBO') define renewable hydrogen eligibility via additionality, temporal and geographic correlation between renewables (with no biomass involved) and electrolysis. These rules apply to imports, hence, Indian exports must satisfy EU definitions and documentary evidence—otherwise, they lose premium pricing, may be excluded from certain subsidies, and could face carbon border costs. [ec.europa.eu], [europex.org] Legal and technical analyses stress that RFNBO rules entered into force in 2024 with phased stringency, shaping contracts for e ammonia/e methanol and altering how PPAs, storage, and certification are structured. Projects should be engineered for hourly matched Energy Attribute Certificates (EACs) and additionality pathways, with contingency to adapt as EU guidance evolves.

The US also finalized its Section 45V clean hydrogen tax credit (Jan 2025), established by the Inflation Reduction Act, preserving the "three pillars" while adding flexibilities for at risk nuclear and specific state regimes.

Even if India is producing for export, the US Section 45V credit matters for partners and competitors whose cost curves include up to $3/kg credits. Indian developers should benchmark against the US Section 45V credit enabled producers to gauge competitive landed price parity in Europe/Japan. Meanwhile, US rules lock projects into specific 45VH2 GREET model versions, which assesses emissions from "well-to-gate" (from raw material extraction to hydrogen production), including various production pathways like electrolysis and steam methane reforming with carbon capture, to determineeligibility and credit amount, encouraging lower-emission hydrogen —reminding us that regulatory model risk can be ten year risk.


## Europe's H2Global and CBAM: Two Levers on Your Netback

Germany's H2Global double auction model has already converted ammonia imports to binding long term contracts (2027–2033) at transparent price points, and expanded its budget architecture toward ~€3 bn to align with ten year developer contracts. For Indian suppliers, these instruments provide bankable offtake—but they also create basis risk between fixed supply prices and shorter dated resale tenders. Hence one needs to price the subsidy gap and be prepared for budget or policy changes in Germany and EU.


Simultaneously, the EU's Carbon Border Adjustment Mechanism (CBAM) moves from reporting to payment obligations on January 1, 2026, covering hydrogen and fertilizers, with obligations phased alongside EU ETS free allowance reductions to 2034. For exports of ammonia (India's likely carrier), embedded emissions will translate to CBAM certificate costs unless you qualify as low emissions under EU methodologies. CBAM simplifications adopted in 2025 eased admin for small importers, but hydrogen remained outside certain mass based exemptions, maintaining compliance costs. This narrows the profitability window for grey or inadequately abated blue molecules.


Hence, while H2Global can secure revenue, CBAM can claw it back. Contract clauses must explicitly address CBAM pass through, embedded emissions verification, and RFNBO eligibility. Without that, CBAM becomes a variable levy on an Indian exporter.

## Japan's 15 year CfD and Cluster Subsidies: The Second Anchor

Japan's Hydrogen Society Promotion Act (2024) empowers two subsidy streams: long term price gap subsidies (Contracts for Difference (CfDs) to bridge the cost gap for low carbon hydrogen and derivatives (including ammonia) and cluster support for import and distribution infrastructure. The government signalled carbon intensity thresholds and a goal to start supply by FY2030 with continuity for ten more years post support. That is both a demand signal and a timeline discipline for Indian exporters.

Industry briefings indicate Japan's Ministry of Economy, Trade and Industry (METI) will roll CfDs project by project, resembling H2Global's market making, while funding clusters to retrofit terminals and pipelines. This provides India with two strategic options: (1) bid into CfDs with Tuticorin/Kakinada-linked supply chains and (2) co develop terminal capacity to ensure bankable logistics. Currency exposure (JPY/INR) and reference price mechanics in CfDs will affect realized margins—hence companies will need to structure FX hedges and base price disclosures with care.


## India's Corridors: Tuticorin and Kakinada as Export Springboards

Policy momentum meets geography at Tuticorin and Kakinada. Tender documentation shows tariff based competitive bidding for transmission supporting green hydrogen/ammonia in the Tuticorin area, and independent transmission projects for Kakinada (Phase I)—a strong indicator that state agencies and central nodal bodies are aligning infrastructure with export ambitions. Pair these corridors with NGHM Hub selection (SECI's CfP) and MNRE's certification scheme to create integrated electron to molecule to terminal pathways.


Indian companies should also track the NGHM's R&D and pilot schemes (including biomass based hydrogen pilots led by BIRAC) that diversify production pathways and hedge feedstock risk. Given water and land constraints, a portfolio mix—coastal wind/solar, hybridized dispatch with storage, and select biomass/biogenic routes—can improve resilience under RFNBO and CBAM accounting.

## Shipping and Terminals: Standards, Safety—and CAPEX Timing Risk


Ammonia remains the practical carrier for hydrogen exports, but maritime rules are still evolving. DNV's latest white paper and class rules outline approval pathways and safety regimes for ammonia/hydrogen fuels, emphasizing crew

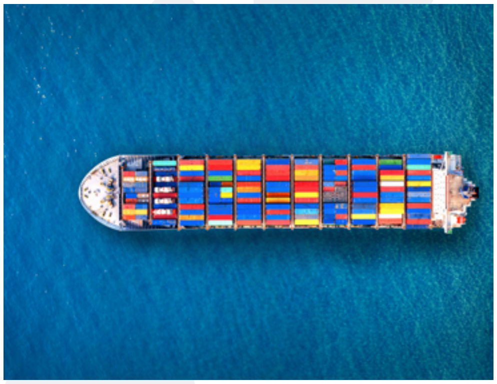
> **India's advantage is proximity to East West trade lanes, competitive renewables, and policy momentum—if we engineer multi standard compliance and secure European/Japanese instruments, we can compete on delivered cost and policy certainty**

training, bunkering safety, and alternative design approvals in the absence of fully mandatory IMO rules. For Indian terminals and port operators (Tuticorin/Kakinada), early alignment with class guidance reduces approval friction and mitigates future retrofit costs.

Peer reviewed work captures adoption risks: NOx/$N_2O$ management, fleet renewal hesitancy, and supply chain readiness across onboard and portside infrastructure. Terminal market analyses add that independent ammonia storage capacity is constrained and project realization rates are low due to cost and offtake uncertainty—making timing a first order risk. Indian companies should price demurrage, premium storage, and contingency capex into models; delays in European/Japanese terminal readiness can erode margins even if Indian upstream plants are on time.

## Competitive Yardsticks and Global Momentum

The International Energy Agency's (IEA) reviews note that while investment is rising (clean hydrogen spending up ~70% in 2025), low emissions hydrogen still accounts for <1% of global hydrogen demand, and project pipelines have been revised down due to policy and infrastructure uncertainty. Successful export plays will therefore be those anchored by policy backed offtake and robust compliance strategies—rather than speculative merchant bets on green premiums.



Saudi Arabia's NEOM demonstrates how long term offtake and sovereign alignment de risk mega projects (≈4 GW renewables, first ammonia by 2027; 30 year offtake), but also how export profitability remains exposed to destination market rules and shipping safety standards. India's advantage is proximity to East West trade lanes, competitive renewables, and policy momentum—if we engineer multi standard compliance and secure European/ Japanese instruments, we can compete on delivered cost and policy certainty.

## Indian Companies Checklist

**Engineer for RFNBO & 45V compatibility**
Design power sourcing, storage, and EAC strategies to meet EU hourly matching and additionality, while ensuring emissions baselines would satisfy US style pillar logic. This preserves offtake optionality and avoids redesign costs if policy tightens.

**Target policy backed offtake first**
Bid into H2Global (ammonia/methanol lots) and Japan's CfDs with Tuticorin/ Kakinada logistics mapped; include CBAM pass through and RFNBO compliance warranties. Don't rely on merchant arbitrage to Europe.

**Build data and verification muscle**
CBAM and RFNBO place heavy weight on audited emissions and correlation proofs. Invest early in metering, traceability, and third party verification to minimize certificate surrender costs and contract disputes.

**Co-develop terminals and safety regimes**
Partner with class societies to pre approve bunkering and storage designs; synchronize port capex timelines with SECI hub schedules to reduce demurrage and storage pricing shocks.

**Portfolio diversification**
Blend electrolytic and high capture blue (where acceptable to offtakers) and diversify offtake across EU/Japan to hedge localized policy shocks; leverage NGHM pilots to add biogenic routes where feasible.

## Conclusion

India's export profitability in hydrogen will be driven by policy impact as much as in engineering drawings. The combination of NGHM execution (hubs, Tuticorin/Kakinada transmission) and policy anchored demand (EU H2Global, CBAM discipline; Japan CfDs and clusters) can turn cost advantages into bankable margins—if projects are structured for multi jurisdiction compliance, long term offtake, and logistics resilience

# SUPPLYING GREEN HYDROGEN AS A STANDALONE PRODUCT TO MEET SOARING INDUSTRIAL DEMAND

HFE is actively exploring a broad range of funding options to support its green hydrogen growth plans

**Srivatsan Iyer**
**Global CEO**
Hero Future Energies

**Hero Future Energies (HFE) established India's first green hydrogen plant for blending with LPG/PNG in Tirupati, Andhra Pradesh, in March 2025. Can you provide an update on actual production, blending ratios achieved (with PNG/LPG), and operational learnings?**

HFE initiated hydrogen blending at the Tirupati facility with LPG at approximately 8 per cent by volume. Subsequently, the customer transitioned to Piped Natural Gas (PNG), which has a lower molecular weight and more favourable combustion characteristics. This transition enabled HFE to safely increase the hydrogen blending ratio to around 10 per cent.

This capability makes the project globally distinctive and among the first of its kind to demonstrate hydrogen blending with both LPG and PNG under commercial operating conditions. HFE has successfully filed a patent covering this innovative approach and has also presented a research paper at ASME (American Society of Mechanical Engineers) International Conference, highlighting the project's technical significance.

The hydrogen blending ratio is maintained as a fixed percentage; however, the absolute hydrogen flow rate dynamically adjusts in real time based on variations in LPG or PNG flow. A fully automated control architecture continuously monitors fuel flow, with a PLC-based system regulating electrolyzer output to ensure stable, safe, and consistent blending across operating conditions.

**What are HFE's near-term rollout plans for expanding hydrogen production beyond Tirupati plant, in terms of capacity (MW or tonnes/year) and locations across India?**

Early-stage hydrogen blending projects such as our Tirupati project are designed to act as market enablers, allowing hard-to-abate sectors to begin decarbonization with minimal disruption to existing fuel and infrastructure systems. This approach is strongly aligned with the Hero Group's ethos of "First learn, then scale," ensuring that future deployments are executed right the first time.

Building on the operational, safety, and integration learnings from Tirupati, HFE is now well positioned to progress towards larger, commercial-scale green hydrogen projects. In the near term, the company is actively evaluating multi-megawatt hydrogen production facilities, along with downstream derivatives to address both domestic industrial demand and export opportunities.

**The HFE–Ohmium partnership targets 1,000 MW of green hydrogen facilities. What is the current project pipeline timeline for this target and which states/industrial clusters are priorities?**

HFE is actively engaged in multiple opportunities that are currently at advanced stages of development, spanning both domestic applications and export-oriented demand for green hydrogen and its derivatives. HFE is also a participant in the MNRE/DST-supported Hydrogen Valley Innovation Cluster (HVIC), contributing to research and development efforts focused on decarbonizing hard-to-abate sectors. The insights and ecosystem partnerships emerging from these initiatives are directly informing the phased rollout of future projects. Specific timelines, capacities, and locations will be disclosed as projects progress toward final investment decisions.


HFE is now well positioned to progress towards larger, commercial-scale green hydrogen projects

**What electrolyser technology will the company primarily deploy as part of its 1 GW green hydrogen facilities, and what factors influence that choice (cost, performance, and local manufacturing)?**

Hero Future Energies follows a technology-agnostic approach to electrolyser selection, with choices driven by the specific requirements of each project rather than a single, fixed technology pathway. Alkaline Water Electrolyser (AWE) technology is currently the most mature and widely bankable option, supported by a long operating track record at scale. Proton Exchange Membrane (PEM) electrolyser, on the other hand, offer advantages in terms of efficiency, compact footprint, and dynamic operating capability, making them well suited for certain applications.

Electrolyser selection across HFE's green hydrogen platform is guided by multiple factors, including long-term reliability and sustainability over plant life, total installed cost, efficiency and degradation performance, local manufacturing and supply chain readiness, as well as standardized balance-of-plant (BoP) design and system modularity. Accordingly, HFE will deploy the most appropriate technology based on the requirements of each project.

**For the Tirupati blending project, what safety, control and monitoring technologies have been used to ensure stable blending with PNG and LPG without modifying existing burner designs?**

The Tirupati blending project incorporates a multi-layered safety, control, and monitoring architecture to ensure stable and safe hydrogen blending with both LPG and PNG. Key safety and control elements include pressure safety valves (PSVs), pressure control valves (PCVs), pneumatically actuated control valves, and continuous monitoring of gas flow and composition. A dual-logic control system dynamically manages the hydrogen blending ratio depending on whether LPG or PNG is in service, accounting for differences in molecular weight and combustion behaviour.

Importantly, hydrogen blending has been achieved without any modification to existing burner designs, demonstrating the feasibility of hydrogen retrofitting into current fuel systems. All safety and operability aspects were validated through a rigorous HAZOP study conducted by an independent Tier-I third-party expert

consultant, ensuring compliance with the highest safety standards.

**How does HFE plan to integrate renewable power, storage, and electrolysers to ensure firm, dispatchable green hydrogen supply, especially for industrial heating and high-temperature use-cases?**

HFE's integration strategy for renewable power, storage, and electrolysers is guided by the applicable regulatory framework and the specific end-use application, whether under domestic banking norms or RFNBO requirements for EU/global customers.

Accordingly, combinations of renewable energy capacity, electricity storage, and hydrogen storage are being carefully modelled to arrive at optimal system configurations that ensure reliable and compliant green hydrogen supply. This approach allows HFE to balance dispatchability, cost efficiency, and regulatory compliance while meeting the requirements of industrial heating and high-temperature applications.

**How is HFE aligning its hydrogen projects with the National Green Hydrogen Mission targets for electrolyser capacity and production by 2030?**

Hero Future Energies is fully aligned with the objectives of India's National Green Hydrogen Mission (NGHM), which targets 5 million tonnes per annum of green hydrogen production by 2030. Having successfully completed its first project, HFE has crossed the early learning phase and is now positioned to scale up. In line with this direction, HFE will continue to assess and deploy green hydrogen projects, contributing meaningfully to the national production targets under the NGHM framework.

**Does the company intend to sell green hydrogen as a standalone product to industrial customers (merchant offtake) or primarily as part of integrated solutions?**

The company is focused on supplying green hydrogen as a standalone product to meet domestic industrial demand, while also assessing integrated green hydrogen and derivative solutions—particularly for export-oriented markets

**What role do climate/green bonds or international financing play in HFE's hydrogen CAPEX plan? Is the company exploring branded hydrogen bonds or similar instruments?**

Green hydrogen and derivative projects are inherently capital-intensive, and access to long-term, competitive

> **HFE is actively engaged in multiple opportunities that are currently at advanced stages of development, spanning both domestic applications and export-oriented demand for green hydrogen and its derivatives**


financing is critical to their successful development. In this context, HFE is actively exploring a broad range of funding options to support its green hydrogen growth plans.

**What steps is HFE taking to localize electrolyser supply chains in India (production and assembly), especially in partnership with Ohmium or other technology providers?**

Localization of electrolyser supply chains is a strategic priority for India. We fully support efforts being made by various companies to localize assembly and manufacturing, indigenous development of balance-of-plant (BoP) components, and the creation of a robust domestic vendor ecosystem. These efforts are critical to reducing costs, enhancing supply-chain security, and enabling the scalable deployment of green hydrogen projects in India.

**Does HFE have a strategy for hydrogen storage, compression, and transport infrastructure in India, either through standalone assets or via third-party logistics partners?**

HFE's approach to hydrogen storage, compression, and transport is application-specific. Where feasible, on-site consumption is prioritized to minimize transportation requirements. As required, HFE will leverage specialized third-party partners, ensuring safe, efficient, and scalable handling of hydrogen and its derivatives.

**How will HFE measure and report the emissions reductions achieved from its hydrogen blending and future green hydrogen plants?**

Currently, emissions reductions are quantified using an equivalence-based methodology, which calculates avoided $CO_2$ emissions based on the displacement of LPG or PNG using standard emission factors. Going forward, HFE will continuously track emissions performance with and without hydrogen blending. This will enable transparent, consistent, and auditable reporting of emissions reductions across its hydrogen projects.

**What is HFE's 5-year hydrogen roadmap for India in terms of capacity, customers, and technologies? How does this align with planned renewable power scale-up?**

Over the next five years, HFE's hydrogen roadmap in India focuses on scaling up green hydrogen projects. The company aims to serve a range of customers, particularly in hard-to-abate industrial sectors, mobility applications, and export-oriented markets. HFE plans to deploy a portfolio of electrolyser technologies suited to different use cases, while ensuring that hydrogen capacity expansion is fully aligned with the scale-up of its renewable power portfolio, enabling integrated, low-carbon energy solutions

# HYDROGEN HUBS: MATERIALIZING INDIA'S ASPIRATIONS FOR A DECARBONIZED ECONOMY

India's hydrogen initiatives hold immense export potential, aiming to capture 10% of global green hydrogen demand by 2030

**Dr. M.P. Sukumaran Nair**
**Director**
Centre for Green Technology & Management

India stands as one of the world's fastest-growing major economies, characterized by a youthful population, robust growth rates, and ambitious goals in poverty alleviation, defense enhancement, and global influence. With a population exceeding 1.4 billion, of which over 65% is under the age of 35, the nation requires substantial energy resources, raw materials, and infrastructure to support people's welfare and developmental needs. As India pursues its vision of becoming a global power, balancing economic expansion with environmental sustainability presents a critical imperative. The development of hydrogen hubs emerges as a strategic initiative to address these aspirations, facilitating a transition toward a decarbonized economy while meeting escalating energy demands.

## Commitment and Challenges

India has committed to achieving net zero emissions by 2070, aligning with global efforts to combat climate change. This pledge is reinforced by international frameworks, including decisions from the Conference of the Parties (COP) and the Sustainable Development Goals (SDGs). At COP30, held in November 2025, nations committed to quadrupling the output of sustainable fuels by 2035, emphasizing the role of low-carbon alternatives in decarbonization. However, the outcomes fell short of expectations, with no unified roadmap for phasing out fossil fuels, underscoring persistent global challenges. The SDGs, particularly Goal 7 (affordable and clean energy) and Goal 13 (climate action), guide India's policies toward inclusive and sustainable growth.

The United Nations Environment Programme's Global Environment Outlook 7 (GEO-7), released in December 2025, highlights the risks of inaction amid interlinked crises such as climate change and biodiversity loss, while emphasizing the potential of sustainable policies to yield substantial economic benefits. For India, decarbonization poses unique challenges, including high dependence on coal for energy and fertilizers, rapid urbanization, and the need to uplift millions from poverty without compromising growth. Traditional development paths followed by major industrialized nations, reliant on fossil fuels, are no longer viable for India due to environmental constraints and global emission reduction targets. Instead, a sustainable, low-carbon, and environmentally friendly approach is essential to harmonize development with ecological preservation.

Globally, the hydrogen economy has encountered setbacks since the inauguration of U.S. President Donald Trump in January 2025, with policy reversals impacting clean energy incentives. For instance, the acceleration of deadlines for Section 45V tax credits has reduced eligibility for clean hydrogen projects, contributing to the cancellation or postponement of several initiatives worldwide. North America's share in the global low-carbon hydrogen market is projected to decline from 46% in 2025 to 28% by 2030 due to these shifts. Despite such international challenges, India remains committed to advancing its hydrogen agenda through domestic innovation and strategic partnerships.

## Current efforts towards Decarbonization

India has made commendable progress in decarbonization through the adoption of natural gas, biomass, and electrification initiatives. Efforts to reduce coal utilization are evident, with a focus on

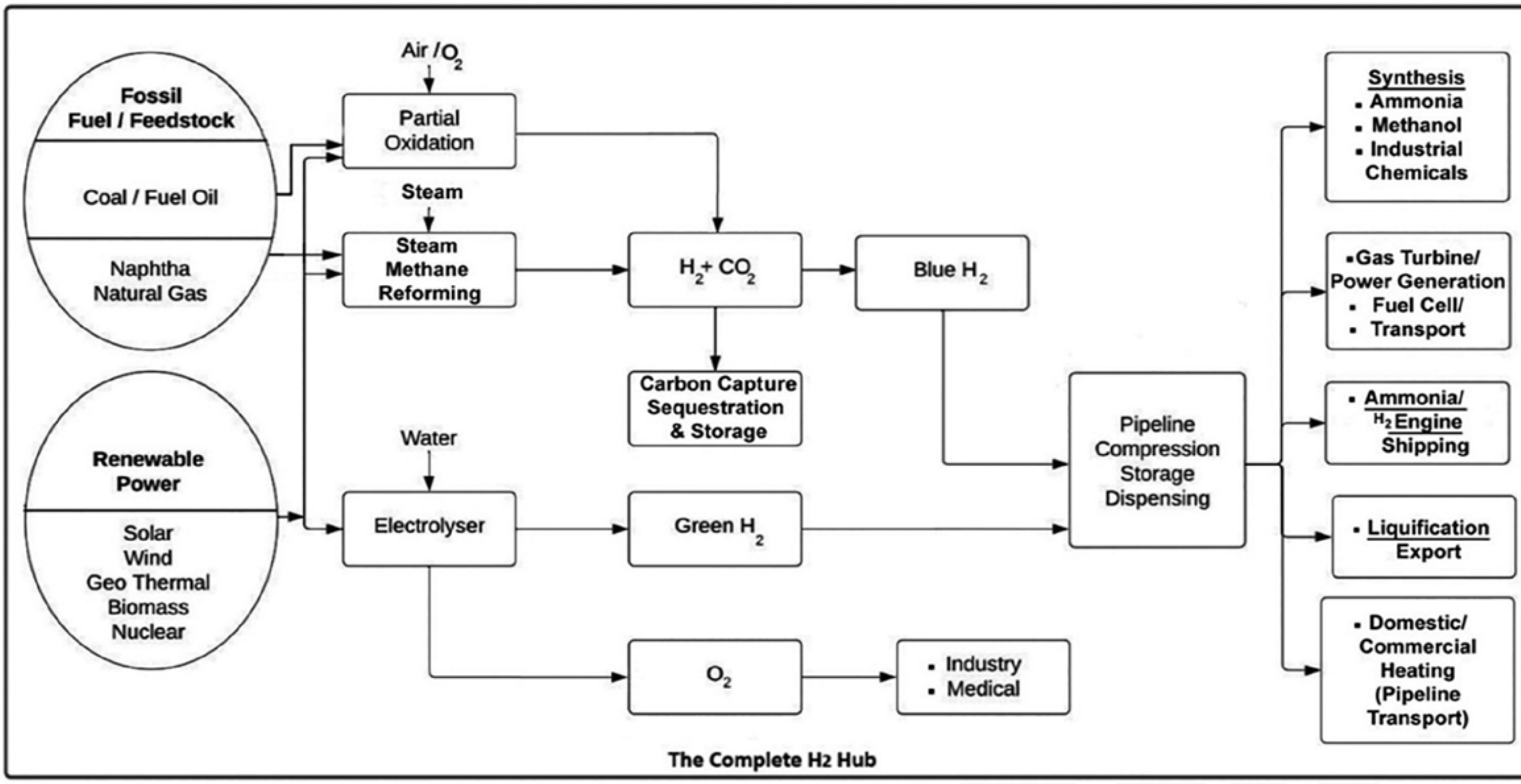



*Fig 1: Hydrogen Hub*

transitioning to cleaner alternatives. The National Green Hydrogen Mission (NGHM), launched in 2023, targets 5 million metric tonnes of annual green hydrogen production by 2030, with updates in 2025 indicating India is on track to meet this goal. This mission emphasizes green hydrogen and ammonia as zero-carbon fuels for energy and fertilizers, addressing the nation's quest for sustainable growth drivers.

Notable advancements include declining costs of renewable energy and green hydrogen production. In 2025, green hydrogen prices in India have fallen to US$ 4.4-4.5 per kg from US$ 5.5 per kg, driven by competitive tenders and technological improvements. Projections indicate further reductions to US$ 2.40 per kg by 2030, a 46% decrease, supported by lower renewable electricity costs units gaining economy of scale in operations. India aims to achieve the world's lowest green hydrogen production costs at approximately Rs. 89 per kg by 2030

## Hydrogen as Fuel and Feedstock of Future

Hydrogen is emerging as a pivotal fuel for the future, offering versatile applications in energy storage, transportation, and industrial processes. For India, this holds particular significance given its strengths in renewable energy sources such as solar, wind, biomass, and tidal power, complemented by adequate water availability for electrolysis. The advent of low-carbon energy needs is shifting global energy resource production centers, positioning India as a potential leader in green hydrogen.

Green hydrogen serves as both a fuel and feedstock, enabling decarbonization across sectors. As a large producer of ammonia-based fertilizers and a major player in the chlor-alkali industry, India possesses inherent potential to integrate hydrogen technologies. Unlike in the past, where technological advancements were often imported, India is now pioneering new developments in hydrogen technology, collaborating with global majors to foster innovation. As of August 2025, India hosts 158 green hydrogen projects at various stages of development, with the NGHM proposing a Strategic Hydrogen Innovation Partnership (SHIP) to pool resources and allocate Rs. 400 crore for research.

Key contributions include

advancements in electrolyser technology, with plans to boost domestic manufacturing through subsidies and government orders. By August 2025, 3 GW of electrolyser capacity has been awarded, progressing toward self-sufficiency. In solar modules, India added 26.6 GW of capacity in the first nine months of 2025, with manufacturing capacity exceeding 125 GW, driven by efficiency improvements and adoption of bifacial, TOPCon, and N-type modules.

## Decarbonization as a National Agenda

Decarbonization has become a cornerstone of India's national agenda, with the government demonstrating determination to develop hydrogen infrastructure. Key components include electrolyser development, storage solutions, pipelines, and dispensing units. Safety and environmental concerns are addressed through protocols for emergency management, accident prevention, and quality standards to mitigate risks in abnormal situations. In April 2025, the Ministry of New and Renewable Energy launched the Green Hydrogen Certification Scheme (GHCS), establishing rules for certification to ensure quality and traceability across the value chain.

The Union Budget 2025-26 allocated Rs. 600 crore to the NGHM, supporting hubs and other projects up to 2025-26. Research and development institutions are actively engaged, focusing on difficult-to-decarbonize sectors such as steel, cement, energy, fertilizers, chemicals, and aviation.

In the steel sector, initiatives include pilot projects for hydrogen integration in direct reduced iron (DRI) processes by companies like Jindal Stainless, JSW Steel, and Tata Steel. Green hydrogen demand in steel is expected to grow at a 13% CAGR, reaching 15.15 million metric tonnes per annum by FY70. A dedicated scheme with Rs. 455 crore budget until 2029-30 supports hydrogen use in steel, mandating new plants to be green hydrogen-ready. For the fertilizer sector, decarbonization leverages green ammonia, with auctions relaunched in 2025 offering incentives to replace grey hydrogen. As of May 2025, 862,000 tonnes of annual green hydrogen capacity has been allocated to 19 companies, targeting fertilizer applications.

> **India aims to achieve the world's lowest green hydrogen production costs at approximately Rs. 89 per kg by 2030**

## Planned Hydrogen Hubs

India's planned hydrogen hubs represent a tangible step toward realizing these aspirations. In 2025, three major ports—Deendayal (Gujarat), V.O. Chidambaranar (Tamil Nadu), and Paradip (Odisha)—were recognized as green hydrogen hubs

**As of August 2025, India hosts 158 green hydrogen projects at various stages of development, with the NGHM proposing a Strategic Hydrogen Innovation Partnership (SHIP) to pool resources and allocate Rs. 400 crore for research**

under the NGHM. Additional initiatives include the Pudimadaka hub in Andhra Pradesh, launched in January 2025 with a $21.6 billion investment for 20 GW of renewable energy capacity, and the Kandla hub involving major players like Reliance Industries and Larsen & Toubro. The State of Kerala is planning primary hubs at the port cities of Kochi and Vizhinjam (Trivandrum), with emerging support for Vizhinjam due to its international port infrastructure, which facilitates potential exports of green hydrogen derivatives such as green ammonia and methanol.

Other states are also taking a lead role, with incentives from the central government to accelerate implementation. Well-defined policies are crucial to ensure seamless progress, including streamlined regulations and viability gap funding for infrastructure.

## Export Potential

India's hydrogen initiatives hold immense export potential, aiming to capture 10% of global green hydrogen demand by 2030. To maximize this, we may have to overcome lessons encountered in the development of Petroleum, Chemicals, and Petrochemicals Investment Regions (PCPIRs). Challenges in PCPIRs included regulatory delays, infrastructure shortages (such as power and water), liquidation of key projects, and community protests. Addressing these through streamlined processes, enhanced stakeholder engagement, and robust funding mechanisms will be vital for hydrogen hubs' success.

Importers are largely advanced economies with high energy demands and limited domestic renewable resources. Europe holds the largest share in 2025, driven by policies like the EU's Renewable Energy Directive (RED) mandating 42% renewable hydrogen in industry by 2030. Japan and South Korea meet approximately 90% of demand through imports, supported by subsidies and tenders requiring low emissions thresholds. Southeast Asia and China also emerge as importers, with Singapore positioning as a bunkering hub. Demand is concentrated in refining, fertilizers, and power generation, with Europe accounting for 50% of offtake agreements.

## Conclusion

Hydrogen production and utilization position India at the forefront of a sustainable future, materializing its aspirations for a decarbonized economy. A 30% materialization of the proposed green hydrogen projects will necessitate the building up of hydrogen hubs at major port cities along India's coastline. By leveraging renewable strengths, fostering technological innovation, and implementing strategic hubs, India can achieve energy security, environmental goals, and global leadership. This pathway not only supports domestic development but also contributes to international climate objectives, ensuring a prosperous and resilient nation for generations to come

# HYDROGEN ECONOMY AND ENERGY TRANSITION: PATHWAYS, CHALLENGES AND OPPORTUNITIES

The global discourse must move beyond net zero targets towards net negative emissions, where carbon dioxide itself becomes a feedstock for fuels, chemicals and materials

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The global energy system is at a critical inflection point, driven by escalating climate risks, rising energy demand, and the urgent need to reduce greenhouse gas emissions. This report examines the hydrogen economy as a central pillar of the energy transition, with particular emphasis on green hydrogen produced from renewable electricity. It analyses the role of hydrogen in decarbonizing hard-to-abate sectors, enabling large-scale energy storage, and facilitating carbon dioxide utilization for net-negative emissions. Integrating policy and academic perspectives, the report highlights India's strategic advantages, identifies key technological and policy barriers, and outlines pathways for scaling hydrogen to achieve a resilient, sustainable, and inclusive low-carbon future.

## Introduction: Energy, Climate and the Imperative for Transition

Energy and environment are inseparably linked. Since the pre industrial era (~ 1750), atmospheric $CO_2$ concentrations have risen from ~280 ppm to over 427 ppm in January 2026, primarily due to the large scale combustion of coal, oil and natural gas. The rapid expansion of industry, power generation and transport has resulted in unprecedented greenhouse gas (GHG) emissions, leading to global warming, climate instability and severe ecological stress.

The period 2020–2024 starkly illustrated this challenge. Global $CO_2$ emissions dipped briefly during the COVID 19 lockdowns in 2020, only to rebound sharply thereafter, reaching record levels by 2023–24. Although renewable energy deployment accelerated during this period, it has not yet been sufficient to reverse the overall emissions trajectory. Natural carbon sinks such as forests and soils are weakening due to deforestation, droughts and wildfires, reducing their ability to offset anthropogenic emissions.

This context underscores a critical point: incremental decarbonization is no longer enough. The global discourse must move beyond net zero targets towards net negative emissions, where carbon dioxide itself becomes a feedstock for fuels, chemicals and materials. The hydrogen economy—particularly green hydrogen—emerges as a central pillar in this deeper energy transition.

## Energy Transition: From Fossil Dependence to Low Carbon Systems

The energy transition refers to a systemic transformation of how energy is produced, stored, distributed and consumed. Globally, the power sector accounts for roughly 40% of $CO_2$ emissions, followed by industry (~25%), transport (~20%), buildings and other sectors. Electrification of end use sectors using renewable power is therefore a necessary but not sufficient condition for deep decarbonization.

Solar and wind power have become the cheapest sources of new electricity generation in many regions, including India. Rapid cost declines, technological learning and scale effects have driven this transformation. However, high penetration of variable renewables introduces challenges related to intermittency, grid stability and seasonal mismatch between supply and demand. These challenges


necessitate complementary solutions such as energy storage, flexible demand, advanced grids and alternative energy carriers.

It is here that hydrogen plays a strategic role. Hydrogen is not a primary energy source but a versatile energy carrier and chemical feedstock, capable of linking electricity with industry, transport, agriculture and materials manufacturing.

## The Hydrogen Economy: Concepts and Typology

Hydrogen has long been used in refineries and fertilizer production, but traditionally it has been produced from fossil fuels (grey hydrogen), emitting large quantities of $CO_2$. When coupled with carbon capture, this becomes blue hydrogen, which reduces but does not eliminate emissions and remains dependent on fossil infrastructure. Green hydrogen, produced via electrolysis of water using renewable electricity, is fundamentally different. It enables:

- Zero carbon hydrogen production
- Large scale integration of renewable electricity
- Decarbonization of hard to abate sectors
- Coupling of power, fuel and chemical systems

Despite its promise, green hydrogen currently represents a very small fraction of global hydrogen production, largely due to cost and infrastructure barriers. Bridging this gap is both a technological and policy challenge.

## Green Hydrogen in the Energy Transition

### Decarbonizing Hard to Abate Sectors

Green hydrogen is uniquely suited for sectors where direct electrification is difficult or impractical:

- **Iron and steel:** Hydrogen based direct reduced iron (DRI) can replace coal based blast furnaces.
- **Cement and lime:** Hydrogen can provide high temperature heat and enable alternative low carbon pathways.

**Green ammonia is emerging as a cornerstone of the hydrogen economy. It is easier to store and transport than hydrogen and leverages existing global infrastructure**

- **Chemicals and fertilizers:** Green hydrogen can directly substitute grey hydrogen in ammonia, methanol and downstream chemicals.
- **Transport:** Hydrogen and hydrogen derived fuels (ammonia, methanol, and SAF) are promising for long haul shipping, aviation and heavy duty transport.

### Green Ammonia and Hydrogen Derived Fuels

Green ammonia is emerging as a cornerstone of the hydrogen economy. It is easier to store and transport than hydrogen and leverages existing global infrastructure. Beyond fertilizers, green ammonia has potential as a shipping fuel, long duration energy storage medium and even for co firing in power plants.

Similarly, hydrogen derived synthetic fuels—such as green methanol, DME and sustainable aviation fuels—enable

> **Green hydrogen currently represents a very small fraction of global hydrogen production, largely due to cost and infrastructure barriers. Bridging this gap is both a technological and policy challenge**

decarbonization of sectors that cannot rely on batteries alone.

## Hydrogen Storage and Grid Integration

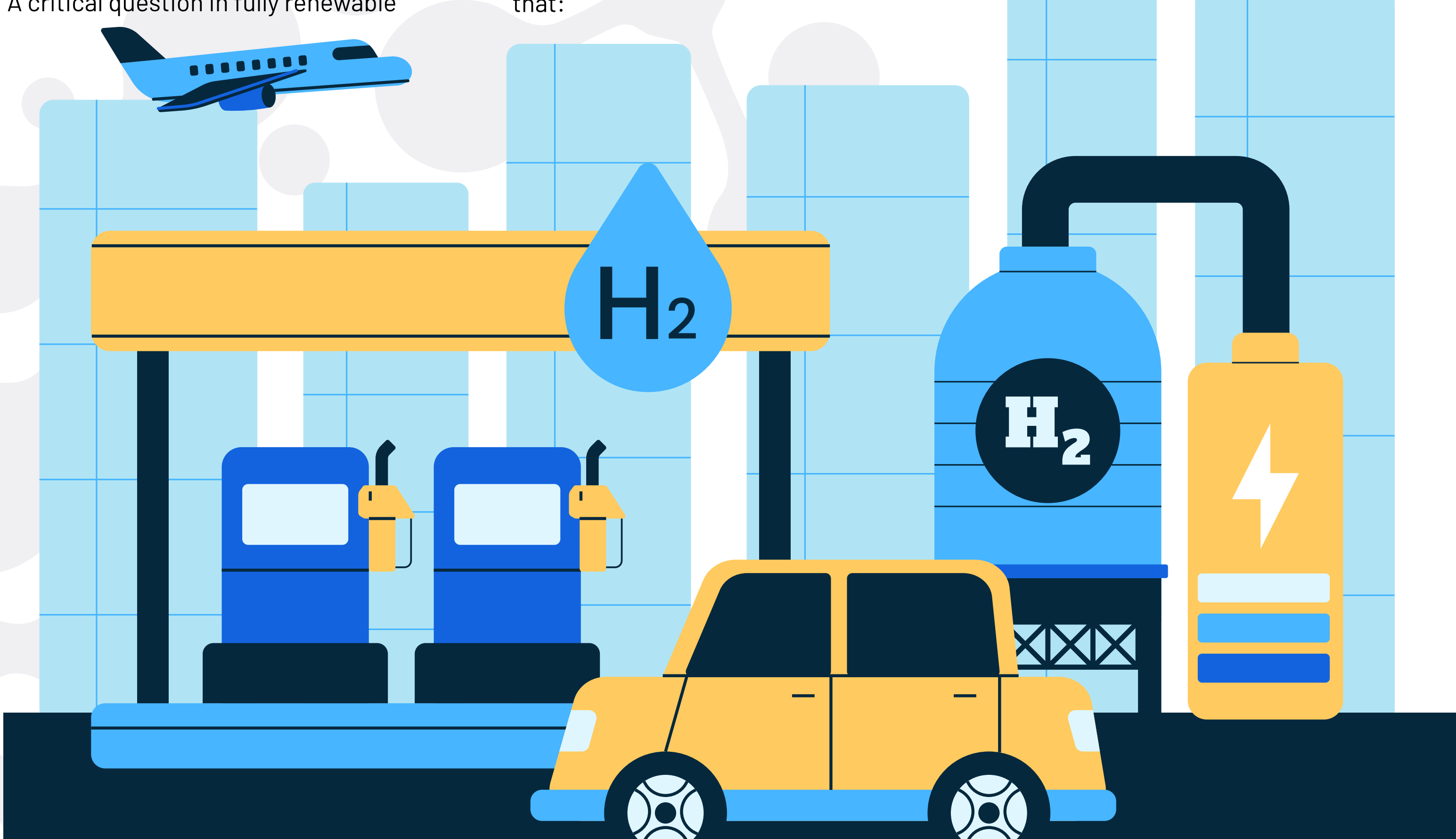
A critical question in fully renewable energy systems is optimal storage. Short duration batteries are well suited for diurnal balancing, while long duration and seasonal storage require alternative solutions. Studies comparing battery storage and hydrogen storage indicate that:

- Batteries are more efficient and cost effective for short term grid balancing.
- Hydrogen is valuable for long duration and seasonal storage, and when integrated with industrial demand.
- Hybrid systems combining batteries, hydrogen and pumped hydro offer the most robust and economical solutions.

Thus, hydrogen should not be viewed as a competitor to batteries, but as a complementary component of a diversified energy storage portfolio.

## Carbon Dioxide as a Resource: Beyond Net Zero

A defining feature of the next phase of the energy transition is the shift from carbon avoidance to carbon utilization. Captured $CO_2$ can be catalytically converted into fuels, chemicals and materials using green hydrogen as a reducing



agent.

This concept of $CO_2$ refineries transforms carbon dioxide into methanol, synthetic hydrocarbons, polymers and specialty chemicals. Such pathways:

- Enable net negative emissions when coupled with renewable energy
- Create economic value from waste carbon
- Integrate energy, chemical and materials industries

Catalytic $CO_2$ valorization, while still facing challenges related to efficiency, selectivity and scale, represents a strategic opportunity for countries with strong chemical engineering capabilities.

## India's Strategic Advantage in the Hydrogen Economy

India is uniquely positioned to become a global leader in green hydrogen due to:

- Abundant solar and wind resources
- A large domestic market for fertilizers, steel and chemicals
- Strong capabilities in chemical engineering and catalysis
- A rapidly expanding renewable power base

The National Green Hydrogen Mission reflects this strategic intent. However, current incentives, while welcome, are insufficient to rapidly scale green hydrogen to global competitiveness. Stronger support mechanisms, long term offtake guarantees and integration with industrial policy are required.

India must also align hydrogen deployment with broader goals such as energy security, rural development, job creation, and technological self reliance.

## Policy Gaps and Structural Barriers

Despite ambitious net zero announcements by many countries, a significant implementation gap persists. Fossil fuel subsidies remain high, carbon pricing covers only a fraction of global emissions, and new fossil infrastructure continues to be built.

For hydrogen specifically, key barriers include:

- High capital costs of electrolysers
- Cost and availability of renewable electricity
- Lack of transport and storage infrastructure
- Uncertain demand and offtake risks

Addressing these barriers requires coherent, long term policy frameworks rather than short term pilot driven approaches.

## Socio Economic Dimensions and a Just Transition

The hydrogen economy is not merely a technological shift; it is a socio economic transformation. Renewable energy and hydrogen value chains have the potential to create millions of jobs, often more distributed and resilient than fossil fuel based employment.

A just transition requires:

- Reskilling workers from fossil dependent sectors
- Ensuring affordability and access to clean energy
- Supporting regions vulnerable to industrial restructuring

Public participation, decentralized energy systems and community level engagement will be essential for long term social acceptance.

## The Decisive Decade: 2025–2035

Scientific evidence is unequivocal that the next decade will determine whether global warming can be limited to manageable levels. Delayed action will lock in irreversible climate damage and economic risk.

Hydrogen must therefore be scaled not as a niche solution, but as a core element of national and global energy strategies, tightly integrated with renewables, storage, industrial decarbonization and $CO_2$ utilization.

## Conclusion

The hydrogen economy offers a powerful pathway to reimagine the global energy system—one that is cleaner, more resilient and more equitable. However, realizing this vision requires moving beyond rhetoric to decisive policy action, sustained investment and systems level thinking.

The transition from fossil fuels to renewables, and from net zero to net negative emissions, is not optional; it is an existential imperative. Green hydrogen, coupled with $CO_2$ valorization and renewable energy, can enable this transformation. The choices made in this decade will determine whether hydrogen becomes a transformative solution or a missed opportunity.

For India and the world, the message is clear: the future energy economy must be hydrogen enabled, renewable powered, and sustainability driven

# MAKING GREEN HYDROGEN ECONOMICALLY VIABLE FOR FERTILIZER PLANTS IN INDIA

India generates approximately 35 million tonnes of urea each year, with ammonia production responsible for nearly 60% of the fertilizer sector's total emissions. Transitioning to green ammonia production could eliminate more than 30 million tonnes of $CO_2$ annually

**Dr. Siba Prasad Mohanty**
**Managing Director**
HURL

India's fertiliser sector occupies a unique and strategic position in the country's industrial and economic landscape. It is not only a backbone of agricultural productivity and food security, but also one of the most energy-intensive segments of the chemical industry. As India advances towards its net-zero commitments and accelerates the clean energy transition, fertiliser plants are increasingly under the spotlight for decarbonisation.

At the centre of this transformation lies a critical question: When will fuel switching to hydrogen, particularly green hydrogen, make economic sense for Indian fertiliser plants? The answer depends on the interplay of cost competitiveness, infrastructure readiness, policy support, and long-term strategic vision.

## Hydrogen and Fertilisers: An Indian Perspective

Hydrogen is already integral to fertiliser production. Ammonia synthesis-the core process for urea and other nitrogenous fertilisers, consumes nearly 70-75% of a fertiliser plant's total energy, with hydrogen as the primary feedstock.

In India, hydrogen is predominantly produced using natural gas through Steam Methane Reforming (SMR) or coal gasification, both of which are carbon-intensive. With India importing over 50 per cent of its natural gas requirements, the fertiliser sector remains vulnerable to global price volatility and supply disruptions.

Green hydrogen-produced through electrolysis using renewable power, offers a compelling alternative by enabling low-carbon or near-zero-carbon ammonia production. However, its adoption hinges on economic viability within India's regulated fertiliser pricing framework.

**India – Hydrogen Cost Snapshot (Indicative)**

| Hydrogen Source | Cost (Rs./ kg $H_2$) | Emissions Profile |
|---|---|---|
| Natural Gas (SMR) | Rs. 120–150 | High |
| Coal Gasification | Rs. 100–130 | Very High |
| Green Hydrogen (2024–25) | Rs. 300–400 | Near Zero |
| Green Hydrogen (Target by 2030) | Rs. 150–180 | Near Zero |

*Source: MNRE, NITI Aayog, Industry Estimates*

## Why Green Hydrogen Is Not Yet Economical-But Inevitable

At present, green hydrogen in India is nearly 2.5-3 times costlier than fossil-based hydrogen. Given that hydrogen cost directly influences ammonia and urea prices, fertiliser manufacturers, operating under government-controlled MRPs and subsidy mechanisms, cannot absorb this differential without support.

Yet, three India-specific developments are rapidly changing the equation: India has some of the lowest renewable energy

> **The true economics of hydrogen will emerge when carbon costs are no longer invisible**

tariffs globally, with solar and wind power available at Rs. 2-2.5 per kWh; electrolyser costs are declining, supported by domestic manufacturing incentives under the National Green Hydrogen Mission; and carbon considerations are entering trade and finance through ESG norms, green finance, and emerging carbon markets.

Together, these factors point to a future where green hydrogen becomes economically viable within the next decade.

For India's fertiliser sector, green hydrogen is not just an environmental choice-it is a strategic necessity.

## Why Fertiliser Plants are Ideal Hydrogen Anchors

Fertilizer plants are ideal for anchoring India's green hydrogen ecosystem because they offer large, continuous (TPD scale) and 24x7 base-load hydrogen consumption, which is perfect for electrolysis. They also bring existing expertise in hydrogen handling and safety, and their role is vital for national food security.

India generates approximately 35 million tonnes of urea each year, with ammonia production responsible for nearly 60% of the fertilizer sector's total emissions. Transitioning to green ammonia production could eliminate more than 30 million tonnes of $CO_2$ annually.

## What Will Make Hydrogen Economically Viable in India?

Fuel switching to green hydrogen becomes economically viable when four critical enablers are in place:

***Green Hydrogen at Rs. 50/kg or Below:*** Economic parity with fossil fuels emerges when green hydrogen costs approach Rs. 150 per kilogram. This price point is achievable through a combination of low-cost renewable energy, the use of high-efficiency electrolysers, and the benefits of large-scale production (economy of scale).

Integrated Renewable-Hydrogen-Ammonia Hubs: Developing co-located hubs that integrate fertilizer plants with renewable energy sources and electrolysis infrastructure can significantly reduce overall costs by minimizing energy


transmission losses and storage expenses.

**Policy and Fiscal Support:** Early adoption requires supportive government intervention. This includes measures such as Viability Gap Funding (VGF), mechanisms for carbon credit monetization, a stable, long-term policy environment, and preferential treatment for green ammonia in the market.

**Carbon Cost Internalization:** The structural competitiveness of green hydrogen improves as the environmental costs (externalities) of using fossil fuels are factored into market prices, either through government regulations or specific carbon trading mechanisms.

## A Phased Transition: The Most Practical Path

It is neither realistic nor prudent to envision an overnight shift. The path forward lies in phased integration. For Indian fertiliser plants, hydrogen adoption will be evolutionary, not disruptive.

In the near term, fertiliser plants can begin with blending green hydrogen into existing systems-5 to 10 per cent substitution, without major process overhauls. This allows operational learning, risk mitigation, and gradual emissions reduction.

In the medium term, dedicated green ammonia production units can be developed, particularly for non-urea applications, exports, or specialised fertilisers. This creates parallel value streams while building confidence and capability.

In the long term, as hydrogen economics improve and infrastructure matures, full fuel switching becomes viable, positioning fertiliser plants as near-zero-carbon facilities.

A pragmatic starting point lies in fertiliser segments where MRP is not fixed, such as NPK, allowing greater pricing flexibility while scaling green hydrogen adoption.

## India's Strategic Advantage

India is leveraging three key strengths to drive progress:

**Lowest renewable energy costs:** The country benefits from having the most competitive renewable energy costs, making clean power economically viable and scalable.

Large fertiliser capacity with assured demand: India possesses significant domestic capacity for fertiliser production, supported by consistent and reliable demand, which is crucial for the agricultural sector.

Strong public sector leadership: Decisive leadership and proactive policies from the public sector are guiding the strategic direction and expansion of key industries, including the green energy transition and infrastructure development.

Public sector fertiliser companies can act as first movers, de-risking investment, building scale, and catalysing the

**India's fertiliser sector can become the cornerstone of the nation's green hydrogen ecosystem**

hydrogen economy, while ensuring farmer affordability remains protected.

## Leadership Beyond Economics

Fuel switching to hydrogen is not merely a techno-economic decision. It requires a comprehensive approach that addresses several critical factors. The successful transition demands a long-term capital vision to ensure sustained investment in infrastructure, production, and technology. It also necessitates widespread workforce reskilling to prepare the labor market for new roles and technical demands in the hydrogen economy. Additionally, the transition calls for enhanced safety and digital systems to manage the unique physical properties of hydrogen (e.g., storage challenges and leak potential) and optimize the new value chains. Finally, cross-sector collaboration is essential to coordinate efforts across energy, transportation, and manufacturing industries, ensuring a cohesive and effective transition.

Fertiliser plants have historically driven industrial transformation, from coal to gas, from manual to automated operations. Hydrogen represents the next chapter in this evolution. Those who invest early in learning, partnerships, and pilot projects will be best positioned to lead when economics turn favourable.

## Conclusion

Fuel switching to hydrogen in Indian fertiliser plants is not a question of if, but when. As green hydrogen costs decline, infrastructure matures, and policy frameworks strengthen, the economic case will align with strategic necessity.

For the fertiliser sector, embracing hydrogen is about future-proofing relevance, enhancing energy security, and supporting India's journey towards sustainable agriculture and industrial decarbonisation, while continuing to fulfil its foundational role of feeding the nation

# GREEN HYDROGEN IN INDIA: FROM POLICY TO ACTION

India currently imports over 85% of its oil and 50% of its natural gas, costing the exchequer over $90 billion annually. Green hydrogen offers a pathway to energy sovereignty

The global climate narrative is shifting from "why" to "how," and India is positioning itself at the center of this transition. With the launch of the National Green Hydrogen Mission (NGHM) in 2023, India signalled its intent to lead the next industrial revolution. As of early 2026, the mission has moved from a conceptual framework to a high-stakes execution phase. Green hydrogen—produced via electrolysis powered by renewable energy—is not merely a clean fuel; for India, it is a strategic necessity to achieve net zero by 2070 and secure energy independence.

India's commitment to achieving net zero by 2070, as pledged at COP26, requires a radical overhaul of its energy architecture. While solar and wind power have decarbonized the electricity grid, they cannot easily reach "harder-to-abate" sectors such as heavy industry and long-haul transport. This is where green hydrogen becomes indispensable.

## The "Whys" (and "Hows") of Green Hydrogen

### Decarbonizing the "Harder to Abate" Core

Industries like steel, cement, chemicals, and refineries account for a significant portion of India's carbon footprint. These sectors require high-grade heat or chemical feedstocks that electricity alone cannot provide. By replacing fossil-fuel-derived "grey" hydrogen with green hydrogen, India can abate nearly 50 MMT of annual greenhouse gas emissions by 2030 (MNRE, 2023). In the steel sector, the shift from coal-based blast furnaces to hydrogen-based Direct Reduced Iron (DRI) could make Indian steel the "greenest" in the world, providing a competitive edge in carbon-tax-heavy markets like the European Union.

### Enhancing Energy Security and Economic Resilience

India currently imports over 85% of its oil and 50% of its natural gas, costing the exchequer over $90 billion annually. Green hydrogen offers a pathway to energy sovereignty. By converting abundant domestic solar and wind energy into a storable chemical form, India can reduce its fossil fuel import bill by over Rs. 1 lakh crore ($12 billion) by 2030 (PIB, 2024). Furthermore, the mission is projected to attract Rs. 8 lakh crore in investment and create 600,000 jobs, fostering a new domestic manufacturing ecosystem for electrolyzers and fuel cells.

### Strategic Interventions for Green Hydrogen Transition (SIGHT) programme

To bridge the initial commercial gap, the Government of India launched the SIGHT programme with an outlay of Rs. 17,490 crore. This scheme provides two critical pillars of support:

- Electrolyzer Manufacturing: Financial incentives for 5 years to boost domestic production, reducing dependence on imports.
- Green Hydrogen Production: Direct incentives (starting at Rs. 50/kg in the first year) to make green hydrogen competitive with its grey counterpart.
- Waivers and Banking: The government has also provided a 25-year waiver of Inter-State Transmission System (ISTS) charges for projects commissioned before 2030, drastically lowering the cost of transporting renewable energy to production sites.

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## The Execution Gap: Identifying the Challenges

Despite the robust policy framework, the transition from "Green Hydrogen on paper" to "Green Hydrogen in pipelines" faces formidable hurdles. As of 2026, while interest is high, only a small fraction of announced projects have reached the construction phase (IEEFA, 2025).

### The "Green Premium" and Economic Viability

The primary barrier remains the cost gap. Green hydrogen currently costs roughly Rs. 350–Rs. 500/kg, whereas grey hydrogen is


produced at Rs. 150–Rs. 220/kg. Without a mechanism to bridge this "Green Premium," industrial offtakers are hesitant to sign long-term purchase agreements. While SIGHT helps, the incentive is seen by some as insufficient compared to the massive tax credits offered by the US Inflation Reduction Act .

### Infrastructure and Storage Bottlenecks

Hydrogen is the smallest molecule and is notoriously difficult to transport.

- Pipeline Readiness: Most existing gas pipelines in India cannot carry pure hydrogen due to "hydrogen embrittlement," which makes metal pipes brittle and prone to cracking.
- Storage Complexity: It requires high-pressure tanks (up to 700 bar) or cryogenic cooling (about -253°C), which are energy-intensive and expensive.

### Resource and Supply Chain Constraints

- Water Intensity: Producing 1 kg of green hydrogen requires roughly 9 litres (or 0.009 cubic metres) of demineralized water. By itself, this is not a large amount – it is estimated that 10% of the water used in agriculture, a total of about 700 billion cubic metres – can be saved at zero or very-low cost. However, the problem is acute in water-stressed regions like Rajasthan and Gujarat, where sourcing this water without depleting local resources is a major environmental and social challenge.
- Critical Minerals: Electrolyzer components like Iridium, Platinum, and Nickel are largely imported, creating a new form of supply chain dependence.

**Producers are waiting for guaranteed demand before reaching Final Investment Decisions (FID), while potential consumers (refineries and fertilizer plants) are waiting for prices to drop**

### Demand Uncertainty

Producers are waiting for guaranteed demand before reaching Final Investment Decisions (FID), while potential consumers (refineries and fertilizer plants) are waiting for prices to drop. The absence of strict Green Hydrogen Consumption Obligations (GHCOs) has left the market in a state of "wait-and-watch" (WEF, 2024).


> **To move from policy to action, the Indian government must also focus on five key measures for ecosystem enablement, apart from the current focus on production incentives**

## Bridging the Gap: Recommended Government Actions

To move from policy to action, the Indian government must also focus on five key measures for ecosystem enablement, apart from the current focus on production incentives. These measures are:

### Demand Aggregation and Mandates

The government should implement mandatory green hydrogen Consumption Obligations (GHCOs). Much like Renewable Purchase Obligations (RPOs) transformed the solar sector, requiring a minimum percentage of green hydrogen in refineries and fertilizer production would provide the "anchor demand" needed for bankable projects.

### Implementing a "Contract for Difference" (CfD) Mechanism

To solve the price disparity, India should adopt a Contract for Difference model. Under this, the government pays the difference between the market price of grey hydrogen and the production cost of green hydrogen. This de-risks the project for the producer and ensures the consumer gets the fuel at a competitive rate until the technology scales.

### Infrastructure "Plug-and-Play" Hubs

Instead of fragmented projects, the government must accelerate the development of green hydrogen hubs. These hubs, located near major ports (like Kandla or Paradip, for green hydrogen export) and industrial clusters (for domestic green hydrogen usage), should provide shared infrastructure: desalination plants, common storage terminals, and dedicated renewable energy evacuation lines.

### Strengthening the R&D and Manufacturing Ecosystem

The government must fund R&D in next-generation technologies that use fewer rare earth minerals (e.g., Anion Exchange Membrane). Establishing a national Critical Minerals Reserve or entering into strategic mineral partnerships with nations like Australia is vital for supply chain security.

### 5. Regulatory Harmonization

Investors need certainty. The government must finalize and implement a unified Green Hydrogen Certification Scheme to ensure that Indian hydrogen meets international standards (like the EU's RED III). This is crucial for India to achieve its goal of exporting 10 MMT annually by 2030 (Argus Media, 2025; RMI, 2025).

## Conclusion

India stands at a pivotal junction. The National Green Hydrogen Mission has laid a sophisticated foundation, but the journey from policy to action requires a shift toward market-making. By enforcing demand mandates, bridging the cost gap through financial innovation, and building integrated industrial hubs, India can overcome the current technical and economic barriers. Success in Green Hydrogen will not only mean a cleaner environment; it will cement India's role as a global energy superpower, proving that economic growth and deep decarbonization can, and must, go hand in hand

# LIFE-CYCLE SUSTAINABILITY: THE REAL CARBON FOOTPRINT OF GREEN HYDROGEN

Currently, India produces 6.5 MMT of hydrogen annually—99%+ grey hydrogen from fossil fuels—with green hydrogen production at merely ~0.01 MMT

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Green hydrogen is widely positioned as the cornerstone of industrial decarbonisation—especially for hard-to-abate sectors such as steel, fertilisers, chemicals, refining, shipping and aviation. With large investments now being committed across India and globally, the key question is no longer whether hydrogen will scale, but whether it will actually deliver genuine climate benefit. That question can only be answered through life-cycle sustainability—a rigorous, evidence-based approach that examines emissions across the entire value chain, not just at the point of production.

## Beyond Electrolysers: Why Full-Chain Accounting Matters

Hydrogen is often labelled 'green' if produced by renewable-powered electrolysis. But green hydrogen also includes pathways based on biomass gasification and compressed biogas (CBG) reforming. These routes differ sharply in their carbon, land-use and resource footprints. A credible sustainability assessment must extend beyond production to the full value chain: feedstock production and transport; electrolyser, gasifier and balance-of-plant manufacturing; electricity generation; conversion to derivatives (ammonia, methanol, e-fuels); compression, storage, shipping and distribution; and end-use applications. International standards such as ISO 14040 and ISO 14044 explicitly require this full life-cycle approach for environmental claims. Without it, hydrogen risks becoming a re-labelling exercise rather than a genuine climate solution.

## Life-Cycle Emissions: A Quantitative Reality Check

Understanding the true carbon footprint of hydrogen requires comparing operational emissions with full life-cycle assessment (LCA) values across different production pathways. The following table presents emission factors particularly relevant to the Indian context:

The calculations above do not include the footprint of electrolyser manufacturing, and maintenance. In our assessment (Waiyaki et.al., 2025) we noted that it could range from about 6 to 9 $CO_2$-eq/kg $H_2$. The numbers could also vary based on assumptions of emission factor of the grid, emission inventory of materials and processes etc. However, the important

| Technology | Operational | LCA (Cradle-to-Grave) |
|---|---|---|
| Grid Electricity (India) | 35–42 | 37–45 |
| SMR (Unabated) | 8–10 | 9–12 |
| SMR + CCS (90%) | 1.2–2 | 1.5–2.7 |
| Coal Gasification | 18–20 | 22–26 |
| Solar PV Electrolysis | 0 | 1.0–2.5 |
| Wind Electrolysis | 0 | 0.5–1.8 |
| Biomass Gasification | 0 (biogenic) | 2–3 |

*Table: Hydrogen Production Emission Factors (kg $CO_2$-eq /kg $H_2$)*

**Critical Insight for India:** Using Indian grid electricity (0.757 $tCO_2$/MWh per CEA v20.0, December 2024) for electrolysis yields **~38–42 kg $CO_2$/kg $H_2$—this is 3–4× worse than even unabated steam methane reforming (SMR) and ~20× above India's green hydrogen threshold** of ≤2 kg $CO_2$-eq/kg $H_2$. Without dedicated renewable capacity, hydrogen from India's grid would have a carbon footprint exceeding that of the dirtiest fossil-based production methods.

point to note is the need for a holistic assessment to get the real picture and the levers for achieving decarbonisation.

## The Biogenic Carbon Blind Spot

Biomass-based hydrogen introduces a major but often overlooked risk. Many carbon accounting frameworks treat biogenic $CO_2$ emissions as zero, assuming biomass regrows and re-absorbs the carbon. This is valid only if biomass harvesting is sustainable, no carbon-rich land is converted, soil carbon losses are avoided, and regrowth occurs within a climate-relevant timeframe. In practice, upstream emissions from fertiliser use, diesel consumption, biomass transport and methane leakage during anaerobic digestion are very real and must be counted. Studies by the IEA Bioenergy Task 38 and IPCC show that poorly managed biomass systems can generate lifecycle emissions comparable to fossil fuels. Ignoring these emissions risks turning 'bio-hydrogen' into one of the largest sources of unintentional greenwashing.

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## India's 5-Million-Tonne Ambition: The Electricity Reality

India has committed to producing 5 million tonnes of green hydrogen annually by 2030 under the National Green Hydrogen Mission. Meeting this target requires far more than electrolysers—it requires enormous quantities of clean electricity. Currently, India produces 6.5 MMT of hydrogen annually—99%+ grey hydrogen from fossil fuels—with green $H_2$ production at merely ~0.01 MMT (negligible pilot projects). Renewable energy installed capacity stands at 217 GW (Solar: 92 GW, Wind: 48 GW, Hydro: 47 GW), generating approximately 403 TWh annually.

Electrolysis typically consumes 50–55 kWh per kg of hydrogen (IRENA, 2022). The mathematics are stark: 5 MMT × 50 kWh/kg = 250 TWh/year of dedicated renewable electricity. This 250 TWh represents approximately 24% of India's projected 2030 RE generation (~1,050 TWh) and requires ~125 GW of dedicated renewable capacity—equivalent to 60% of India's entire current RE installed base. The National Green Hydrogen Mission recognises this, allocating 125 GW specifically for hydrogen production.

The required growth rates are extraordinary: green $H_2$ production must achieve ~200% CAGR from virtually zero to 5 MMT in five years, while electrolyzer capacity must scale from ~0.1 GW to 60 GW (~180% CAGR). RE capacity must grow at ~18% CAGR from 217 GW to 500 GW.

## Why Digital Traceability Is Becoming Critical

Global hydrogen markets are now governed by carbon-intensity thresholds—particularly under EU RFNBO rules, Guarantees of Origin, and CBAM-linked green fuel certification. These regimes require verifiable, real-time emissions

**Key Insight on Competing Demands:** Contrary to popular discourse framing EVs as the primary grid planning challenge, green hydrogen requires 4× more renewable electricity than EVs. By 2030, EVs (~28 million vehicles) will need ~60 TWh (5.7% of RE generation), while green $H_2$ demands 250 TWh (23.8%). If dedicated RE capacity is not built fast enough, hydrogen projects will inevitably draw from India's coal-heavy grid—producing hydrogen with 20× higher emissions than the green threshold and completely negating any climate benefit.

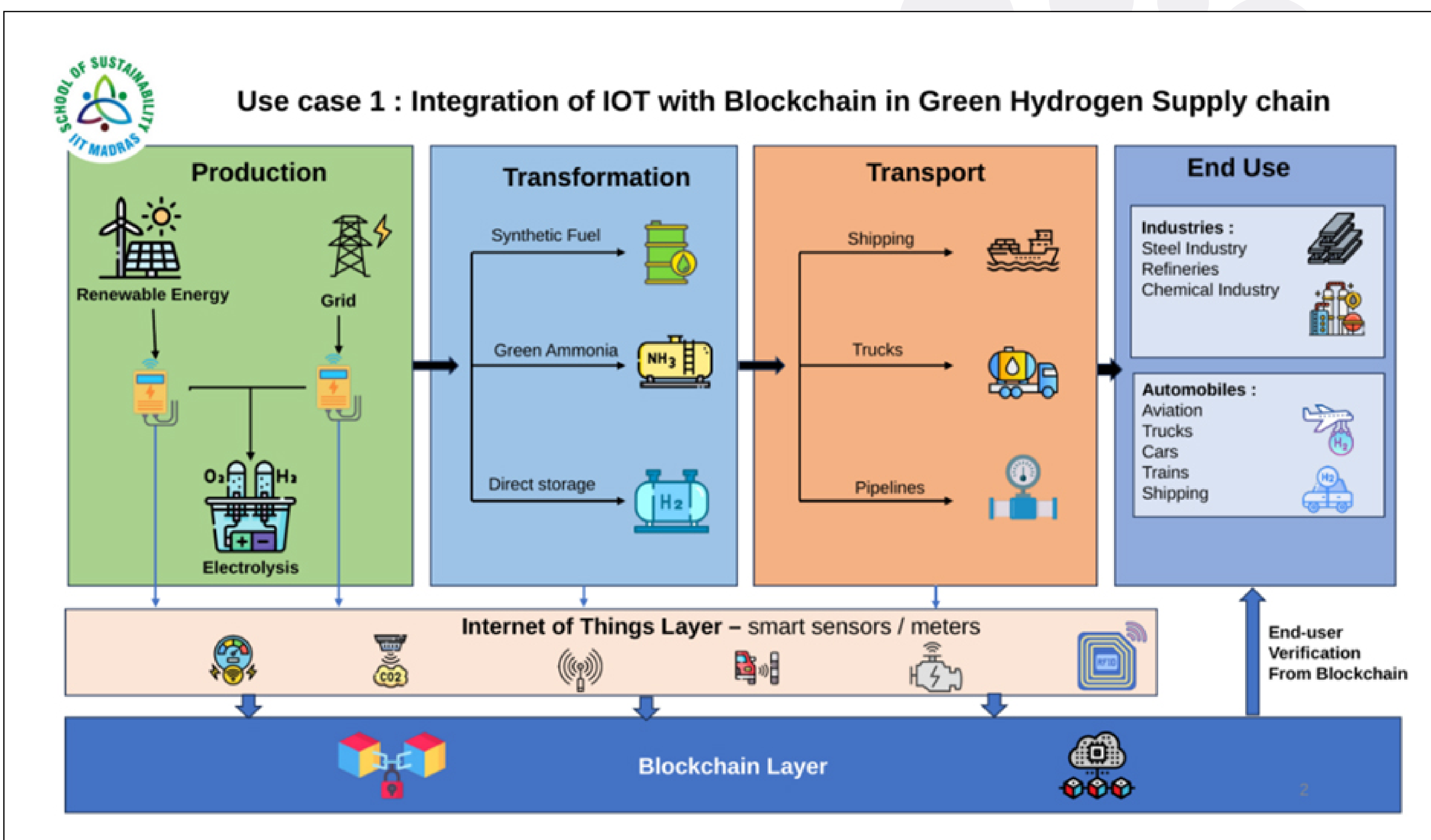


*Figure 1: Integration of IoT with Blockchain in the Green Hydrogen Supply Chain*


**IoT-blockchain-based monitoring, reporting and verification must become the backbone of hydrogen certification and trade, providing the verifiable, real-time data that international markets now demand**

data, not annual self-declarations. This is where IoT integrated with blockchain becomes transformative.

Smart sensors deployed across the hydrogen value chain measure electricity input, hydrogen flow, purity, compression energy, storage losses and process emissions. When recorded on blockchain, these data become tamper-proof, auditable and trade-ready. Smart contracts can automatically verify whether a hydrogen batch meets required carbon-intensity thresholds, enabling automated certification and compliance with international regulations. This shifts hydrogen from self-reported sustainability to digitally verified climate performance. Practitioners—including IIT-incubated consultancies now assisting Indian SMEs with LCA-based carbon accounting and EU CBAM compliance—are demonstrating that robust lifecycle intelligence is not just technically feasible but commercially actionable for industry.

## What Must Be Embedded from Day One

If green hydrogen is to become a credible pillar of India's industrial transition, three things must be embedded into every project:

**Standardised life-cycle accounting:** Based on ISO 14040/44 with explicit treatment of biogenic carbon, land-use change and electricity sourcing—recognising that even solar and wind electrolysis carries embodied carbon (1.0–2.5 and 0.5–1.8 kg $CO_2$-eq/kg $H_2$ respectively).

**Realistic renewable energy planning:** Hydrogen targets must be matched by physically deliverable renewable capacity—125 GW dedicated to electrolysis by 2030—not accounting offsets. Annual RE additions must nearly double from ~28 GW/year to 50+ GW/year to meet combined grid and hydrogen demands.

**Digital MRV infrastructure:** IoT-blockchain-based monitoring, reporting and verification must become the backbone of hydrogen certification and trade, providing the verifiable, real-time data that international markets now demand.

Only with these safeguards will green hydrogen deliver what it promises—real decarbonisation rather than accounting-led emission shifting. The building blocks exist; what matters now is rigorous, evidence-based implementation across India's emerging hydrogen ecosystem. With Rs. 8+ lakh crore (~$100 billion) of investment at stake and India's climate commitments on the line, there is no room for greenwashing—only for genuine, verifiable sustainability

# FOSTERING INNOVATION IN INDIA'S HYDROGEN ECOSYSTEM: A BLUEPRINT FOR A SUSTAINABLE FUTURE

## The transition to a hydrogen is not merely a change in fuel; it is a change in the industrial DNA of the nation

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The global energy landscape is undergoing a seismic shift. As the world moves away from carbon-intensive fuels, green hydrogen (GH2) has emerged as the cornerstone of deep decarbonization. For India, this transition is a strategic economic imperative. With the National Green Hydrogen Mission (NGHM) targeting an annual production of 5 million metric tonnes per annum (MMTPA) by 2030, the path forward requires more than capital; it demands a robust, indigenous innovation engine. To transform India into a global GH2 hub, we must pivot from adopting foreign technologies to fostering an ecosystem that addresses local technical constraints while setting global benchmarks in efficiency and cost.

The true test of India's hydrogen ecosystem lies in sectors where high energy density and high-grade heat are non-negotiable. While steel and cement are the usual suspects, the frontiers of marine and aviation present the most complex engineering challenges.

The shipping industry currently contributes nearly 3% of global emissions, driving a strategic shift away from gaseous hydrogen—which is hindered by its massive storage requirements toward green ammonia ($NH_3$) as a viable alternative. This transition is being spearheaded by Indian R&D through dual-fuel innovation, specifically targeting the challenges of ammonia's low flame speed and high auto-ignition temperature. By developing high-pressure injection systems and "pilot fuel" strategies, engineers are ensuring stable combustion within massive two-stroke marine engines.

> **Green hydrogen currently represents a very small fraction of global hydrogen production, largely due to cost and infrastructure barriers. Bridging this gap is both a technological and policy challenge**

Beyond the engine room, the transformation extends to bunkering logistics, where the establishment of "Green Corridors" at ports like V. O. Chidambaranar involves the deployment of cryogenic loading arms and sophisticated leak detection sensors to safely manage ammonia's toxicity. Furthermore, while ammonia powers primary propulsion, onboard auxiliary power is transitioning to PEM Fuel Cells. This requires advanced integrated "reformers" capable of cracking ammonia back into hydrogen on-demand, creating a comprehensive and sustainable energy ecosystem for the future of maritime transport.

To address the aviation sector's demand


for the highest power-to-weight ratio of any industry, India is pioneering a multi-pronged approach to decarbonization focused on Sustainable Aviation Fuel (SAF) and Cryogenic Integration. For long-haul transport, innovation centers on Power-to-Liquid (PtL) technology, which synthesizes "drop-in" kerosene by reacting to green hydrogen with captured CO2. This synthetic fuel is particularly effective because it requires zero engine modifications, offering the most immediate path to reducing emissions in existing fleets.

Innovation is often stifled by the "Green Premium." India has addressed this head-on through the Strategic Interventions for Green Hydrogen Transition (SIGHT) scheme, creating a transparent marketplace for price discovery. Under the SIGHT Mode 2A framework, SECI has stepped up as a central demand aggregator, successfully pooling requirements from across the fertilizer sector. The late 2025 auctions marked a major milestone for the industry discovered rates ranging from approximately Rs. 49.75 to Rs. 64.7 per kilogram for green ammonia. This is a real game-changer because it finally brings green fuel prices close to those of traditional "Grey" ammonia, giving private and Govt. Fertilizer companies the confidence to switch without facing huge financial risks.

Side by side, SIGHT Mode 2B is specifically designed to help our refineries procure green hydrogen through a clear-cut incentive roadmap. By offering a direct subsidy that starts at Rs. 50/kg in the first year and tapers down to Rs. 30/kg by the third, the government is effectively bridging the gap in Levelized Cost of Hydrogen (LCOH). This financial support is crucial to handle the heavy upfront CAPEX and daily OPEX, allowing developers to scale up fast. The goal here is to push the LCOH down to the $1.5–$2.0/kg mark by 2030, ensuring Green Hydrogen can stand toe-to-toe with traditional SMR-based hydrogen much earlier than anyone expected.

While the economic incentives for green hydrogen are robust, the physical integration of electrolytic hydrogen into existing refinery Hydrogen Generation Units (HGUs) presents substantial engineering hurdles. The primary challenge lies in reconciling the intermittency of renewable-derived hydrogen with the steady-state, baseload requirements of traditional Steam Methane Reformers (SMR); this necessitates advanced buffer storage and sophisticated control systems to prevent pressure fluctuations that could destabilize critical downstream hydrocrackers. Furthermore, the high purity of electrolytic hydrogen, while typically exceeding 99.9%, introduces moisture that differs from the CO and CO2 impurity profiles found in SMR-gas, requiring the recalibration or retrofitting of existing Pressure Swing Adsorption (PSA) units.

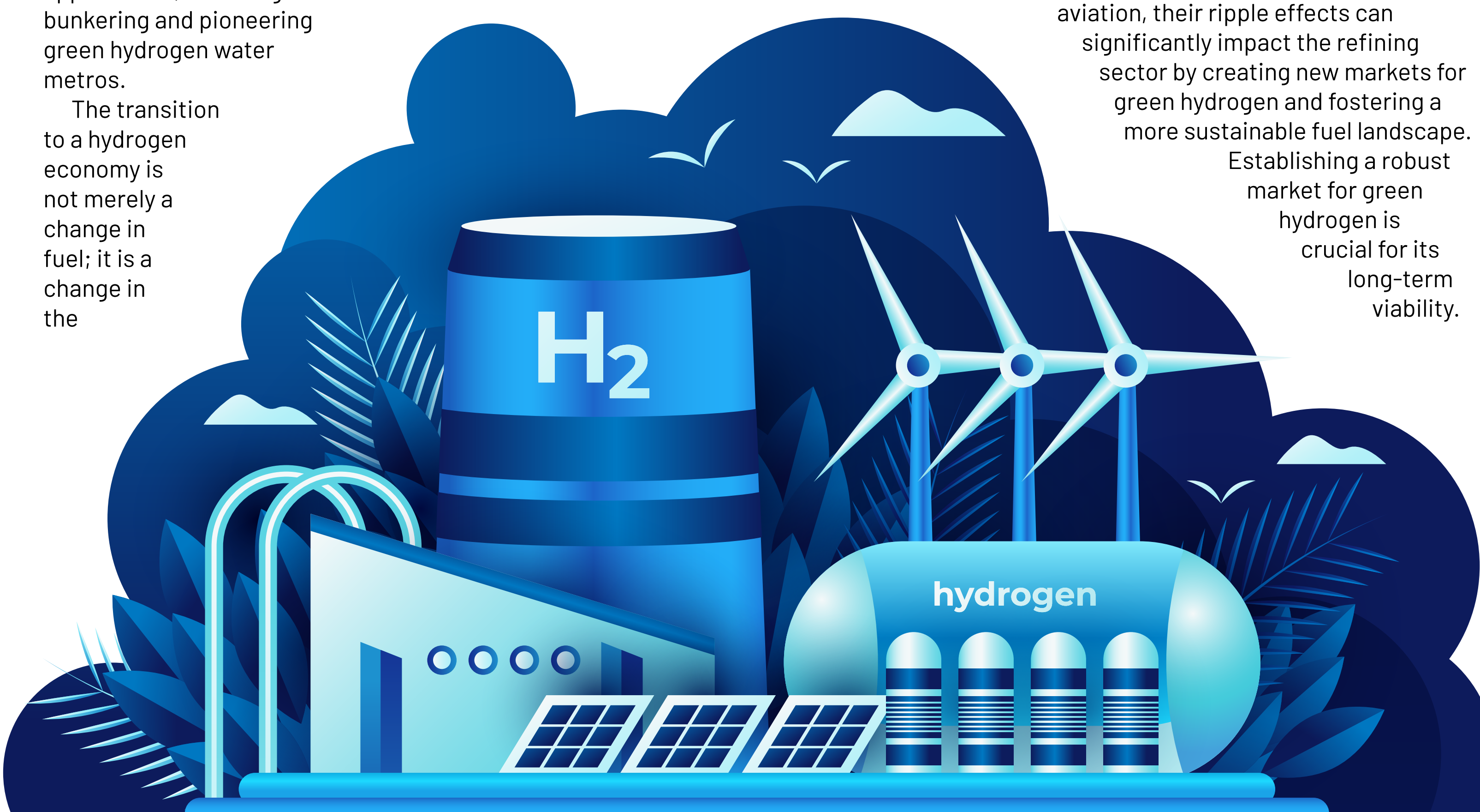
From a structural standpoint, the injection of green hydrogen alters concentration profiles within vintage piping, mandating rigorous metallurgical studies to mitigate the risk of hydrogen embrittlement. To manage these variables, refineries must implement hybrid control systems capable of seamlessly synchronizing SMR production with electrolytic supply based on real-time renewable availability and fluctuating grid pricing.

To foster a robust "lab-to-market" culture, India has sanctioned four Hydrogen Valley Innovation Clusters, designed as integrated regional ecosystems where the production, storage, and consumption of green hydrogen occur in proximity. By co-locating these activities, these valleys effectively solve the "chicken-and-egg" dilemma of matching supply with demand. Each cluster is strategically specialized: Pune focuses on heavy-duty transport and industrial chemicals; Jodhpur leverages Rajasthan's vast solar potential for large-scale production; Bhubaneswar centres its efforts on mining and the critical "Green Steel" transition; and Kochi (Kerala) prioritizes maritime applications, including bunkering and pioneering green hydrogen water metros.

The transition to a hydrogen economy is not merely a change in fuel; it is a change in the industrial DNA of the nation. The success of the SIGHT auctions proves that India has the market appetite. By tackling the technical challenges of HGU integration and utilizing the Mode 2B incentives to bridge the LCOH gap, India will become the "Hydrogen Refinery" for the world.

Carbon credits, a market-based mechanism that rewards emissions reductions, can significantly boost the viability of green hydrogen for refineries. By offering financial incentives for refineries to adopt cleaner technologies like green hydrogen, carbon credits can help offset the initial investment costs. This makes green hydrogen a more attractive alternative to traditional fossil fuels. The Bureau of Energy Efficiency (BEE) is actively developing the Indian Carbon Credit Trading Scheme (CCTS). This scheme aims to reduce greenhouse gas emissions in India by creating a market for carbon credits. The BEE has published the Detailed Procedure for Compliance Mechanism under the CCTS and the Accreditation Procedure and Eligibility Criteria for Accredited Carbon Verification Agencies. The Compliance Mechanism mandates obligated entities (Refineries) to meet GHG emission intensity targets. This can accelerate the transition to a low-carbon economy and contribute to achieving ambitious climate goals.

The Carbon Border Adjustment Mechanism (CBAM) and the Carbon Offset and Reduction Scheme for International Aviation (CORSIA) can indirectly influence the adoption of green hydrogen in the refinery sector. CBAM's carbon tax on imports, including aviation fuel, can incentivize airlines to seek more sustainable alternatives like green hydrogen-powered aircraft or green hydrogen-derived fuels. This growing demand for sustainable aviation fuels (SAF) can create a new market for green hydrogen. Additionally, CORSIA, which allows airlines to offset carbon emissions through carbon credits, can indirectly support green hydrogen projects if these credits are used to fund such initiatives. While CBAM and CORSIA primarily target aviation, their ripple effects can significantly impact the refining sector by creating new markets for green hydrogen and fostering a more sustainable fuel landscape. Establishing a robust market for green hydrogen is crucial for its long-term viability.




**The transformation extends to bunkering logistics, where the establishment of "Green Corridors" at ports like V. O. Chidambaranar involves the deployment of cryogenic loading arms and sophisticated leak detection sensors to safely manage ammonia's toxicity**

Facilitating demand aggregation among multiple refineries can create a larger market, enabling refineries to negotiate better terms with suppliers. Developing a market for green hydrogen derivatives, such as green ammonia or green fuels, can expand its applications and increase demand. Exploring the potential for refineries to earn carbon credits by using green hydrogen can provide an additional revenue stream and incentivize its adoption.

Ultimately, India's transition to a green hydrogen economy is far more than a simple fuel swap; it is a fundamental re-engineering of the nation's industrial core. The success of the SIGHT auctions has already demonstrated a powerful market appetite, but the long-term victory lies in our ability to bridge the gap between financial incentives and engineering realities. By mastering the complexities of HGU integration, managing intermittency, ensuring purity, and safeguarding metallurgical integrity, India is transforming its refineries into high-tech hubs of sustainable innovation. As we optimize electrolyzer technology and leverage our massive renewable energy potential, the goal of reaching a competitive LCOH of $1.5–$2.0/kg is no longer a distant dream. Through strategic demand aggregation, robust government policy, and pioneering "lab-to-market" R&D, India is not just securing its own energy future; it is stepping onto the global stage as the "Hydrogen Refinery for the World," setting the standard for a low-carbon industrial era

# HYDROGEN VALUE CHAIN INNOVATION: TRANSFORMING ENERGY FOR A SUSTAINABLE FUTURE

IndianOil's hydrogen strategy is inherently collaborative, involving partnerships with engineering firms, academic institutions, automotive OEMs, and start-ups

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## Hydrogen as a Strategic Imperative for a Sustainable Energy Future

As the world accelerates its transition toward low-carbon energy systems, hydrogen has emerged as a critical enabler of deep decarbonisation across industry, mobility, and energy storage. For India—balancing rapid economic growth with ambitious climate commitments—hydrogen offers a strategic pathway to reduce emissions while strengthening energy security. At the forefront of this transformation is Indian Oil Corporation Ltd. (IndianOil), India's largest integrated energy company, driving innovation across the hydrogen value chain through a combination of large-scale deployment, indigenous technology development, and ecosystem partnerships.

Hydrogen has long been integral to IndianOil's refining operations, primarily for hydrocracking and desulphurisation. Traditionally produced from fossil feedstocks, this "grey" hydrogen has contributed to industrial emissions. The current transition marks a fundamental shift toward low-carbon and green hydrogen pathways, driven by three strategic imperatives:

I. Deep decarbonisation of refining and petrochemicals, which account for a significant share of industrial emissions.
II. Creation of new clean energy markets, including hydrogen mobility and merchant hydrogen supply.
III. Energy security and Atmanirbhar

demonstrated hydrogen's potential as a clean transport fuel and laid the foundation for future hydrogen-based mobility solutions.

A decade later, IndianOil set up India's first electrolyser-based hydrogen refuelling station at its R&D Centre, Faridabad in 2015. Powered by solar electrolysis, this facility became the country's first dedicated green hydrogen station, equipped with advanced high-pressure storage and dispensing systems for hydrogen vehicle trials. These efforts closely align with the objectives of the National Green Hydrogen Mission (NGHM), which seeks to position India as a global hub for green hydrogen production, utilisation, and export.

## Green Hydrogen Production: Scaling from Pilots to Industry

A major milestone in IndianOil's hydrogen journey is the development of India's largest green hydrogen project at the Panipat Refinery & Petrochemical Complex in Haryana. With a proposed capacity of around 10,000 tonnes per annum, the project represents one of the earliest commercial-scale green hydrogen


deployments within the Indian refining sector.

The facility integrates renewable electricity with electrolysis to replace fossil-derived hydrogen currently used in refinery operations. IndianOil has undertaken comprehensive techno-economic evaluations, including levelised cost of hydrogen (LCoH) assessments, to ensure long-term commercial viability. Beyond emissions reduction, the Panipat project serves as a replicable template for deployment across other refineries and industrial clusters.

This initiative marks IndianOil's transition from pilot-scale demonstrations to industrial-scale implementation—an essential step for mainstreaming hydrogen within India's energy and industrial ecosystem.

## R&D Leadership and Indigenous Technology Development

Cost reduction, efficiency improvement, and operational reliability remain central challenges for hydrogen adoption. Recognising this, IndianOil has placed strong emphasis on research, development, and indigenous innovation through its R&D Centre in Faridabad.

### Hydrogen Generation and Refuelling Infrastructure

IndianOil has established a reformer-based hydrogen generation and refuelling station to support hydrogen fuel cell buses. The facility produces fuel-cell-grade hydrogen using natural gas via a steam methane reformer (SMR) with a capacity of 20 kg/hour, supported by 200 kg of hydrogen storage at 500 bar and a dispenser capable of 2 kg/min refuelling rates. Importantly, the system is designed to accept compressed biogas (CBG) as feedstock, enabling low-carbon hydrogen production from locally available organic waste and agricultural residues. This approach offers a scalable pathway for decarbonising both mobility and refinery hydrogen demand using existing SMR infrastructure.

In parallel, IndianOil is setting up a solar PV-powered electrolyser-based green hydrogen production and refuelling

> **IndianOil is developing hydrogen-ready infrastructure, including refuelling stations, integration with existing energy systems, and comprehensive safety and materials-compatibility standards**


> **IndianOil R&D, in collaboration with IIT Kharagpur, has indigenously developed a 57-litre Type-III composite hydrogen cylinder for 350-bar storage in light-duty vehicles**

station at its R&D-II campus in Sector-67, Faridabad. A 1 MWp solar PV plant will power multiple electrolyser technologies, including alkaline (45 $Nm^3/hr$), PEM (45 $Nm^3/hr$), and solid oxide (5 $Nm^3/hr$) electrolysers. Configured as test benches, these systems will enable comparative performance assessment under Indian climatic conditions, supporting informed technology selection and scale-up.

### Electrolyser Manufacturing and Innovation

To address supply-chain dependence and cost barriers, IndianOil is actively promoting domestic electrolyser manufacturing. The R&D Centre has developed an indigenous 1 kW Anion Exchange Membrane (AEM) electrolyser stack using non-noble metal catalysts, scheduled for demonstration at IEW 2026. Development of a 5 kW AEM stack and associated balance of plant is underway, while a joint proposal with Nanosol Inc. for a 20 kW AEM electrolyser system has been submitted under the MNRE R&D scheme.

### Alternative Hydrogen Production Pathways

IndianOil is also pursuing hydrogen production from biomass and waste-derived feedstocks. In collaboration with IISc, an oxy-steam biomass gasification process has been developed and demonstrated at 5 kg/hr using agro-residues and woody biomass. Plans are in place to establish a 100 kg/hr green hydrogen unit at an IndianOil refinery, reinforcing the role of indigenous, resource-diverse pathways in sustainable hydrogen production.

### Hydrogen Storage Innovation

Hydrogen's low volumetric density poses storage challenges. Addressing this, IndianOil R&D, in collaboration with IIT Kharagpur, has indigenously developed a 57-litre Type-III composite hydrogen cylinder for 350-bar storage in light-duty vehicles. The cylinder has successfully passed all ISO 15869 tests at certified facilities in the United States, marking a significant step toward domestic manufacturing of advanced hydrogen storage solutions.

### Hydrogen Mobility and Fuel Cell

### Applications

Fuel cell electric vehicles (FCEVs) are gaining traction globally in heavy-duty transport due to their zero tailpipe emissions, long driving range (500–700 km), fast refuelling, and high efficiency. Recognising their suitability for Indian conditions, IndianOil is actively demonstrating hydrogen mobility solutions.

IndianOil has deployed 15 ARAI-approved hydrogen fuel cell buses across Delhi-NCR and Gujarat. These buses have already covered ~80,000 km under real-world operating conditions, with additional deployments with the Indian Army and Navy. The programme targets 3 lakh km of


cumulative operation to generate robust performance and reliability data for future scale-up.

Under the NGHM, the Ministry of New & Renewable Energy (MNRE) has awarded four Hydrogen Demonstration Mobility projects to IndianOil in consortium with Tata Motors Ltd., with a total sanctioned outlay of Rs. 70.05 crore. IndianOil is establishing new hydrogen refuelling stations on the Jamshedpur-Kalinganagar and Mumbai-Pune corridors, while leveraging existing stations in Faridabad and Vadodara to support a fleet of 16 hydrogen vehicles.

Beyond road transport, IndianOil R&D has developed a 1 kW hydrogen fuel cell system for drone applications in collaboration with Urjahub Pvt. Ltd., with testing underway. A 2.4 kW air-cooled fuel cell system for mobility applications is also under development with High Energy Batteries (India) Pvt. Ltd.

Under the NGHM R&D scheme, IndianOil has been awarded three of the 23 sanctioned national projects, covering hydrogen fuel cell drones, hydrogen retrofitment kits, and hydrogen direct-injection engines, with a combined outlay exceeding ₹50 crore.

## Infrastructure, Ecosystem Partnerships, and Policy Alignment

A sustainable hydrogen economy requires robust infrastructure for storage, transportation, and dispensing. Leveraging its extensive fuel logistics expertise, IndianOil is developing hydrogen-ready infrastructure, including refuelling stations, integration with existing energy systems, and comprehensive safety and materials-compatibility standards.

IndianOil's hydrogen strategy is inherently collaborative, involving partnerships with engineering firms, academic institutions, automotive OEMs, and start-ups. These collaborations extend beyond technology deployment to encompass standardisation, skill development, and knowledge sharing.

As a public sector enterprise, IndianOil plays a pivotal role in translating national policy into implementation. Its hydrogen initiatives directly support the objectives of the National Green Hydrogen Mission by reducing industrial emissions, strengthening domestic manufacturing capabilities, and creating green jobs across emerging hydrogen clusters.

## Conclusion: Advancing India's Hydrogen Future

IndianOil's hydrogen value chain innovations demonstrate how a traditional energy company can lead the transition to a low-carbon future. By combining large-scale green hydrogen production, indigenous technology development, infrastructure creation, and ecosystem collaboration, IndianOil is enabling hydrogen adoption across refining, industry, and mobility.

As India moves toward 2030 and beyond, IndianOil's integrated and pragmatic approach positions it as a catalyst for the country's emergence as a global hydrogen leader—aligning energy security, industrial competitiveness, and environmental stewardship in the pursuit of a cleaner, more resilient energy future

# VIJAIPUR PLANT UTILIZES 10 MW PEM ELECTROLYSER TO PRODUCE 4.3 TPD OF HYDROGEN WITH 99.99% PURITY

The unit has successfully produced approximately 120 MT of hydrogen during FY 2024-25


**How central is hydrogen to GAIL's long-term transition from a gas marketing company to a broader clean-energy player? What strategic objectives does GAIL aim to achieve through its green hydrogen initiatives by 2030?**

GAIL is very much at the forefront of transition from a gas marketing company to a broader clean-energy player. GAIL has intensified its focus on renewable energy and green hydrogen, driven by its advanced target to achieve 100% reduction in Scope 1 and Scope 2 emissions by 2035.

**What were the key considerations behind choosing PEM electrolyser technology for GAIL's first 10 MW green hydrogen plant at Vijaipur? What are the initial learnings?**

Vijaipur plant utilizes a 10 MW PEM (Proton Exchange Membrane) electrolyser unit to produce 4.3 TPD of hydrogen with 99.99% purity through the electrolysis of water using renewable power. During FY 2024-25, the unit has successfully produced approximately 120 MT of hydrogen. This production was immediately utilised for the captive purpose, being blended as a fuel along with natural gas in the existing plant processes and equipment at Vijaipur.

**The Vijaipur plant produces around 4.3 tonnes/day of green hydrogen. How does GAIL plan to scale this capacity over the next few years?**

GAIL has installed its first mega watt scale green hydrogen plant at Vijaipur complex in Madhya Pradesh. The plant marks a significant step into new and alternate energy sources and aligns with the National Green Hydrogen Mission of Government of India.

**GAIL is setting up around 20 MW of solar power (ground-mounted + floating) to support the hydrogen project. How will this enhance cost competitiveness? Does GAIL foresee integrating wind or hybrid renewable power for future hydrogen projects?**

GAIL's strategy is built around diversification and scaling up its portfolio through both internal development and strategic partnerships. GAIL currently holds an installed renewable energy capacity of 145 MW (118 MW wind and 27 MW solar). Upcoming projects include setting up a 7.75 MW floating solar power and 1.85 MW project at Vijaipur, Madhya Pradesh. These initiatives have the potential to enhance the cost competitiveness of the hydrogen project.

**Is GAIL planning pilot projects for hydrogen-powered buses or heavy-duty vehicles through its partnerships?**

GAIL has planned to dispense the hydrogen produced at Vijaipur to retail customers in nearby geographies. It is planned to be transported through the high-pressure cascades

# ELECTROLYSER

## The Catalyst of Change

# ELECTROLYSERS: POWERING THE GREEN HYDROGEN REVOLUTION

## Manufacturing incentives, corporate CAPEX and global partnerships are reshaping India's clean energy supply chain

TEAM ICN

In the global shift toward decarbonisation, green hydrogen has transitioned from a futuristic ideal to a central pillar of clean energy strategy. At the heart of this transformation lie electrolysers, the high-tech devices that use renewable electricity to split water into hydrogen and oxygen.

Europe, an early technology leader, is struggling with high costs, supply-chain constraints and slow project execution, leaving many deployments heavily subsidy-dependent despite continued support through innovation funds and hydrogen bank mechanisms.

The United States has reshaped the market through the Inflation Reduction Act, which has accelerated electrolyser demand and factory expansion by guaranteeing attractive hydrogen economics, while also inflating global cost expectations.

China dominates electrolyser manufacturing volumes, particularly in alkaline systems, leveraging scale, deep supply chains and aggressive pricing to export low-cost units worldwide, even as concerns persist around standards, durability and strategic dependence.

In contrast, Japan and South Korea are prioritising overseas investments and long-term offtake agreements, positioning themselves as anchor demand centres rather than manufacturing leaders.

Within this global context, India's electrolyser push sits at a crossroads. It lacks the subsidy intensity of the US and the manufacturing dominance of China, but it offers a compelling combination of low-cost renewable power, growing domestic demand and policy-driven market creation. The success of India's electrolyser ecosystem will depend on whether it can rapidly scale manufacturing, localise critical components, improve efficiency and reliability, and compete globally on cost without sacrificing quality, before global supply chains and standards become locked in elsewhere.

### Why Electrolysers are the Cost Lever in India's Green Hydrogen Push

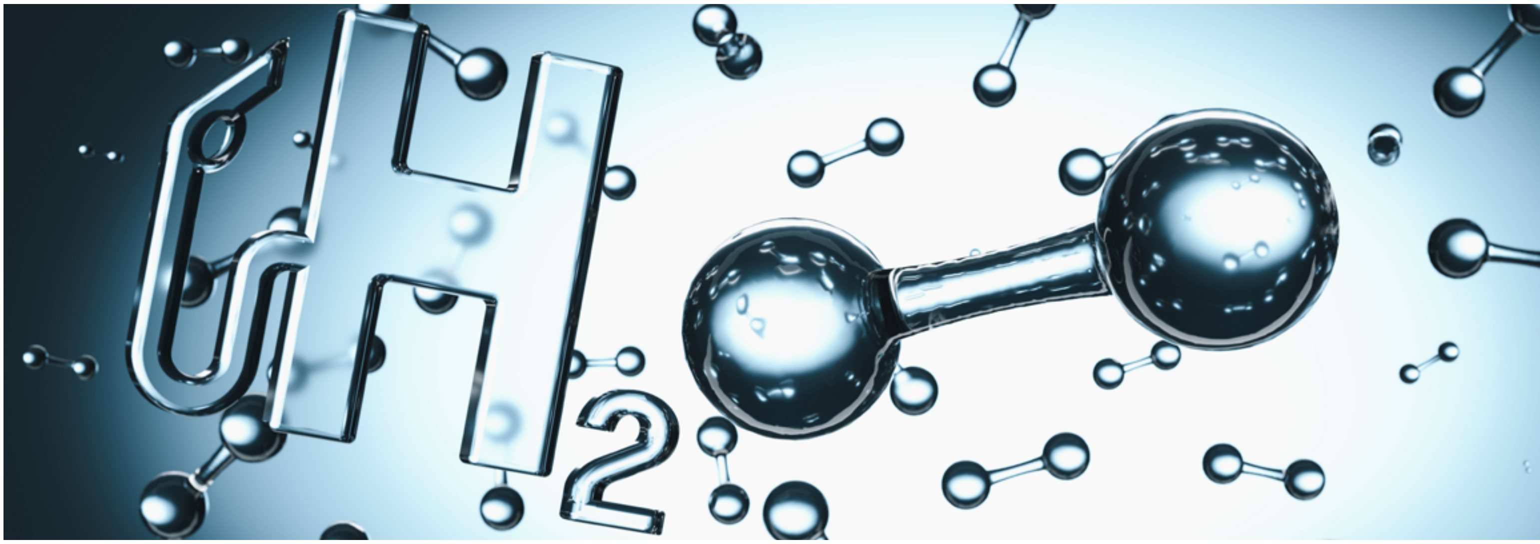
Falling renewable energy prices and policy incentives are reshaping the conomics of green hydrogen in India. With low-cost solar and wind power and support mechanisms that reduce transmission and capital costs, electrolyzers are emerging as the critical link between renewables and competitive hydrogen production, driving costs closer to fossil-based alternatives.

### Industry Gears Up

Indian engineering majors, energy conglomerates, global technology partners and a new generation of clean-tech firms are all stepping up investments, manufacturing and technology development, positioning electrolysers at the centre of the country's hydrogen transition.

Larsen & Toubro (L&T) marked a significant milestone by commissioning its first indigenously manufactured electrolyser at the Hazira green hydrogen plant in Gujarat. This 1 MW pressurised alkaline electrolyser, developed in collaboration with French partner McPhy Energy, is capable of producing hydrogen at scale appropriate for industrial offtake, and the project lays a foundation for L&T's plans to expand into gigascale manufacturing facilities to meet surging domestic demand. At Deendayal Port Authority (DPA) Kandla, indigenous electrolysers manufactured by L&T have been flagged off for a green hydrogen plant, marking a milestone in port-based hydrogen infrastructure and the "Make in India" initiative for local electrolyser production.

Private players have also stepped up with aggressive investments. Ohmium Operations, a key subsidiary of the US-headquartered green hydrogen company, Ohmium International, has inaugurated a gigawatt-scale proton exchange membrane (PEM) electrolyser factory in



## Electrolysers Explained: One Technology, Multiple Pathways

Alkaline, PEM and emerging anion exchange membrane electrolyzers are shaping India's green hydrogen roadmap. While alkaline systems dominate early deployment due to lower costs and proven reliability, PEM electrolyzers offer faster response to variable renewables, and AEM technologies promise a middle ground with reduced material costs. Together, these technologies are defining how efficiently and affordably India can scale green hydrogen production.

Doddaballapura, Karnataka. This facility is part of a broader strategy to build modular, highly efficient electrolysers that can be scaled from pilot projects to industrial operations. Alongside Ohmium, companies such as Advait Infratech, Waaree Energies, Hild Electric and Matrix Gas & Renewables are investing in manufacturing facilities for alkaline and PEM electrolysers across Gujarat and other industrial hubs. These investments signal a maturing supply landscape where diverse technologies and product forms are being developed domestically rather than imported.

GreenH Electrolysis has unveiled its first 1 MW PEM electrolyser manufactured at its plant in Jhajjar, Haryana. This unit is set to supply hydrogen to India's first hydrogen train under the Indian Railways' "Hydrogen for Heritage" initiative, demonstrating a practical application of domestically made electrolyser technology.

Greenzo Energy has made notable strides in indigenous electrolyser development. The company launched a 1 MW indigenous alkaline electrolyzer stack, engineered for Indian operating conditions, and has secured robust orders (with an order book reported around Rs. 1,200 crore), while also winning an R&D contract from Engineers India Limited (EIL) to supply a modular hydrogen electrolyser unit for deployment at EIL's R&D complex in Gurgaon, a key step toward scalable, homegrown solutions.

Ceres Power and Shell have achieved a milestone in solid oxide electrolyser technology with a megawatt-scale SOEC demonstrator system in Bangalore now producing hydrogen, underscoring emerging high-efficiency electrolyser deployments beyond traditional alkaline and PEM systems.

In the broader industrial context, Jakson Green Infinity, part of India's expanding green hydrogen ecosystem, reports an electrolyser manufacturing capacity of about 300 MW per year, with ambitions to scale into gigawatt capacity aligned with long-term hydrogen targets.

The push for local manufacturing is complemented by strategic corporate initiatives. Reliance Industries has entered into technology licensing agreements with global electrolyser technology providers, such as Nel Hydrogen Electrolyzer AS, to secure intellectual property and know-how necessary for manufacturing alkaline electrolysers at scale.

Joint ventures and licensing arrangements are enabling faster knowledge transfer, as seen in Waaree Group's Valsad electrolyser manufacturing facility, which integrates global technology and supply chains, and Advait's licensing partnership with China's Guofu Hydrogen. Such collaborations are helping Indian manufacturers compress development timelines and move rapidly toward commercial scale.

Indian electrolyser makers are also looking beyond domestic demand. As Europe and East Asia expand hydrogen investments and seek diversified supply chains, Indian manufacturers with rising capacity and operational experience are positioning themselves for export opportunities.

On the deployment side, electrolysers are increasingly embedded in Indian hydrogen projects. JSW Energy's green hydrogen plant in Karnataka, commissioned under the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, uses electrolysers to supply hydrogen directly to industrial feedstocks, such as steel production for low-carbon direct reduced iron (DRI). Similarly, corporate investments in off-grid electrolyser installations, such as Adani New Industries' 5 MW pilot plantin Kutch, demonstrate applications where decentralised hydrogen production meets coastal industrial demand without reliance on grid infrastructure.

Innovation Takes Centrestage

While manufacturing and deployment are ramping up, Indian companies are also investing in research and development to enhance technology performance.

Electrolyser innovation focuses on improving energy efficiency, reducing reliance on rare or costly materials, and enhancing durability under variable renewable power inputs. These are critical for making electrolysers not just cheaper to build but cheaper to operate over long lifecycles.

Collaboration between industry and academic institutions, such as partnerships involving IITs and technology developers like Hyundai at innovation centres, aims to localise key components, such as advanced membranes and catalysts, while building human capital that can sustain long-term commercialisation.

Beyond the large conglomerates, smaller deep-tech firms are also innovating. Singapore-based HYDGEN, with significant operations in Mangaluru, recently raised $5 million to scale its proprietary anion exchange membrane (AEM) electrolyser technology, an approach that blends the strengths of alkaline and PEM systems while reducing reliance on costly materials like platinum group metals. HYDGEN's modular platforms, ranging from small 1 kW systems to 250 kW stack configurations, demonstrate the emerging potential for on-site hydrogen generation applications that reduce logistics costs and enhance supply resilience, particularly for decentralised industrial demand.

## Electrolyser

**Alkaline (ALK):** Proven, lowest-cost option for large, steady hydrogen production, but less flexible with variable renewables

**Proton Exchange Membrane (PEM):** Fast-ramping and compact, ideal for solar and wind integration, though higher cost due to precious metal use

**Anion Exchange Membrane (AEM):** Emerging hybrid technology aiming to cut costs by avoiding noble metals, still at early commercial scale

**Solid Oxide Electrolysis Cell (SOEC):** High-temperature, high-efficiency systems using steam, promising but largely at pilot stage due to durability challenges

## Policy Push

India's policymakers have recognised that building a competitive electrolyser ecosystem is essential not just for domestic green hydrogen supply but also for industrial competitiveness. The National Green Hydrogen Mission, launched by the government, aims to elevate India's green hydrogen production to 5 million tonnes annually by 2030, a target that inherently depends on large-scale deployment of electrolysers. Government incentives, including production-linked incentives (PLI) for electrolyser manufacturing, have been structured to support this objective, allocating approximately 1.5 GW of domestic manufacturing capacity to a diverse set of companies through competitive tenders. This approach is designed to foster a local supply chain, reduce technology import dependence and improve cost competitiveness in green hydrogen production.

## Future Outlook

Looking ahead, India's electrolyser market is projected to exceed US$ 620 million by 2030, driven by renewable energy expansion, industrial decarbonisation and export-led hydrogen demand. If manufacturing capacity scales as planned, India could emerge as a key hub for both domestic green hydrogen supply and global electrolyser value chains. Challenges persist, particularly in competing with low-cost Chinese manufacturers, addressing component supply constraints, and establishing robust standards and financing frameworks.

Despite these hurdles, the momentum in India's electrolyser industry is unmistakable. With policy support, corporate commitment and a blossoming manufacturing ecosystem, India is poised to convert its renewable energy advantage into green hydrogen capacity backed by domestic electrolyser production. In doing so, the country is not only advancing its decarbonisation goals but laying the foundation for a competitive position in the global hydrogen economy

# INDIAN RAILWAYS HYDROGEN TRAIN PROJECT UNDER COMMISSIONING

Localization, as it matures, facilitates significant cost reductions, which are critical for making hydrogen globally competitive

**GreenH Electrolysis positions itself as a full-stack green hydrogen solutions provider. How does this differentiate the company from a pure electrolyser manufacturer and what market gap is it specifically trying to address?**

GreenH was created to address a clear gap in India's hydrogen ecosystem — the lack of end-to-end, execution-ready green hydrogen solutions. While pure electrolyser manufacturers typically stop at supplying stacks or skids, GreenH integrates electrolyser manufacturing, system engineering, EPC, commissioning, and long-term O&M under one roof. This full-stack approach is critical in India, where customers are often new to hydrogen and need performance-guaranteed solutions rather than individual components. By owning the system integration and lifecycle performance, GreenH reduces project risk, accelerates deployment timelines, and enables customers to move from pilot to scale.

**GreenH has set up state-of-the-art 1,000 MW electrolyser plant in Reliance MET Industrial Park, Jhajjar. What is the current and planned manufacturing capacity of this facility over the next 2–3 years?**

GreenH's Jhajjar facility has an initial manufacturing capacity of 100 MW per year, designed with a modular layout that allows rapid scaling to gigawatt-scale production as market demand accelerates. Over the next 2–3 years, capacity expansion will be market-linked, ensuring capital discipline while remaining ready to support India's National Green Hydrogen Mission. Importantly, the facility is future-proofed to accommodate next-generation technologies, including AEM and SOEC, aligned with ongoing R&D within the H2B2 Electrolysis Technologies group.

**Dhiman Roy**
**Chief Executive Officer**
GreenH Electrolysis

**What performance benchmarks has GreenH's 1 MW PEM electrolyser achieved in real-world operating conditions? How critical is indigenous manufacturing for meeting India's green hydrogen cost targets?**

Indigenous manufacturing is absolutely central to meeting India's green hydrogen cost targets. Local production reduces import dependency, logistics costs, and currency exposure, while enabling faster customization for Indian operating conditions. Over time, localisation also unlocks cost reduction through supply chain development, learning curves, and service efficiency, all of which are essential to achieving globally competitive hydrogen costs.

**H2B2, your parent company, has been among the early movers in executing green hydrogen projects globally. What are the key strategic and execution learnings that the Indian operations are drawing from H2B2's experience across the US, Europe, Latin America, Asia, and Asia-Pacific?**

H2B2's global project experience, with over 19 installations worldwide, has provided invaluable learnings in system design, project execution, and long-term operability. Moreover, all this knowledge is brought forward from EPC and O&M activities, to design and engineering early stages, on a virtuoso cycle. Indian operations benefit directly from proven approaches to stack configuration, balance-of-plant optimisation, safety engineering, and performance monitoring across diverse regulatory and climatic conditions.

**How competitive are GreenH's PEM electrolysers in terms of efficiency, durability, and cost compared to imported systems?**

GreenH's PEM electrolysers are globally competitive on safety, efficiency, reliability and durability, with performance benchmarks comparable to established international OEMs. From a cost perspective, local manufacturing provides a clear advantage by reducing import duties, logistics costs, and lead times. Equally important is lifecycle economics — proximity of service teams, faster spares availability, and integrated O&M


> **GreenH's PEM electrolysers are globally competitive on safety, efficiency, reliability, and durability, with performance benchmarks comparable to established international OEMs**

significantly lower total cost of ownership compared to imported systems.

**What were the key technical and commercial challenges in setting up India-based PEM electrolyser manufacturing?**

From a technical standpoint, achieving consistent quality in precision manufacturing, especially for stacks and critical balance-of-plant components, required close supplier development and rigorous qualification processes. Commercially, the challenge was balancing early-stage market volumes with capital-intensive manufacturing. GreenH addressed this by adopting a scalable, modular factory design and leveraging H2B2's proven technology to accelerate time to market while managing risk.

**GreenH is building hydrogen production and refuelling station for India's first hydrogen-powered train. How does this collaboration help Indian Railways reduce emissions, fuel costs, and operational dependence on diesel?**

The hydrogen production and refuelling station enables Indian Railways to replace diesel with a zero-emission fuel, directly reducing $CO_2$ emissions and local air pollutants. Over time, green hydrogen also offers greater price stability compared to diesel, which is exposed to global fuel price volatility. Additionally, domestically produced hydrogen strengthens India's energy security by reducing reliance on imported fossil fuels.

**What outcomes have emerged so far from the hydrogen production and refuelling station being built by GreenH for Indian Railways? How scalable is this hydrogen refuelling model for wider rail, bus, or heavy-duty mobility deployment?**

Indian Railways project is currently under commissioning and expected to be operational soon, serving as a critical real-world validation platform for hydrogen mobility in India. The modular design of the production and refuelling infrastructure makes it highly scalable, not only for rail applications but also for buses, trucks, and other heavy-duty mobility segments, where centralized hydrogen hubs can serve multiple fleets.

**From GreenH's perspective, how does working with Indian Railways accelerate technology validation and market adoption for indigenous PEM electrolysers?**

Indian Railways provides a high-duty, mission-critical operating environment, which is ideal for validating electrolyser performance, reliability, and safety at scale. Successful deployment builds confidence among other public and private sector users, and accelerates


> **GreenH has developed strong EPC and O&M capabilities to ensure high uptime, safe operation, and predictable performance, which are critical for customer confidence and project bankability**

broader market adoption of indigenous electrolysis technology.

**Q How GreenH customizes electrolyser and refuelling solutions for different mobility use cases such as trains, buses, and trucks?**

GreenH customizes solutions based on duty cycle, refuelling pressure, footprint constraints, and redundancy requirements. While the core electrolyser technology remains standardised, balance-of-plant, storage, and dispensing systems are tailored to meet the specific operational needs of each mobility segment.

**Q Beyond manufacturing, GreenH is offering EPC and O&M services. How important is systems integration to successful hydrogen project deployment? What capabilities has GreenH developed to ensure high uptime and reliability of hydrogen plants?**

Systems integration is fundamental to hydrogen projects success. Electrolysers (or any other piece of equipment) do not operate in isolation — performance depends on how well power electronics, water treatment, compression, storage, and controls are integrated. GreenH has developed strong EPC and O&M capabilities to ensure high uptime, safe operation, and predictable performance, which are critical for customer confidence and project bankability. Products and services are tailor-made for each and every hydrogen project, to optimize its utilization on this nascent market.

**Q How is GreenH addressing key PEM challenges such as catalyst cost, stack lifetime, and water quality requirements? Is the company investing in R&D to move beyond PEM such as AEM or next-generation electrolysis technologies?**

Beyond PEM, the GreenH and H2B2 group is actively investing in AEM and SOEC technologies to continue fostering technology development, positioning GreenH to adopt the most suitable electrolysis technology as use cases and economics evolve.

**Q Where does GreenH aim to be in the green hydrogen value chain by 2030? Any expansion plans beyond India and does the company see export opportunities for Indian-made electrolysers?**

By 2030, GreenH aims to be a leading integrated green hydrogen solutions provider, spanning manufacturing, EPC, O&M, and hydrogen infrastructure for industrial and mobility applications. India is expected to become a global manufacturing and export hub, and GreenH sees strong opportunities for exporting Indian-made electrolysers and derivatives such as green methanol, aligned with global decarbonisation demand

# EXPLORING THE MULTIVERSE OF HYDROGEN ENERGY TECHNOLOGIES

Hydrogen multiverse will likely expand along three main axes such as decarbonisation, diversification, and digitisation & control

**Dr. Balaji Rengarajan**
**Senior Scientist**
ARCI - Centre for Fuel Cell Technology

Hydrogen has long been considered as a hazardous energy carrier due to its flammability, invisible flame and low ignition energy, which historically overshadowed its potential in energy systems. As global decarbonization efforts intensify, its clean combustion properties and high gravimetric energy density position it as a keystone for storing and transporting renewable energy, fueling sectors like heavy industry, and long-haul transport, thereby reshaping its narrative from a perilous outlier to an indispensable enabler of the energy transition.

## Renewable Integration: Power-to-Gas and Sector Coupling

Hydrogen plays a significant role in linking intermittent renewable sources; by converting surplus electricity into hydrogen via electrolysis and it reconverts to electricity via fuel cells (50-60% efficiency) or turbines, enabling flexible dispatch in industry and mobility. Power to gas (P2G) technology significantly contributes to sector coupling, facilitating the smooth integration of energy systems encompassing electricity, heating, gas, and transportation. This synergy balances intermittent renewables while decarbonizing hard-to-electrify sectors through gas grid injection or synthetic fuels.

## Production Innovations: Advanced Electrolysis Routes

While, alkaline water electrolysis is the conventional "green hydrogen" route, the advanced methods focus three key aspects such as reduced electricity consumption, utilize different primary resources and co produce value added chemicals.

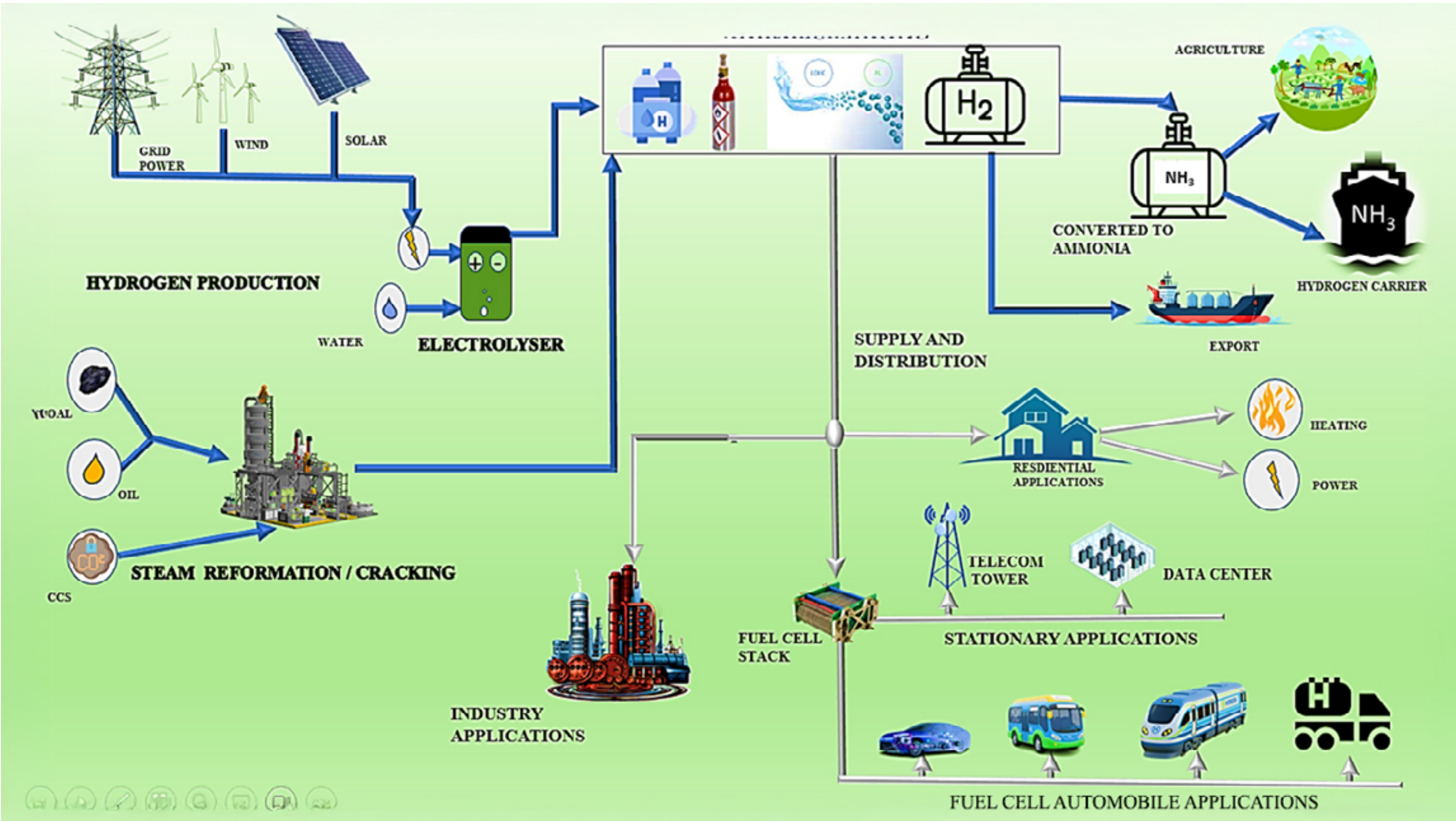
Proton Exchange Membrane (PEM) based electrolyser system offering quick response to fluctuating power inputs with maximum operating current densities up to 2 A/cm$^2$, unlocks low Capex by maximizing hydrogen productivity per unit area. In addition, Anion Exchange Membrane (AEM) bridges alkaline cost advantages with PEM compactness using non-precious metal-based catalysts in a solid membrane, for distributed applications, while Solid Oxide Electrolyser cell (SOEC) operates at 600-900°C, achieves 80-90 per cent efficiency by utilizing high-temperature steam, reducing electrical needs with emerging proton-conducting variants minimizing steam use.

Beyond water electrolysis, electrochemical reforming of energy dense liquids such as methanol and ethanol is emerging as low temperature pathways that can reduce the electrical energy requirement and simplify downstream purification. It replaces the energy-intensive oxygen evolution reaction (OER) in water electrolysis with alcohol oxidation enabling hydrogen production at lower voltages (often <1.5 V) while co-generating value-added chemicals like acetaldehyde or CO2 with efficiencies up to 3x better than pure water electrolysis. These systems gain additional environmental benefits when bio-derived alcohols are employed as hydrogen sources.

In addition, Battery Electrolysers often termed "battolyser" enable efficient green hydrogen production by storing surplus power from renewables, then converting it to hydrogen for long-term energy storage. Unlike separate batteries and electrolysers, they avoid idle periods, achieve up to 90 per cent efficiency, and arbitrage between electricity and hydrogen markets for economic viability. Battolyser systems have raised over €70 million in funding, with operational pilot plants. However, many of these routes are at lab to early pilot scale, offering clear efficiency advantages but needing durability and scale up work and industrial deployment yet reported.

## Diverse Approaches to Hydrogen Storage

Hydrogen storage requiring conditions of up to 700 bar or temperatures below 253°C.




These storage conditions necessitate the development of advanced materials and infrastructure improvements. There are four different approaches used for storing hydrogen in diverse material include metal hydrides, liquefication, compressed gas as well as physisorption/chemisorption.

### Compressed Gas and Material Advances

Hydrogen gas is subjected to elevated pressures, typically between 200 and 700 bar, to reduce its volume and increase its storage capacity in compressed storage method and usually employs high-pressure cylinders, which come in various types based on their construction materials and design. Advances in materials science, such as the exploration of nanocomposites and carbon fiber composites, are aimed to fabricate lighter and stronger high-pressure hydrogen storage tanks. The key target gravimetric and volumetric capacity values for hydrogen storage in carbon composite cylinders (Type III and Type IV pressure vessels) for light-duty vehicle applications are 6.5 wt% and 50 g $H_2$/L respectively when compared to existing with gravimetric capacities of approximately 5.7 wt% and volumetric densities around 36-38 g $H_2$/L.

### Solid-State and Subsurface Solutions

Solid-state hydrogen storage is a highly promising, maturing technology, seen as a safer, denser alternative to gas/liquid storage, using materials like metal hydrides or nanoporous carbons to absorb $H_2$. The current research focuses on improving kinetics, gravimetric density, and durability through nanostructuring and catalysis, with breakthroughs in materials showing potential for mobile and stationary uses, though challenges remain in achieving ideal gravimetric density for all applications of 9 wt.%.

Subsurface hydrogen storage involves storing hydrogen in geological formations below the Earth's surface, such as salt caverns or depleted gas reservoir. Ongoing R&D in subsurface hydrogen storage is focused on optimizing the efficiency and precision of salt cavern creation and employing advanced technologies like 3D seismic imaging for better management of hydrogen storage in geological formations

### Cryogenic Liquefaction

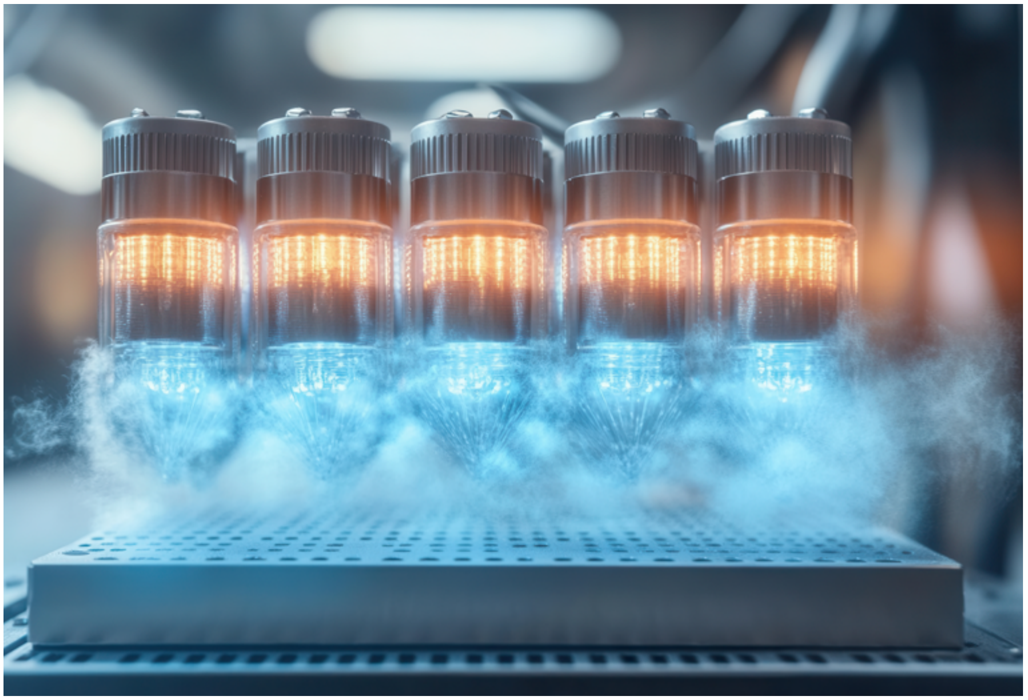
Storing hydrogen in liquid form involves specialized tanks include vacuum-insulated tanks, vacuum insulation panels, aerogels, cryogenic insulation foams, double-walled tanks, and multilayer insulation to maintain hydrogen at cryogenic temperatures(-253oC). However, the liquefaction requires significant energy input, around 6 to 13 kWh of electricity/kg $H_2$, which can lead to energy losses during the storage phase although theoretical minimums are lower, and future technologies aim for 6.5 kWh/kg.

These approaches collectively enable scalable, efficient hydrogen utilization across mobile and stationary applications.

## Transportation Methods - Carriers for Efficient Delivery

In the overall hydrogen supply chain, hydrogen transportation is a crucial part,

> Battery Electrolysers often termed "battolyser" enable efficient green hydrogen production by storing surplus power from renewables, then converting it to hydrogen for long-term energy storage



which include gaseous, liquid hydrogen transportation, and the use of hydrogen carriers. Hydrogen carriers, providing an alternative to the complexities involved with transporting hydrogen in its gaseous or liquid forms. Common carriers include ammonia, metal hydrides, and Liquid Organic Hydrogen Carriers (LOHCs).

Ammonia serves as an efficient hydrogen carrier, storing 17.6 wt% $H_2$ with high volumetric density (108 kg $H_2$/$m^3$) for easy liquefaction, transport, and cracking into pure hydrogen using existing infrastructure. This enables long-distance shipping of green $H_2$ without compression challenges. While LOHCs involve the chemical combination of hydrogen with a liquid organic carrier like dibenzyltoluene or n-ethylcarbazole (NEC), typically using a catalyst under high pressure. Research continues into enhancing LOHCs like NEC for their hydrogen storage capacity and improved thermodynamic properties. In general, hydrogen carriers mitigate the logistical challenges associated with transporting hydrogen in more traditional forms.

## Industrial Decarbonization Role

The industrial sector is where hydrogen most clearly surpasses its image as a fuel in fuel cell, acting instead as reducing medium and a direct process agent. It is hard to achieve decarbonisation target through electrification alone, so hydrogen becomes central to net zero roadmaps in heavy industry.

In iron and steelmaking, hydrogen based direct reduction of iron ore (H DRI) replaces coke as the reductant, enabling emission reductions of roughly 90–95% when coupled to renewable hydrogen and it can be blended with existing fuels in blast furnaces (BF-BOF route) or used in DRI processes (H2-DRI) to reduce reliance on coal. In the chemical sector, it remains an indispensable feedstock for ammonia and methanol production; replacing fossil derived hydrogen with low carbon or renewable hydrogen and avoids $CO_2$ emissions from nearly 1.8 tons/ton of ammonia (grey) and 2.8 tons/ton of methanol (grey) to near zero, using only water vapor as a byproduct could, while allowing new electro fuel (e fuel) value chains from green ammonia and green methanol.

Beyond its role as a reductant and feedstock, hydrogen also excels in decentralized energy production. Hydrogen-based combined heat and power (CHP) systems use hydrogen as fuel in engines, turbines, or fuel cells to generate electricity and capture waste heat for industrial processes. These systems offer high efficiencies up to 90 per cent and provide reliable on-site power and heat for sectors like manufacturing, chemicals, and refineries. Lifecycle emissions drop 50 per cent + compared to fossil CHP, with potential near-zero $CO_2$ via green hydrogen.

## Combustion and Fuel Cells

The combustion of hydrogen primarily produces water vapor, resulting in relatively low levels of Green House Gases (GHGs) compared to fossil fuels. It has significant implications across a wide array of applications, including ICEs and gas turbines.

> **Hydrogen fuel cells provide an electrochemical alternative for cleaner power generation and achieve higher energy efficiency by results in only heat and water as secondary byproducts**

$H_2$ ICEs, which operate similarly to traditional gasoline or diesel engines but use hydrogen as the primary fuel, there are two main configurations: spark-ignition and compression-ignition engines. The current efforts are focusing on increased efficiency, reducing emissions, and optimizing engine design to better facilitate hydrogen combustion. Furthermore, the concept of flameless hydrogen combustion, which burns hydrogen fuel in an oxygen-deficient atmosphere to achieve uniform and low-temperature combustion, is gaining attention. This method promises to reduce NOx emissions, improve efficiency, and enhance safety due to its low flame temperature and gradual combustion kinetics.

### Fuel cells

Complementing these combustion approaches, hydrogen fuel cells provide an electrochemical alternative for cleaner power generation and achieve higher energy efficiency by results in only heat and water as secondary byproducts. It can be designed in various sizes and capabilities, suitable for a broad spectrum of applications from compact electronic devices to large-scale power production .They are known for their low noise levels, which enhances their suitability for urban and residential settings.

In this, PEM (Proton Exchange Membrane) fuel cells dominate the market (60-70% share in 2025) due to their low operating temperatures, quick start-up, compactness, and high-power density, though they need pure hydrogen to avoid catalyst poisoning at low temperatures. They dominate automotive adoption due to high efficiency (up to 60%) and cold-start capability, as seen in commercial fleets and models from Toyota and Hyundai offering zero-emission range exceeding 450 kms with refueling under 5 minutes. For stationary applications, it provides reliable, quiet electricity for data centers, hospitals, and homes, often co-generating heat for combined heat and power (CHP) efficiency over 85%. Their modularity suits distributed energy, with stacks scaling from kilowatts to megawatts. However, the widespread adoption of fuel cells depends on the development of a comprehensive hydrogen infrastructure that includes manufacturing, storage, and distribution.

## Conclusion

Amid intensifying efforts to achieve net-zero emissions, hydrogen-based systems have emerged as sustainable alternatives. Essential to this transition is a comprehensive sustainability analysis that weighs both environmental and economic factors. This analysis reveals that the hydrogen multiverse will likely expand along three main axes such as decarbonisation, diversification and digitisation & control. In this evolving landscape, fuel cells remain the flagship conversion technology. The interplay among production, infrastructure and fuel cell applications forms a genuinely multi-dimensional "multiverse" of hydrogen technologies that is central to the global clean energy transition

# TRANSPORTATION

## The “Clean Motion” Revolution

# HYDROGEN ON THE MOVE

## Government, industry, and OEMs converge to decarbonise long-haul transport

TEAM ICN

Hydrogen is no longer a futuristic concept in India's transportation playbook. What began as a series of controlled pilot experiments has evolved into a coordinated national push, driven by policy clarity, industrial participation, and growing confidence in hydrogen's ability to decarbonise the most difficult segments of mobility. While India trails early adopters in refuelling density and vehicle volumes, its integrated policy framework and low-cost renewable energy base could give it a long-term cost advantage in hydrogen mobility.

At the heart of this transition lies the National Green Hydrogen Mission, which has repositioned hydrogen not merely as an industrial feedstock but as a transport fuel capable of reshaping logistics, public transport, and inter-modal mobility.

From a business perspective, hydrogen transportation in India is transitioning from grant-driven pilots to early commercial experimentation. Fleet operators, logistics companies, and public transport authorities are evaluating hydrogen vehicles based on total cost of ownership rather than upfront costs alone. While hydrogen vehicles remain expensive, lower fuel price volatility, longer range, and faster refuelling offer compelling advantages for high-utilisation fleets.

Globally, the shipping industry is emerging as a major demand driver for hydrogen and its derivatives, particularly green methanol and ammonia. Leading shipping lines have placed orders for methanol-fuelled vessels, while ports in Europe and Asia are developing hydrogen bunkering infrastructure. These trends directly influence India's port-linked hydrogen ambitions.

While battery electric vehicles dominate passenger mobility, countries across Europe, East Asia and North America are turning to hydrogen for trucks, buses, trains, ships and aviation, segments where range, payload and refuelling time remain key constraints. In Europe, hydrogen trucks and buses are being rolled out under the European Union's Hydrogen Strategy, with countries such as Germany, France and the Netherlands investing heavily in hydrogen refuelling corridors. Germany alone plans more than 100 hydrogen refuelling stations by the end of the decade, while hydrogen trains are already operating commercially on regional routes, replacing diesel locomotives. Japan and South Korea have positioned hydrogen at the centre of their mobility transitions. Japan operates the world's largest fleet of hydrogen fuel cell passenger cars and buses, supported by a dense refuelling network, while South Korea has committed to deploying tens of thousands of hydrogen trucks and buses by 2030. Both countries view hydrogen mobility as a strategic industrial opportunity, linking vehicle manufacturing with fuel supply and export markets.

In the United States, hydrogen adoption is gaining traction in freight and port operations. California leads the push, mandating zero-emission trucks and supporting hydrogen refuelling infrastructure for drayage trucks and long-haul transport. Major logistics players are testing hydrogen fuel cell trucks to meet tightening emissions norms and corporate sustainability targets.

### Hydrogen goes Multimodal in India

India's approach stands out for its breadth and scale of experimentation. Rather than focusing on a single mode, India is simultaneously piloting hydrogen across road freight, buses, railways and inland waterways.

Public sector utility NTPC has led early demonstrations of hydrogen fuel cell buses, deploying fleets that operate in diverse conditions including high-altitude regions and urban corridors such as the Greater Noida–Noida Expressway showcasing ranges of 600–650 km per refill and rapid refuelling. Complementing

### Hydrogen Vehicles move from Demo to Deployment

India has moved beyond proof-of-concept hydrogen vehicles. Under the National Green Hydrogen Mission, 37 hydrogen-powered buses and trucks are being deployed across 10 identified routes, supported by the development of nine hydrogen refuelling stations.


this, vehicle manufacturers such as Tata Motors and Ashok Leyland are conducting extended trials of hydrogen-powered trucks on major freight routes, testing both fuel cell electric and hydrogen internal combustion configurations to assess performance, payload efficiency, and total cost of ownership. Oil marketing companies including Indian Oil Corporation Limited (IOCL), Bharat Petroleum Corporation Limited (BPCL), and Hindustan Petroleum Corporation Limited (HPCL) are developing hydrogen refuelling station prototypes and exploring integrated production-to-dispensing supply chains. These moves align with broader decarbonisation strategies and position legacy energy firms as future hydrogen fuel providers.

In rail transportation, Indian Railways is testing hydrogen fuel-cell propulsion for non-electrified routes, aiming to reduce annual diesel consumption of approximately 2.5 billion litres and offer cleaner alternatives where electrification is challenging. For railways, hydrogen also aligns with the railways' broader sustainability goals, including net-zero operations by 2030. While still at an early stage, hydrogen rail initiatives signal the government's intent to evaluate hydrogen across all major transport modes rather than confining it to niche applications.

## Long-haul Trucking Emerges as Hydrogen's Strongest Use Case

Heavy-duty trucks account for less than 5% of vehicles on Indian roads, but consume over 40% of diesel used in road transport. This imbalance has made long-haul freight the primary focus for hydrogen trials.

Perhaps the most ambitious element of India's hydrogen mobility strategy is the concept of hydrogen highways dedicated corridors equipped with refuelling infrastructure to support hydrogen-powered freight and public transport. These corridors are being planned along high-traffic industrial routes, creating predictable demand clusters that can justify early infrastructure investment.

Ports are expected to play a crucial role in this network. Hydrogen corridors linked to ports such as Kandla, Paradip, and Gopalpur are being explored to support not only road transport but also maritime bunkering and export logistics for green fuels.

Hydrogen's entry into India's maritime and inland waterways sector marks another significant milestone. The launch of India's first indigenous hydrogen fuel cell vessel on the Ganga represents a convergence of clean energy, shipbuilding, and inland water transport policy. Built by Cochin Shipyard, the

vessel is part of a broader effort to green India's inland waterways under the Harit Nauka initiative. For shipping, hydrogen and its derivatives offer clear advantages. Fuel cells eliminate emissions and noise, making them particularly attractive for passenger ferries and vessels operating in ecologically sensitive areas. Over time, green hydrogen-based fuels such as methanol and ammonia could further expand hydrogen's footprint in coastal shipping and port operations.

## Policy Architecture

The Indian government's hydrogen push in transportation is anchored in a broader vision of energy independence and decarbonisation. The Ministry of New and Renewable Energy, in coordination with the Ministries of Road Transport, Railways, Ports, and Petroleum, has rolled out funding support for hydrogen vehicles, refuelling infrastructure, and integrated supply chains.

A major policy signal came with the allocation of public funding to deploy hydrogen buses and trucks across multiple routes, supported by hydrogen refuelling stations. The initiative is structured through consortia that bring together vehicle manufacturers, oil marketing companies, renewable energy developers, and fleet operators. This model reflects a clear understanding that hydrogen mobility cannot scale through isolated efforts; it requires tightly integrated ecosystems.

Equally important are enabling measures such as waivers on interstate transmission charges for renewable power used in hydrogen production, priority access to open-access electricity, and support for pilot-scale electrolyser deployment. Together, these measures are designed to address hydrogen's biggest hurdle which is its cost, while stimulating early demand in transportation.

## Indigenous Innovation

Technological progress is quietly reshaping hydrogen mobility's prospects in India. Fuel cell systems are becoming more efficient and durable, while advances in high-pressure storage, cryogenic tanks, and safety systems are addressing long-standing concerns around hydrogen handling.

Indian companies are also beginning to develop indigenous capabilities. From hydrogen-compatible steel pipelines and pressure vessels to power electronics and control systems, localisation is emerging as a strategic priority. This not only reduces costs but also strengthens India's position in the global hydrogen value chain.

There is also a need for integration of renewable energy with hydrogen production. Solar and wind-powered electrolysers are increasingly seen as the backbone of green hydrogen supply for transportation, ensuring that hydrogen vehicles deliver genuine lifecycle emissions reductions rather than shifting emissions upstream.

## The Path Ahead

India's hydrogen transportation journey is still in its formative years, but the direction is unmistakable. What sets India apart is not just the ambition of its hydrogen vision, but the breadth of its experimentation, across buses, trucks, trains, ships, and highways, backed by public-private collaboration.

Over the next decade, hydrogen is unlikely to replace batteries or biofuels entirely. Instead, it will carve out a critical role in segments where electrification struggles, complementing other clean mobility solutions. If costs fall, infrastructure expands, and policy support remains steady, hydrogen could become a cornerstone of India's low-carbon transport architecture.

In that sense, hydrogen in transportation is no longer about whether it will work, but about how fast India can make it work at scale, and whether it can turn early leadership into a lasting competitive advantage in the global clean mobility race

# ROLE OF GREEN HYDROGEN IN INDIA'S MOBILITY TRANSFORMATION

SIAM will work with government and other stakeholders to embed a "safety by design" culture into hydrogen mobility ecosystem

**Prashant K. Banerjee**
**Executive Director**
Society of Indian Automobile Manufacturers (SIAM)

India's green hydrogen push is rapidly moving from vision to implementation, and transport is emerging as one of its strategic applications. Within this transition, the Indian automotive industry, through SIAM (Society of Indian Automobile Manufacturers), is leading a structured engagement with the National Green Hydrogen Mission (NGHM) focused on designing a safe, scalable and globally competitive hydrogen mobility ecosystem for the country.

## Green Hydrogen and India's Mobility Moment

India has committed to achieve energy independence by 2047 and net zero by 2070, with green hydrogen identified as a key enabler across hard to abate sectors, including transport. Hydrogen can replace fossil fuels in long haul road transport and other segments where batteries alone face range, weight and charging-time constraints, thereby complementing the electric mobility transition.

The National Green Hydrogen Mission (NGHM), approved in January 2023, aims to make India a global hub for production, usage and export of green hydrogen and its derivatives, explicitly recognising clean transportation as one of the major demand pillars. The Mission's targets—at least 5 MMT of green hydrogen production annually by 2030, backed by about 125 GW of additional renewable capacity—are calibrated to unlock use in mobility along with industry and power. [1]

## National Green Hydrogen Mission and Transport Focus

The NGHM seeks to decarbonise the economy, reduce fossil fuel imports and position India as a technology and market leader in green hydrogen. In mobility, it prioritises hydrogen-fuelled long haul automobiles and marine vessels, recognising their role in deep emissions reduction and in diversifying India's clean transport technology mix.

Financially, the Mission carries an outlay of Rs. 19,744 crore till 2029-30, expected to leverage over Rs. 8 lakh crore of total investments, create more than 6 lakh jobs and reduce fossil fuel imports by over Rs. 1 lakh crore cumulatively, with mobility as a key beneficiary of diesel substitution. The Mission also anticipates annual abatement of nearly 50 MMT of greenhouse gas emissions, to which hydrogen-based transport, refineries and fertiliser applications together contribute significantly.

## Hydrogen Mobility Pilots: From Concept to Road

To translate strategy into on ground outcomes, NGHM has launched a dedicated pilot scheme for hydrogen-fuelled buses and trucks. Under this initiative, the Ministry of New and Renewable Energy (MNRE) invited proposals for different types of hydrogen vehicles, operational routes and refuelling stations, and has now sanctioned five pilot projects involving 37 vehicles—15 fuel cell-based and 22 hydrogen internal combustion engine-based—supported by nine hydrogen refuelling stations.

These pilots are designed to demonstrate safe and secure operations, validate technical feasibility and performance, and evaluate economic viability of hydrogen-based vehicles and refuelling infrastructure under real world Indian conditions. The learnings will directly inform future policy, regulations, business models and scale up plans, including the government's intention to have at least 1,000 hydrogen trucks and buses on Indian roads by 2030.

## SIAM's Role in Shaping Hydrogen Mobility Governance

Against this backdrop, SIAM has assumed a structured and multi layered role in the governance architecture of hydrogen mobility under NGHM.


## SIAM as convener of Sub Group III on Hydrogen Mobility Application

- SIAM is the convener of Sub Group III on Hydrogen Mobility Application under the Advisory Group of the National Green Hydrogen Mission.

- In this capacity, SIAM has coordinated and submitted a detailed report on Regulations, Codes and Standards (RCS) for hydrogen mobility applications, consolidating inputs from automotive OEMs, component suppliers and other technical stakeholders.

## SIAM as member of Sub Committee III on Hydrogen Mobility Application

- SIAM is also a member of Sub Committee III on Hydrogen Mobility Application under the Mission's Advisory Group.

- As part of this committee SIAM has reviewed, evaluated and recommended R&D projects, and mobility pilot projects, ensuring that proposals are aligned with real world vehicle requirements, safety imperatives, indigenous technology development and commercial scalability.

SIAM in the National Hydrogen Safety Panel (NHSP)

- In the latest development, SIAM has been nominated as a member of the National Hydrogen Safety Panel (NHSP).

Within NHSP, SIAM will support the government through whitepapers, recommendations on required policies, capacity building initiatives for a safe hydrogen energy transition, and training programmes to build a skilled workforce across the country.

Through these three roles, SIAM effectively bridges policy intent with engineering reality, ensuring that India's hydrogen mobility roadmap is grounded in safety, practicality and global best practices while still being tailored to Indian operating conditions.

**SIAM effectively bridges policy intent with engineering reality, ensuring that India's hydrogen mobility roadmap is grounded in safety**

## SIAM's Role in Enabling Safe and Scalable Hydrogen Mobility

For developing a robust green hydrogen economy, safety, robust standards and practical regulations are pre conditions, which will help ensure, public confidence and attract long term investments in hydrogen mobility.

Hydrogen touches multiple domains—energy, transport, urban infrastructure and emergency response—which makes coordinated, industry backed frameworks


> **For developing a robust green hydrogen economy, safety, robust standards and practical regulations are pre conditions, which will help ensure, public confidence and attract long term investments in hydrogen mobility**

essential for deployment at scale.

As convener of the Sub Group III on Hydrogen Mobility Application, SIAM has been at the core of this effort, leading the preparation of a detailed report on regulations, codes and standards specific to hydrogen use in mobility applications. This supported the government's objective of aligning Indian provisions with global benchmarks while tailoring them to local duty cycles, climate conditions and operating practices.

In parallel, SIAM's participation in Sub Committee III on Hydrogen Mobility Application ensures that R&D and pilot projects recommended under the Mission reflect real world vehicle requirements, safety imperatives and commercial viability. By reviewing and evaluating project proposals, SIAM helped prioritise technologies and business models that can move from demonstration to deployment in a phased and orderly manner.

With SIAM now nominated to the National Hydrogen Safety Panel (NHSP), this engagement is set to deepen further. Through whitepapers, policy recommendations, capacity building initiatives and training programmes, SIAM will work with government and other stakeholders to embed a "safety by design" culture into every layer of India's emerging hydrogen mobility ecosystem, from vehicle engineering and depot design to driver training and emergency response.

## What Green Hydrogen means for India's Mobility Future

For the automotive and transport ecosystem, green hydrogen is not just another fuel; it represents a strategic opportunity to reshape long haul and heavy duty mobility while reducing oil imports and emissions. As NGHM pilots for buses and trucks move ahead, and as the government progresses towards putting at least 1,000 hydrogen vehicles on Indian roads by 2030, the contours of a new value chain are beginning to emerge.

This value chain spans domestic manufacturing of electrolysers, fuel cells, hydrogen ready engines, storage systems and refuelling equipment, alongside digital solutions for fleet optimisation and safety management. It will create new interfaces between vehicle manufacturers, energy companies, city and state transport undertakings, logistics players and skill development institutions, demanding close coordination and shared learning.

In this context, SIAM's structured role under the National Green Hydrogen Mission—shaping regulations and standards, guiding R&D and pilots, and contributing to the National Hydrogen Safety Panel—ensures that industry insights are embedded in every key decision. By working in partnership with government, SIAM is helping ensure that India's hydrogen mobility transition is technologically sound, globally competitive and, above all, safe and reliable for users. This collaborative approach will be central to turning green hydrogen from a promising concept into a visible, everyday reality on India's roads over the coming decade

# HYDROGEN HIGHWAYS: FUELLING A TRANSPORT REVOLUTION

Hydrogen is a strategic architecture for energy independence, industrial competitiveness, and clean mobility

India stands at a pivotal juncture—balancing rapid economic growth with the urgent need to decarbonize. As we chart a course toward carbon neutrality by 2070, hydrogen emerges as a strategic, scalable, and resilient pillar of the transition, including mobility

## Why Hydrogen Fits India's Long-Term Strategy

Hydrogen aligns with Energy Atmanirbharta 2047 and net zero 2070. India can produce green hydrogen using abundant solar and wind potential, biomass-derived hydrogen in agricultural belts, and blue hydrogen via natural gas with carbon capture. This enhances energy security and reduces import dependency on crude. Hydrogen helps decarbonise hard-to-abate sectors—heavy transport, industrial heat, steel, refining, and fertilizer—where direct electrification is challenging. This helps to build long term strategic manufacturing capacity of electrolyzers and fuel cell stacks to storage tanks and refuelling hardware, creating high-quality jobs and local supply chains.

## Hydrogen is root energy/ fuel

Hydrogen can store surplus renewable power for months, across seasons, solving variability and grid balancing more effectively and for longer periods than batteries alone.

Hydrogen connects different sectors: power, industry, and transport (fig. 1)—allowing excess renewables to become transport fuel or industrial heat, smoothing demand, and supply across sectors.

Hydrogen infrastructure can support both mobility and stationary applications (backup power, microgrids), improving reliability during peak demand and outages.

Costs decline with scale—electrolyzer manufacturing, renewable deployment, and standardized refuelling networks fuel virtuous cycles of adoption.

No single technology can deliver Net Zero due to India's diversity of geography, resources, and use-cases. Hydrogen promotes electrified mobility by enabling long-range, heavy-duty, and quick-refuel applications where uptime and payload matter. Hydrogen can include biofuels in agriculture and aviation pathways, while hydrogen-derived e-fuels and ammonia serve shipping and industrial heating. CNG/ LNG with pilot-scale blends of hydrogen as transitional fuels in select corridors, paving the way for deeper decarbonization.

Hydrogen thus does not replace other paths— it integrates them, making India's decarbonization resilient, affordable, and tailored to local constraints.

**Sudeep S. Dalvi**
**Chief Communication Officer; Senior Vice President & Director - Technical & Purchase and Head - State Affairs**
Toyota Kirloskar Motor

**Hydrogen promotes electrified mobility by enabling long-range, heavy-duty, and quick-refuel applications where uptime and payload matter**

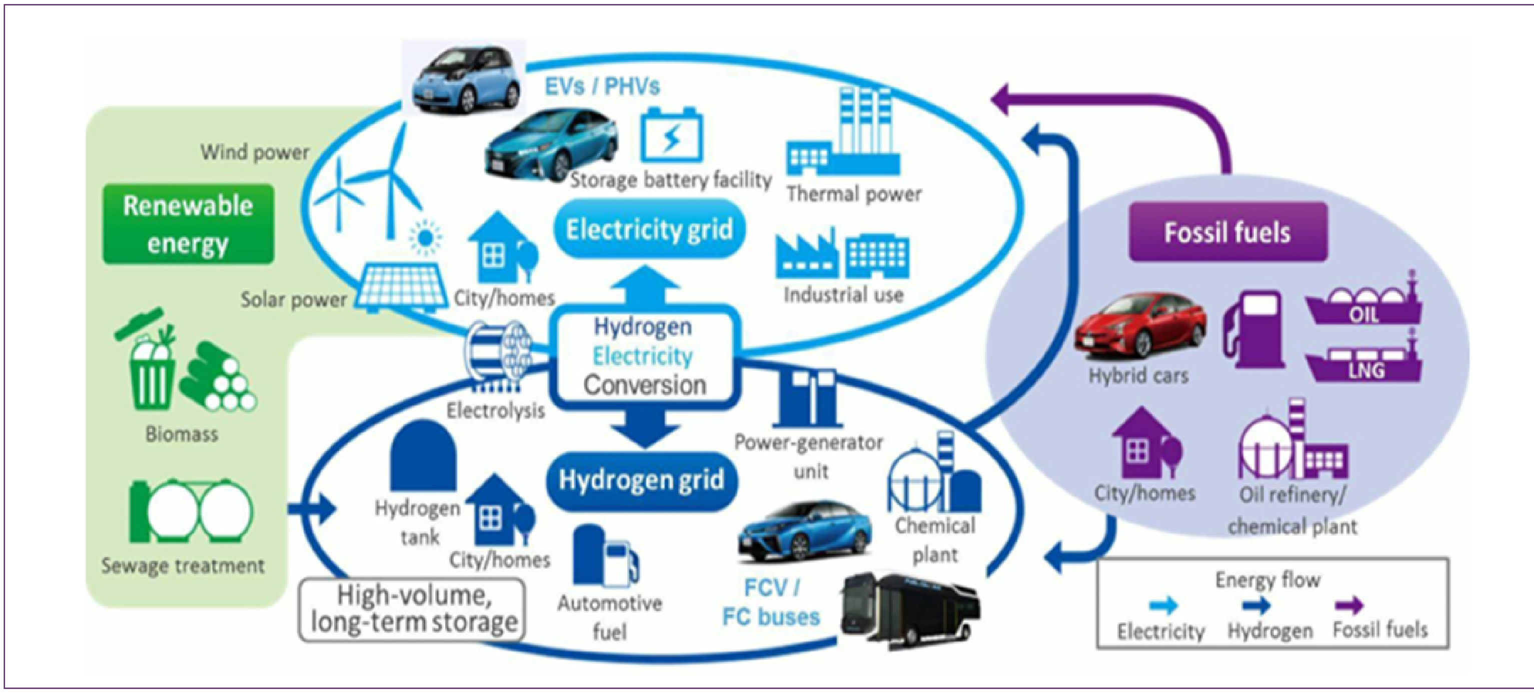



*Fig. 1.: Hydrogen connects Power, Industry & Mobility sectors*

## India's actions to building hydrogen ecosystem

India has excellent capacity building program 'National Green Hydrogen Mission for 2030' and beyond, fully supported by the government with clear targets for production capacity, incentives, target usage areas *(Fig.2)*.

The focus begins with decarbonisation of fertiliser, refineries/petrochemical industries, hard to abate sectors: Steel, Cement, Aluminium, then transportation, mainly buses and trucks.

## Why Hydrogen will be a long lasting solution for heavy transport?

Performance & Uptime in Heavy Transport

Hydrogen fuel cell vehicles (FCEVs) offer fast refuelling (5~10 minutes, similar to diesel), long range, and high payload—critical for freight and public transport where vehicle downtime is costly *(Fig.3)*. FCEVs maintain performance across extreme temperatures and duty cycles, making them strong candidates for intercity trucks and buses, especially on fixed-route corridors.

## Total Cost of Ownership Improves with Scale

While early-stage hydrogen may carry premium costs, fleet operations—buses, trucks, and depot-based logistics—can optimize utilization of refuelling

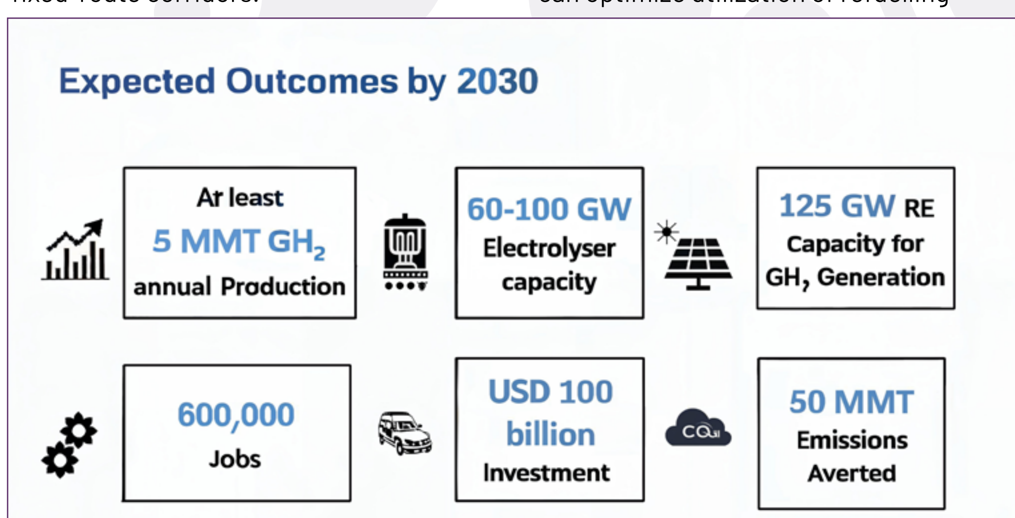



*Fig. 2.: National Green Hydrogen Mission outcomes*

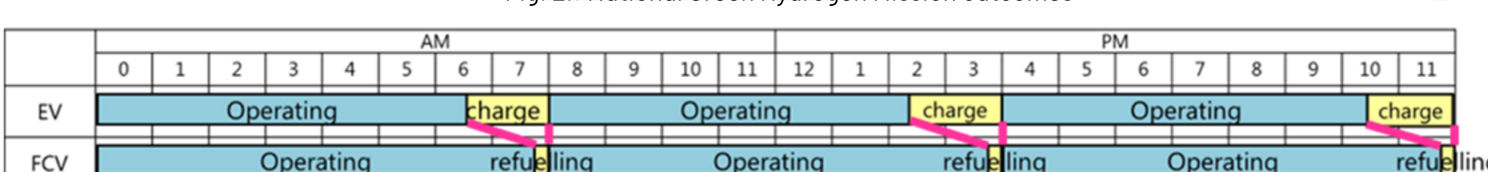



*Fig. 3 Faster refuelling with hydrogen*

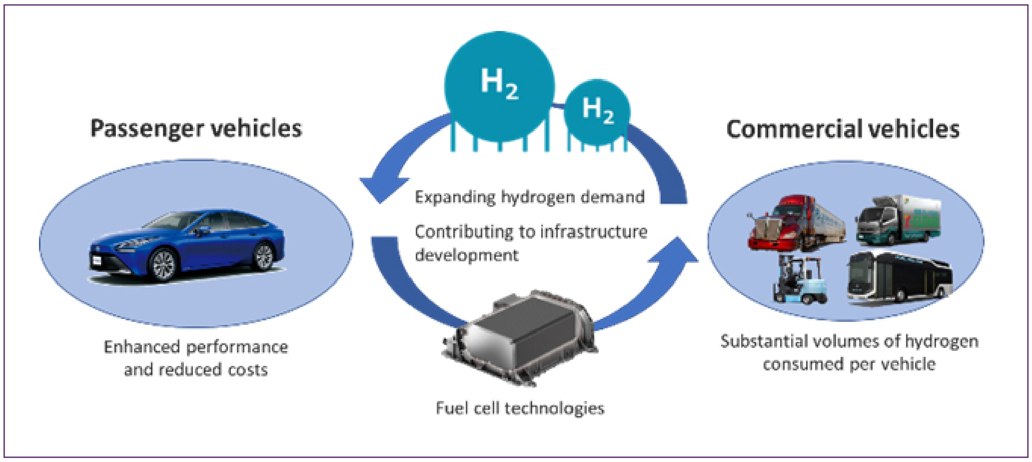



*Fig. 4 Cost of ownership improve with common use*

infrastructure. As electrolyzer, renewable, and fuel cell costs fall, hydrogen becomes competitive, particularly for high-mileage, high-mass use-cases *(Fig.4)*. Moreover, hydrogen's dual role (mobility and stationary backup) improves asset utilization and economics. Hydrogen brings in valuable carbon credits which further reduces the TCO.

## Global Approach: Learning, Localizing, Leading

Technologies for production, storage and use have matured and are implementation ready. The challenge is to step out of the chicken-egg conundrum and kickstart the hydrogen ecosystem. Different countries have different strategies towards adoption of hydrogen.

## Consortium Approach

Hydrogen society/ecosystem needs multiple stakeholders for effective operation & sustenance. Governments/ industry/customers alone cannot drive the success. Many countries have adopted the 'Consortium approach' to boost the hydrogen ecosystem.

**HYGEAR:** See Hydrogen Ltd. (Bulgaria) HyGear (Netherlands), and Green Energy Park-Global (Netherlands), RESATO Hydrogen Technology (Netherlands)

**HydroGEN Consortium:** A United States DOE sponsored program for R&D in splitting water

**Hydrogen Council:** Global Consortium with 140 members

## Hydrogen Strategy of Asian countries

**Japan**

Japan created the world's first Hydrogen Policy in 2017, outlining technologies related to hydrogen: production, transportation, and combustion updated periodically to reflect the evolving environment. Government and private sector plan to mobilize around ¥15 trillion ($100+ billion) over the next 15 years to build a hydrogen supply chain, reduce costs, and scale infrastructure. Japan started utilizing Hydrogen in Commercial Vehicle space. Govt. & industry had set aggressive target to expand the FC vehicles from current 7,700+ vehicles to 800,000 vehicles by 2030. Japan Govt. is also offering significant incentives to cover ~75% of the new vehicle cost.

Japan has set up a consortium: Japan H2 Mobility (JHyM) consisting of 11 companies: AutoOEMs, banks, Gas distribution companies in line with global pathways.

**China**

China is leading globally in building a comprehensive hydrogen ecosystem, driven by strong government policy, massive production, and rapid deployment, especially in fuel cell vehicles (FCVs). China's strategy (mid-long term till 2035) is to establish domestic R&D and manufacturing of core components (PEM electrolyser, fuel cells, hydrogen storage tanks), with emphasis on Transportation, Energy storage, Generate electricity and Industry, in that order.

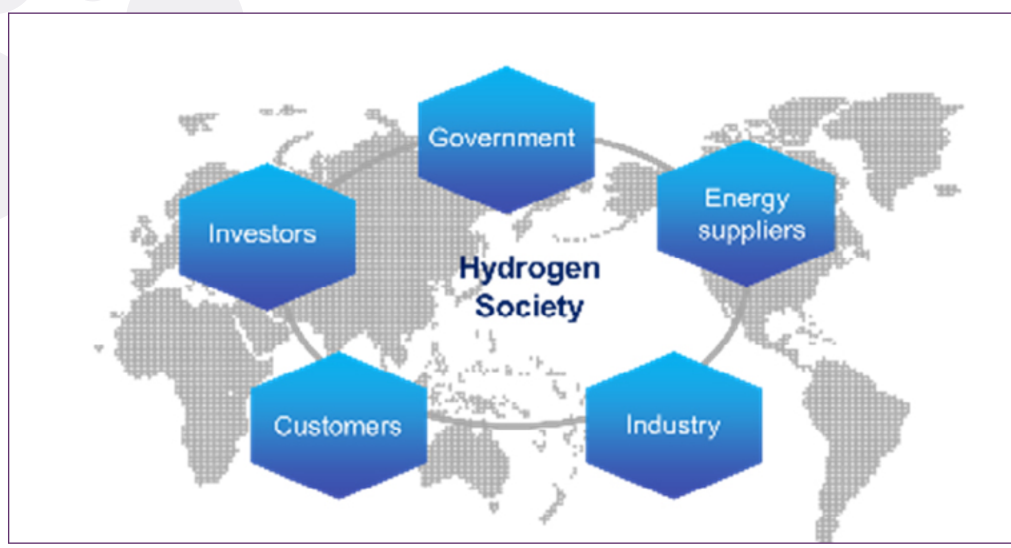



*Image of Global Consortium*

China has consortia: Central Enterprise Green Hydrogen Consortium, China Hydrogen Alliance (CHA), UNIDO Green Hydrogen Project, among the significant.

## Toyota's Hydrogen leadership in India

Toyota's leadership in fuel cell technology

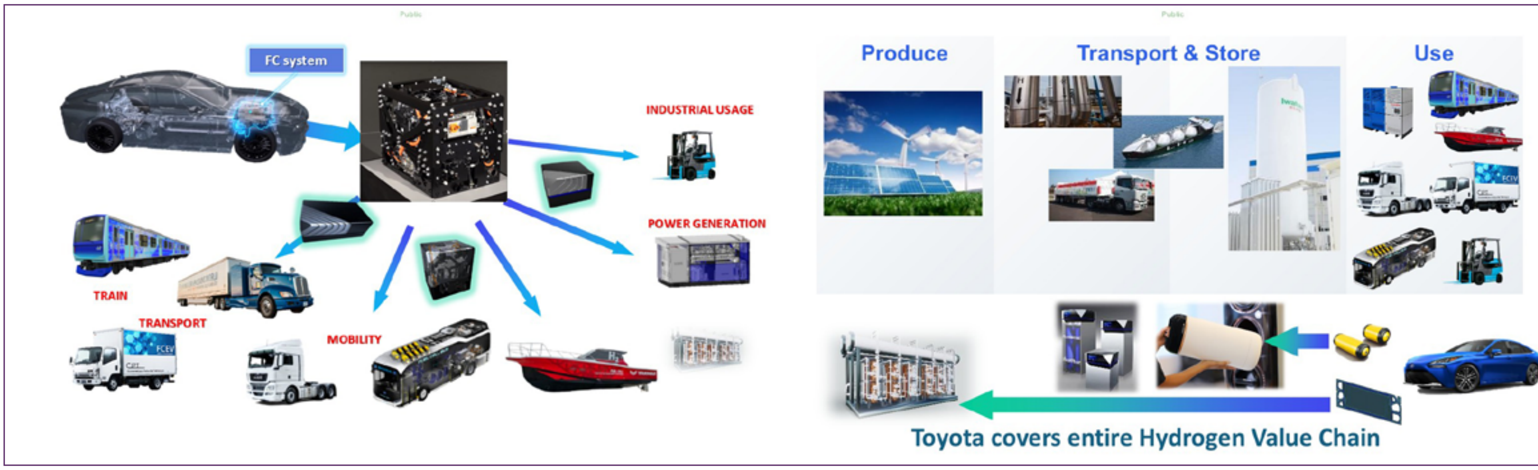



*Fig. 5 Toyota's Core technologies covering end – to – end use, for both transport and storage*

provides a mature, multi-application platform that aligns naturally with Hydrogen Highways: One stack, many use cases, proven and reliable performance across mobility and stationary platforms and seamless fit into hydrogen production and refuelling reducing technology risks for all stakeholders *(Fig. 5)*.

Toyota Kirloskar Motor (TKM) initiated hydrogen mobility in 2019 using Toyota Mirai Gen #1 to initate studies with government agencies, helping seed the hydrogen ecosystem in India. TKM is focussing on building a strong self-sustaining hydrogen ecosystem with pilot/demonstration projects across the spectrum, not limited to mobility only.

**MoU with NISE (under MNRE), Government of Kerala**

Toyota Mirai Gen#2 will be used to study the feasibility of FuelCell EVs with the hydrogen ecosystem in India: domestic hydrogen production & refuelling, performance on India roads and weather, generating valuable data for both GoI & OEMs.

**Toyota's Fuel cell stack integration with Ashok Leyland truck**

Toyota Kirloskar Motor (TKM) partnered with Ashok Leyland to advance zero-emission commercial mobility in India by supplying their advanced hydrogen fuel cell modules.

## With IOCL

Since 2020, Toyota's Mirai fuel cell vehicle successfully completed refueling trials at the IOCL R&D Faridabad hydrogen station, proving its compatibility with India's developing green hydrogen infrastructure and supporting national goals for sustainable mobility.

## MoU with Ohmium

This covers a wide range of applications from production of hydrogen to deployment of fuel cells to create microgrids . These are suitable for numerous self sufficient applications.

*Fig 6: Toyota Fuel Cell with AL Truck*

## Kick-starting FCEV Commercial Transport in India

The primary obstacle to overcome is the high Total Cost of Ownership (TCO). This high TCO stems from several key, interconnected challenges such as vehicle costs, hydrogen production, infrastructure gaps, and storage and transportation. Addressing these challenges, particularly lowering the cost of hydrogen production and developing robust infrastructure, is crucial for FCEVs to become economically viable and competitive with other zero-emission options like BEVs, especially for long-haul applications.

*Fig. 7 Toyota Mirai Refuelling at IOCL*

## Create demand for hydrogen

Accelerate hydrogen adoption by establishing refuelling stations along high-demand corridors, starting with a base fleet to ensure sustainable demand. As routes expand, this model enables rapid breakeven for both infrastructure and vehicles, fostering a virtuous cycle of growth. Standardized storage and dispensing protocols are crucial to ensuring a seamless, reliable refuelling experience.

## Reduce acquisition cost of fuel cell trucks

A public procurement program similar to PM E-DRIVE would generate initial demand through government fleets, municipal

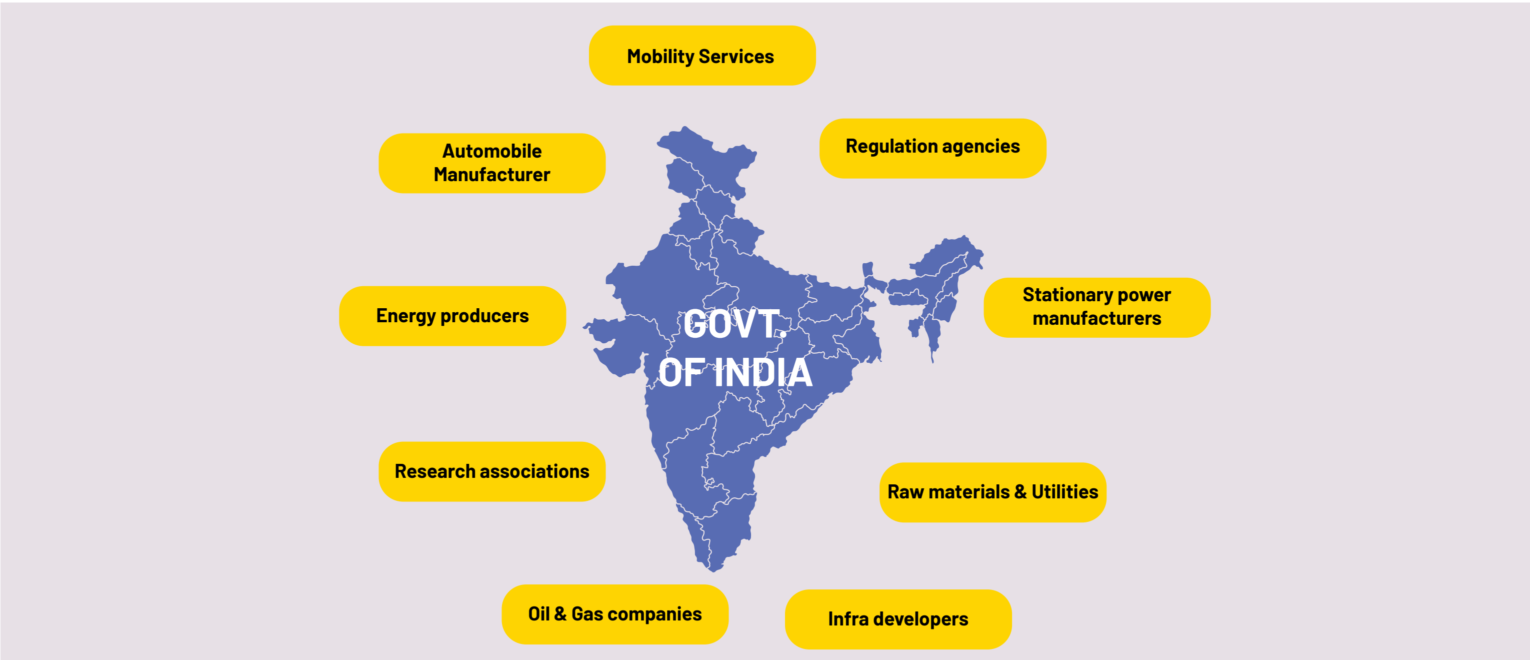



*Fig. 5 Toyota's Core technologies covering end – to – end use, for both transport and storage*

**Toyota Kirloskar Motor partnered with Ashok Leyland to advance zero-emission commercial mobility in India by supplying their advanced hydrogen fuel cell modules**

buses, and strategic industrial users. Furthermore, utilizing carbon markets and green certification to monetize well-to-wheel emissions reductions would significantly improve the Total Cost of Ownership.

The increased number of trucks on the road helps lower electrolyser cost due to higher volume effect. This pushes more R&D effort towards making fuel cells cheaper and easier to manufacture propagating a self-sustaining cycle.

## Final Frontier: Hydrogen Production and Price

While green hydrogen is the ultimate goal for net-zero, its required production volumes and cost-competitiveness are still several years away. It is smart to start with existing blue (/grey) hydrogen to grow volumes of hydrogen availability, refuelling stations, and trucks. Blue (/grey) hydrogen is relatively affordable making it attractive, now! This approach helps refuelling stations break even earlier. As electrolyser costs fall and production scales, pivoting to green hydrogen is critical. By bypassing new refueling infrastructure, green hydrogen can achieve near parity with conventional fuels. This self-sustaining hydrogen ecosystem can easily expand to include passenger buses & cars.

Moreover, establishing an all-stakeholder India-centric hydrogen consortium will act as a force multiplier, accelerating the implementation of a national hydrogen society roadmap *(Fig. 8)*.

## Conclusion: A Highways-to-Hydrogen Flywheel

Green hydrogen generates a powerful virtuous cycle: as renewable energy grows, it fuels the adoption of hydrogen in fleets and heavy industry. This increasing adoption makes investing in refueling infrastructure more attractive, which in turn reduces costs, driving even higher adoption, while shared technology components bolster scale advantages.

For a self-reliant India by 2047 on the path to Net Zero by 2070, hydrogen is not just a fuel—it is a strategic architecture for energy independence, industrial competitiveness, and clean mobility

# ADAPTING HYDROGEN DERIVED FUELS IN SHIPS

## While pure hydrogen is a clean fuel, it is difficult to use in shipping because it has low volumetric energy density, requiring massive tanks that reduce cargo space

Over 98 per cent of current world cargo fleet runs on Heavy Oil. However, signs of change are witnessed in new ships as over 26 per cent of ships on order have the capability to use alternatives fuels. This drive towards alternative fuels has been driven by International Maritime Organization's (IMO) commitment to make maritime transport green, as Shipping is claimed to be one of the biggest pollutant means of transport. Accordingly IMO has adopted the below emission norms for ships worldwide: 20% reduction in emissions by 2030; 70% reduction in emissions by 2040; and Net zero emissions by 2050.

These are highly ambitious target taking into account the fact that this has to be adopted by the entire world. Ships generally have an operating life of 20~30 years and vessels built today need to have the cleaner fuel combustion system otherwise come 2050 and they will have to be phased out early before the end of their operating life. Hence time is running out and the maritime community has been working relentlessly to achieve these targets by preparing to phase out older tonnage burning Heavy Oil and getting in new tonnage which would burn relatively cleaner fuels. There have been few roadblocks though, as in October 2025, the IMO could not get a majority to implement some of the milestones for decarbonisation and has deferred the decision by one year. This is owing to difference in opinion between member countries on the need to set up such tough targets and also the feasibility to achieve such ambitious results in such short a time.

This sudden change in stance of IMO members is perhaps a minor stumbling

**Rajnish Khandelwal**
**CEO - Agency**
JM Baxi Marine Services

block and shipping would definitely move towards cleaner fuels, if not today, tomorrow. While writing on the wall is clear, there is no agreement within the shipping industry as to what the preferred carbon free solution should be. Various alternatives are emerging and it will perhaps take at least a decade, when there would be clear pathway on the best fuels for ships. Possible options include:

- **Conventional Fuels** (e.g. HSFO, VLSFO, MGO) with post-combustion carbon capture
- **Renewable version of Existing Marine Fuels** (e.g. biodiesel, bio-lng, green methanol)
- **Renewable version of Emerging Marine Fuels** (e.g. green ammonia, green hydrogen)
- **Alternative Propulsion methods** (Wind-assisted Sail Systems, Battery-Electric Power, Nuclear Propulsion)

Of all the alternatives being worked upon, hydrogen and hydrogen-based alternatives are the best option owing to their least emission properties. If the world has to move towards net zero, only hydrogen can offer this alternative. However, even though being the safest and cleanest fuel, hydrogen is not easy to transport and store for supplies to ships. Technically, it is feasible, however, commercially it's a huge cost which the industry cannot bear.

While pure hydrogen is a clean fuel, it is difficult to use in shipping because of it has low volumetric energy density, requiring massive tanks that reduce cargo space. A large 22,000 TEU ship burning hydrogen will have to forgo upto 5 per cent of its cargo space to built space of storing hydrogen bunker. This is a major challenge commercially, as ships are getting big and bigger to achieve scale economics and any forfeiture of cargo space is not welcome by shipowners. Further, for storing in limited space, hydrogen must be kept at -253°C, which is energy-intensive and vastly expensive.

Hence, the only way of adapting hydrogen as fuel has to be through hydrogen-derived carriers, which are :

- **Green Ammonia ($NH_3$) -** Offers up to a 90 per cent reduction in GHG emissions compared to conventional fuels. It is carbon-free at the point of use but requires specialized handling due to toxicity.
- **Green Methanol ($CH_3OH$) -** More technologically advanced with existing compatible engines. It reduces $CO_2$ emissions but typically requires carbon

> **Of all the alternatives being worked upon, hydrogen and hydrogen-based alternatives are the best option owing to their least emission properties. If the world has to move towards net zero, only hydrogen can offer this alternative**

capture (CCS) for full carbon neutrality.

- **E-LNG / E-Diesel:** Synthetic versions of existing fuels that use renewable hydrogen and captured $CO_2$.

The present world fleet (December 2025) consumes about 340 million tonnes of fuel each year or 14.2 Petajoules of Energy (based on 42 Gigajoules per tonne of Heavy Fuel oil). This energy mainly comes from burning Heavy Fuel oil or Marine Diesel. Based on an average price of US$ 500 per tonne, world bunkering market is worth over US$ 165 billion. For meeting the IMO timelines, Hydrogen based alternatives is likely to constitute following share of this market:

- **2030 Target:** 5–10% of the energy used to come from hydrogen-based fuels.
- **2040 Target:** 70–80% of energy to come from hydrogen-based fuels
- **2050 Target:** 95% of energy to come from hydrogen-based fuels.

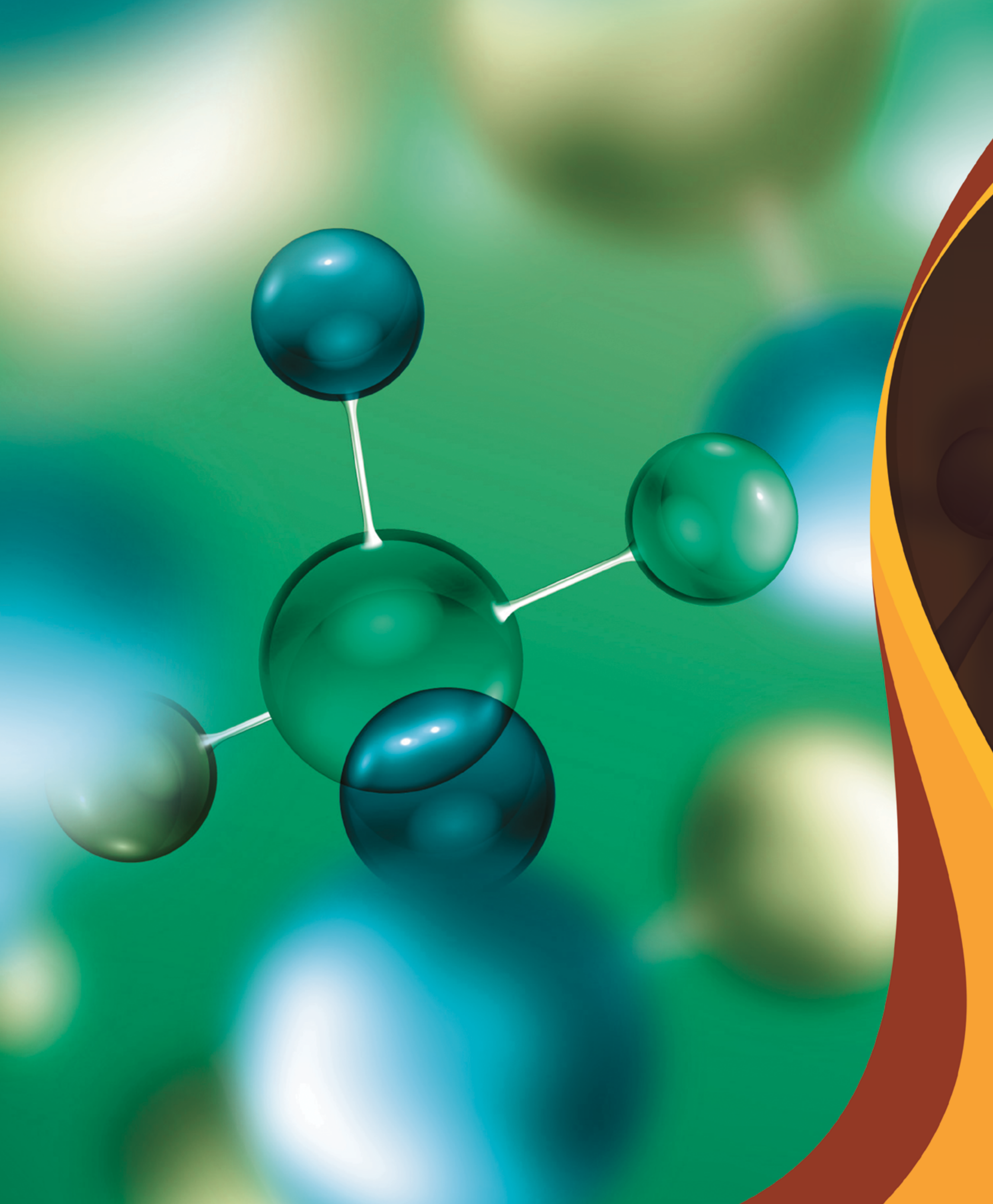
This is easier said than done. Developing an entire logistics chain to supply 95 per cent of bunker fuel for the world merchant fleet is a tall order. Even supply to 5~10 per cent of the world fleet in the next four years is an impossible target. Just to meet 2030 targets, the industry needs approximately 70 million tons of hydrogen based fuel. Presently only a mere 1 per cent of this volume is being


> **There is a huge cost differential between hydrogen-based fuel and conventional fuel. Green methanol costs about $2,000 per tonne, which is steep compared to about US$ 500~600 per tonne for Very Low Sulphur Fuel Oil (VLSFO)**

traded today. Further, there is a huge cost differential between hydrogen- based fuel and conventional fuel. Green methanol costs about $2,000 per tonne, which is steep compared to about US$ 500~600 per tonne for Very Low Sulphur Fuel Oil (VLSFO). Is the industry prepared to pay four times higher price for bunkers to meet the emission norms. Let's not forget bunker costs are substantial portion of operational costs of running ships and the landed costs of goods would go up substantially should the industry adapt the newer fuel.

Further, supplies of hydrogen is still at nascent stage and global standards and bunkering infrastructure for ammonia and hydrogen are still in early development compared to established LNG bunkering infrastructure. It will still take decades for setting up hydrogen- based fuel bunkering infrastructure. Firstly, it has to be analysed how such large scale of Hydrogen can be produced. This requires a process of Electrolysis and then Synthesis on a commercial scale, which is lacking as of now.

Hence, we are all going to witness the switch to hydrogen based fuel for small segment of short sea shipping in the initial days. Before it can be scaled to fuel a larger international fleet around the world, advances in technology and infrastructure are needed to overcome the barriers described above. So while the pathway clearly laid out, the milestones are not yet finalised. It will take years and years before we see a worldwide switch and till that time, shipowners placing orders for new tonnage would continue to play it safe and go for existing fuel options which is LNG in its various forms



# GREEN AMMONIA/ METHANOL

Powering the Net-Zero Transition

# GREEN AMMONIA: THE CENTRAL PILLAR OF INDIA'S HYDROGEN FUTURE

India's most practical pathway to scale clean energy and global trade

TEAM ICN

For all the attention that green hydrogen has received in recent years, its most immediate and commercially viable expression may not be hydrogen itself, but green ammonia.

As India accelerates its clean energy transition, green ammonia is emerging as the crucial bridge between renewable power and hard-to-abate sectors such as fertilizers, shipping, chemicals and power generation. It is hydrogen's most scalable industrial avatar, easier to store, transport and trade, and increasingly, the molecule through which India hopes to convert its renewable energy advantage into global economic leadership.

In a country where ammonia underpins food security and fertilizer subsidies, and where hydrogen is being positioned as a future fuel, green ammonia sits at the intersection of energy transition, industrial decarbonisation and geopolitics. India's push into green ammonia is therefore not an isolated chemical story. It is part of a broader hydrogen-led reimagining of industrial production, trade flows and energy security.

## Global Perspective

Globally, enthusiasm around pure hydrogen has met the realities of physics and economics. Transporting hydrogen across oceans remains costly and inefficient, while pipeline infrastructure is limited. As a result, major hydrogen-importing economies have pivoted towards derivatives such as ammonia and methanol, which can carry hydrogen in chemically stable form.

Europe, facing structural constraints on renewable expansion, has been particularly aggressive. Countries like Germany and the Netherlands have formally identified green ammonia as a cornerstone of their hydrogen import strategies. German utilities and industrial players are signing long-term supply agreements with producers in regions rich in renewable energy, including the Middle East, Australia, Chile and increasingly, India. Japan and South Korea, constrained by land and renewable availability, are pursuing ammonia not just as a hydrogen carrier but also as a direct fuel. Japanese power utilities are co-firing ammonia in coal plants as a near-term decarbonisation pathway, while shipping majors are commissioning ammonia-fuelled vessels. These developments are creating a pull for large, reliable suppliers of green ammonia at scale. Australia, meanwhile, has positioned itself as an early mover in green ammonia exports, building port-based projects aimed at Asian markets. However, high capital costs and slower project execution have opened space for new contenders.

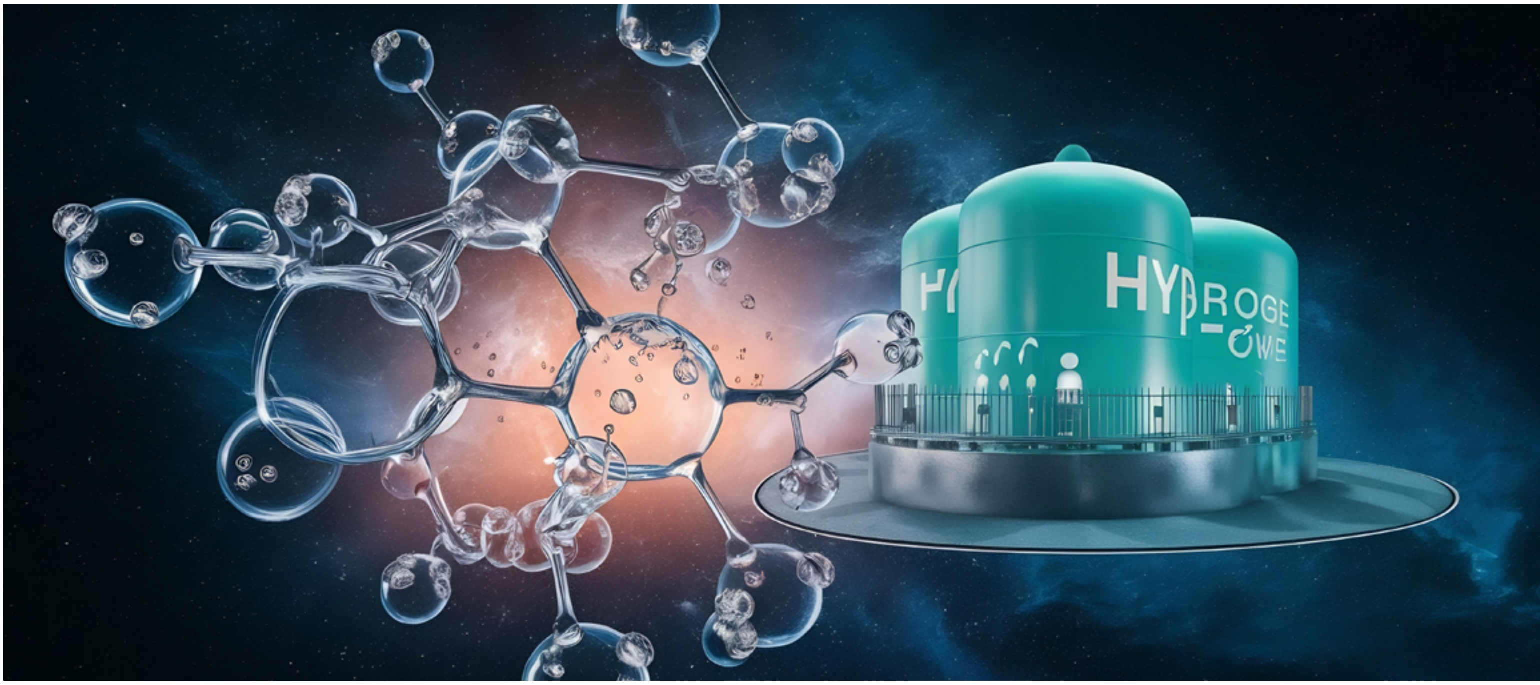
### India's Green Ammonia Advantage

What sets India's green ammonia story apart is the convergence of domestic demand and export ambition. Fertilizers provide immediate, policy-backed volume, while exports offer scale, foreign exchange and long-term growth. As a result, many projects are structured to supply domestic fertilizer companies under government tenders while allocating the balance to overseas buyers seeking low-carbon molecules, improving risk diversification and financial resilience.

Financing models are evolving in parallel. Given the capital-intensive nature of green ammonia projects, developers are blending project finance, strategic equity and long-term offtake agreements to secure funding, with global buyers playing a critical role in lender confidence. As competition intensifies, India's cost advantage will hinge on rapid scale-up, domestic electrolyser manufacturing and efficient logistics.

## Industry Bets Big on Hydrogen-to-Ammonia

India's corporate push into green ammonia reflects a broader realignment around hydrogen. A landmark CAPEX move is AM Green Ammonia's final investment decision on a 1 MTPA green ammonia project at Kakinada, Andhra Pradesh, backed by



investors including Gentari and GIC. The project will convert an existing urea plant into an integrated facility combining green hydrogen production with ammonia synthesis, with commissioning targeted for the second half of 2026. Beyond meeting domestic demand, it anchors AM Green's expansion plans to 5 MTPA of green ammonia capacity by 2030, equivalent to nearly 1 MTPA of green hydrogen.

In Andhra Pradesh, another transformational project is unfolding near Mulapeta port. Vijayawada-based Juno Joule Green Energy has partnered with Germany's Select Energy GmbH to develop a green hydrogen and green ammonia facility with a total investment of about US$ 1.3 billion (~Rs 10,000 crore). The site plans to produce approximately 180 kilotonnes per annum of green hydrogen, which will be converted into up to 1 million tonnes of green ammonia annually for export markets, particularly in Europe.

Avaada Group, another major renewable energy player, is pursuing similarly ambitious plans. Its green ammonia projects in Odisha and Rajasthan are designed around gigawatt-scale renewable power and advanced ammonia synthesis technologies, with a clear focus on both domestic fertilizer demand and exports. Another notable development is Oswal Energies' MoU with the Deendayal Port Authority at Kandla-Gandhidham to develop green hydrogen, green methanol and green ammonia facilities alongside a 100 MLD desalination plant, underscoring how clean molecule projects are being designed with critical infrastructure such as freshwater sourcing built in from the outset.

Beyond production plants, companies are investing heavily in enabling infrastructure. In Gujarat, Adani Energy Solutions secured a Rs 2,800 crore transmission project to support a green hydrogen and ammonia facility at Mundra. The Tata Steel Gopalpur Industrial Park is allocating about 25 percent of its area to green hydrogen and green ammonia, backed by investments of nearly Rs. 27,000 crore. The multi-phase development is designed to produce over two million tonnes of green ammonia annually.

On the technology front, Tecnimont and Nextchem are undertaking engineering studies for a 200,000 tonnes-per-year green ammonia plant in India. Jackson Green plans to invest around Rs. 22,400 crore in a phased green hydrogen and green ammonia project in Rajasthan, while ACME Group is developing a 1.2 MTPA green ammonia facility at the Gopalpur Tata SEZ and targeting a 10 MTPA portfolio of green ammonia and hydrogen derivatives by 2032, with a clear export orientation.

At the conglomerate level, Reliance Industries has earmarked nearly Rs. 75,000 crore for its Dhirubhai Ambani Green Energy Giga Complex in Jamnagar, spanning renewable manufacturing, energy storage and electrolysers. It is expected to underpin large-scale green hydrogen and ammonia production with a strong focus on domestic technology capability.

## Policy as a Market Creator

The Indian government has taken an unusually proactive role in shaping the green ammonia market, recognising that early demand certainty is essential for hydrogen investments. Through the National Green Hydrogen Mission and its Strategic Interventions for Green Hydrogen Transition (SIGHT) scheme, the government has provided direct production incentives for green hydrogen and its derivatives, including ammonia.

Perhaps the most consequential policy intervention has been the decision to mandate and aggregate demand for green ammonia in the fertilizer sector. Through tenders floated by the Solar Energy Corporation of India (SECI), the government has effectively guaranteed


## Addressing Roadblocks

**Infrastructure Gaps:** Storage, pipelines, and logistics need further scaling

**Financing and Bankability:** Long payback periods and early commercial risks require robust off-take contracts and financing frameworks

**Standardization and Certification:** While progress is being made, universal standards are needed to streamline international trade

**Electrolyser Cost:** Domestic electrolysers remain cost-competitive with imports but require further scaling to lower prices

long-term offtake for green ammonia producers, reducing risk and improving bankability. These tenders have already delivered a signal moment for the industry. State governments have also joined the race. Andhra Pradesh, Gujarat, Rajasthan and Odisha are positioning themselves as green hydrogen and ammonia hubs, offering land, renewable power access, port connectivity and policy support.

## Technology Trends Shaping the Sector

The economics of green ammonia are inseparable from advances in hydrogen technology. Electrolysers remain the single largest cost component, and Indian projects are increasingly adopting a mix of alkaline and PEM electrolysis depending on scale, flexibility requirements and renewable integration.

Indian projects are being planned in hundreds of thousands to millions of tonnes per year, forcing innovation in electrolyser manufacturing, power management and ammonia synthesis efficiency. There is also growing interest in optimising the Haber-Bosch process, the century-old method of making ammonia, to better align with variable renewable energy. Traditionally designed for steady fossil-based hydrogen supply, ammonia plants are now being re-engineered to ramp up and down with solar and wind generation. This integration challenge is driving collaboration between technology licensors, EPC firms and digital solution providers.

Storage and transport technologies are evolving in parallel. Port-based ammonia terminals, pipelines and bunkering infrastructure are being designed not just for fertilizers, but for future use in shipping fuel and power generation. This multi-use infrastructure logic strengthens the investment case for green ammonia projects.

## The Road Ahead: From Molecules to Markets

Green ammonia is India's most immediate opportunity to translate its renewable energy scale into industrial and geopolitical influence. By anchoring hydrogen demand, enabling exports and decarbonising fertilizers, green ammonia could do for hydrogen what urea once did for India's agricultural transformation.

Over the next decade, as shipping fuels shift, carbon border taxes bite and global hydrogen trade takes shape, green ammonia is likely to become one of India's most valuable clean energy exports. The countries that master its production early will shape the rules of the hydrogen economy.

Meanwhile, India has moved decisively from intent to execution. The question is no longer whether green ammonia will be produced, but whether India can produce it fast enough, cheap enough and at sufficient scale to lead rather than follow. In the hydrogen era, green ammonia may well be the molecule that defines India's place in the global energy order

# INDIA'S AMBITIOUS BET ON A CLEANER MOLECULE ECONOMY

Methanol represents both a familiar industrial chemical and a potential corner stone of a future clean economy

TEAM ICN

In the rapidly evolving global energy landscape, methanol has emerged as one of the most pragmatic and versatile molecules for the mid-transition era of decarbonisation. Positioned at the intersection of clean fuels, circular carbon chemistry and hydrogen value chains, methanol in its low-carbon forms, including green and $CO_2$-derived variants, is capturing the attention of policymakers and businesses alike.

Methanol's attractiveness is rooted in its molecular simplicity and flexibility. As a liquid chemical, it is easier to handle, store and transport compared with gaseous alternatives. It has applications as a fuel for transport and shipping, a feedstock for a wide range of chemicals, and a medium for hydrogen storage and distribution. This dual utility, as both energy carrier and chemical input, makes it especially relevant for a country like India transitioning from fossil fuels while striving to build competitive clean manufacturing ecosystems.

## Global Scenario

The global studies suggest that the green methanol market alone could reach tens of billions of dollars by the early 2030s, driven by demand in chemicals and clean marine fuel applications. Methanol is evolving from a conventional chemical feedstock into a strategic low-carbon fuel and energy carrier, driven by decarbonisation pressures across shipping, chemicals and heavy industry. The strongest momentum is coming from the maritime sector, where tightening regulations under the International Maritime Organization and Europe's FuelEU Maritime framework have accelerated demand for methanol-fuelled vessels. Major shipping lines have placed large orders for dual-fuel methanol ships, creating a clear demand signal for low-carbon and green methanol supply.

In response, commercial-scale green and e-methanol projects are advancing across Europe, North America, and Asia, using renewable hydrogen combined with biogenic or captured $CO_2$. Ports such as Rotterdam, Singapore and Shanghai are developing methanol bunkering infrastructure, while price benchmarks for low-carbon methanol are beginning to emerge in global trading hubs. China currently leads in scale, leveraging biomass-based methanol and carbon-recycling technologies, while Europe is positioning itself as an early adopter market anchored by shipping and chemical offtake.

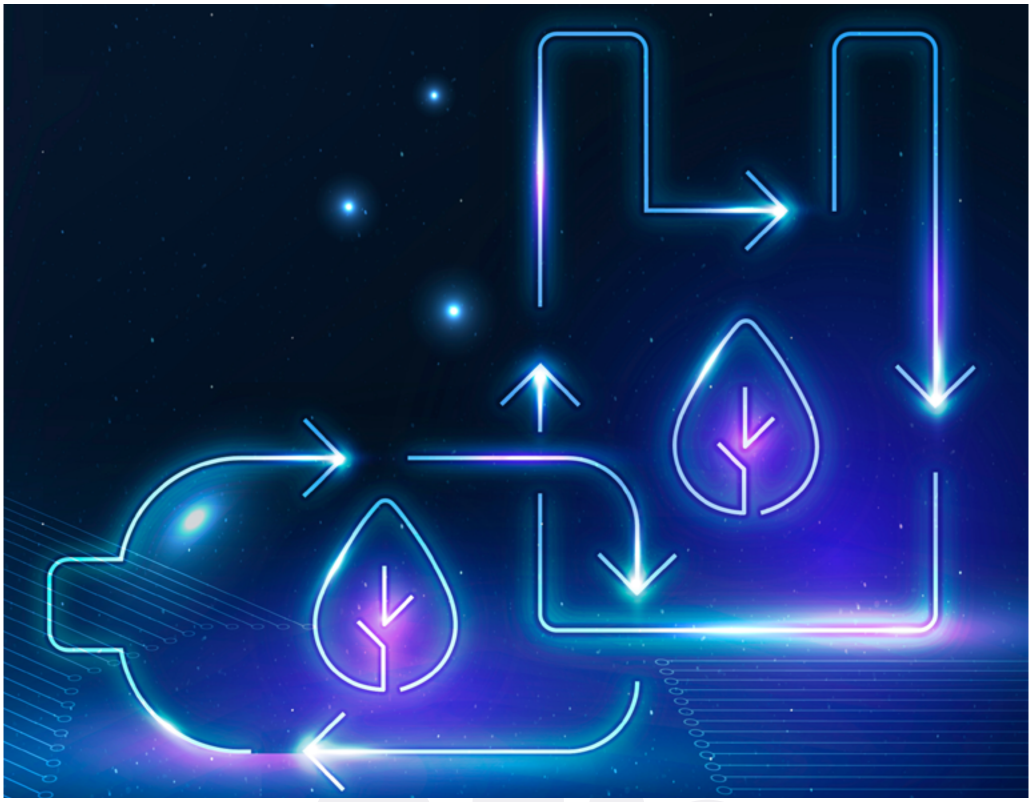
These trends are redefining methanol as a bridge molecule between hydrogen, carbon management and fuels, making it a core component of the emerging Power-to-X economy. For India, aligning with this global shift opens pathways to export markets, international partnerships and participation in a rapidly forming global clean-fuel value chain.

India's Methanol Transition

In India, methanol is moving from policy intent and pilots toward early industrial execution. A key signal has been the deployment of carbon capture-to-methanol pathways, notably at NTPC's Vindhyachal power station where affinity with methanol is reflected not only in its technology collaborations but also in downstream production ambitions. The Vindhyachal $CO_2$-to-methanol plant, a first of its kind in India is expected to pave the way for larger scale commercial rollouts. Another example is the partnership between Jakson Green and NTPC to build a $CO_2$-to-methanol production plant at the same Vindhyachal site. This facility will convert flue gas $CO_2$ using catalytic hydrogenation and green hydrogen, producing methanol that can be used for

### Why Methanol Makes Commercial Sense for India

Methanol's commercial case in India rests on converging forces: rising global demand for cleaner fuels led by shipping, falling green hydrogen costs that improve methanol economics, and resilient multi-sector demand across fuels and chemicals. As emissions norms tighten at home and abroad, methanol's integration with hydrogen value chains and its versatility as an industrial feedstock are attracting capital. Projects are increasingly structured around long-term offtake, strategic partnerships and export-oriented supply chains, positioning India to serve both domestic markets and low-carbon demand in Asia and Europe.



fuel and product applications.

Large public and private energy players are also positioning methanol within broader hydrogen derivative strategies, supported by international partnerships such as NTPC Green Energy's collaboration with Japan's ENEOS to explore green methanol and related fuels. Projects such as those being developed under the National Green Hydrogen Mission and by private players like Greenko-linked AM Green are creating supply chains that can feed clean hydrogen into methanol synthesis at scale. In addition, methanol is increasingly being integrated into industrial clusters and clean fuels strategies. Several green hydrogen-oriented projects in states like Odisha, which has approved hydrogen, ammonia and methanol projects by players such as ReNew Power's ReNew E-Fuels and Welspun New Energy, illustrate a trend toward ecosystem development where methanol is one of several hydrogen derivatives pursued in tandem.

## Technological Milestones

One of the most significant recent developments in India's methanol landscape has been the successful demonstration of methanol production from captured carbon dioxide at scale. At NTPC's Vindhyachal Super Thermal Power Station in Madhya Pradesh, a project led by NTPC Energy Technology Research Alliance (NETRA) and implemented with technology from companies like Carbon Clean and Toyo Engineering India has begun producing methanol by converting $CO_2$ from flue gas using green hydrogen generated by electrolysis.

This milestone is meaningful on multiple fronts. First, it demonstrates carbon capture utilisation and storage (CCUS) at industrial scale in India, a technology that until recently has been largely theoretical in the country. Second, it validates a circular carbon approach, where emissions from existing power plants are integrated into usable products rather than released into the atmosphere. And third, it lays the groundwork for future commercial scale e-methanol facilities that combine green hydrogen with captured carbon, a prerequisite for realising low-carbon methanol at competitive costs.

The involvement of major energy players such as NTPC also signals strategic intent. NTPC Green Energy has also signed partnerships (such as with Japan's ENEOS) to explore the production and export of green methanol and other hydrogen derivatives, anchoring these initiatives in global demand for alternative fuels.

> **Methanol is a $30–40 billion global market, with annual production exceeding 100 million tonnes. As shipping and fuels drive demand for low-carbon alternatives, green methanol is emerging as one of the fastest-growing segments in the clean-molecule economy**

Complementing carbon capture innovations are broader technological collaborations. For instance, Honeywell and AM Green entered a memorandum of understanding to assess the feasibility of producing green methanol, along with sustainable aviation fuel and green hydrogen, using advanced carbon capture, ethanol feedstocks and clean hydrogen technologies. This collaboration seeks to position India as a global exporter of green methanol, particularly for shipping and aviation sectors, which are under mounting regulatory pressure to reduce emissions.

## Policy Framework

India's policy interest in methanol is most prominently articulated through NITI Aayog's 'Methanol Economy' programme, an initiative designed to reduce crude oil import dependence, lower greenhouse gas emissions and repurpose domestic resources into cleaner fuels and chemicals. Under this plan, methanol produced from coal, agricultural residues, $CO_2$ and other carbon sources can be used across sectors including transport, energy, and industry. The programme highlights methanol's potential to substitute petrol and diesel in transport, distributed energy systems such as generators and boilers, and even retail cooking fuels, while significantly improving air quality and reducing emissions.

The National Green Hydrogen Mission, which aims to scale green hydrogen production to 5 million tonnes annually by 2030, also explicitly includes methanol as a derivative product alongside other molecules such as ammonia. This integration signals government recognition of methanol as a key pathway to absorbing green hydrogen and enabling industrial adoption of hydrogen-based pathways.

At the state level, policies such as Gujarat's new Green Hydrogen Policy 2025 are fostering supportive environments for green hydrogen and associated derivative production, which naturally benefits upstream methanol producers that rely on clean hydrogen inputs.

## Barriers

Despite enthusiasm and strategic alignment, India's methanol journey is not without hurdles. Financing remains a challenge for capital-intensive projects that require significant upfront investment before commercial returns materialise. While policy support exists under broader green hydrogen missions, specific incentives for methanol, particularly green and carbon-derived variants, are still emerging and may need further clarity to unlock institutional capital at scale.

Infrastructure constraints, including needed logistics for methanol storage, marine bunkering and distribution networks, also pose challenges that need coordinated investment and regulation.

Technological scaling, especially for $CO_2$-to-methanol synthesis and integration with intermittent renewable power supplies, remains an active area of innovation, and commercial-scale demonstrations will be critical to validate both cost and reliability at industrial scales.

A Molecule Poised for Growth

In a world looking for transitional molecules that can deliver emission reductions while enabling industrial continuity, methanol's role is set to grow significantly. For India, the methanol opportunity, deeply connected to hydrogen, carbon management and clean fuels, represents not just a way to reduce emissions, but also a pathway to industrial leadership in the emerging global clean molecules economy.

As green hydrogen and carbon capture technologies scale, methanol will increasingly become a bridge between clean energy generation and end-use applications across fuels and chemicals. With expanding global demand for low-carbon alternatives, Indian producers could leverage domestic advantages, notably abundant renewable energy potential and a strong chemicals manufacturing base, to become exporters of clean methanol. Policy evolution that further aligns incentives for methanol production, carbon capture utilisation, renewable integration and export facilitation will accelerate this transition. Corporate commitment to upstream value chains, international collaborations and technology partnerships will also be decisive factors in shaping India's competitive stance

### Key Challenges

**Cost Competitiveness:** Green methanol is currently more expensive than fossil methanol. Scaling production, improving electrolyzer efficiency, and lowering renewable power costs will be crucial to narrowing this gap.

**Infrastructure & Supply Chain Development:** Robust supply chains, from renewable power and electrolyzers to transport and bunkering infrastructure needed.

**Policy and Market Signals:** Clear mandates for blending, incentives for green molecule deployment, and long-term purchase commitments from hard-to-abate industries will be essential to give producers the confidence to invest large capital sums.

# METHANOL: A PRAGMATIC PATHWAY IN INDIA'S ENERGY TRANSITION

Leveraging methanol can help India advance hydrogen adoption, strengthen energy security, and support industrial competitiveness while preserving flexibility in its transition pathway

India stands at a defining moment in its energy journey. With a rapidly growing economy, rising energy demand, and a stated commitment to achieve net-zero emissions by 2070, the country is pursuing a transition that must be ambitious, inclusive, and resilient. Hydrogen is widely recognized as a central pillar of this vision, offering the potential for deep decarbonisation across power, industry, and transport. However, translating hydrogen ambition into scalable deployment requires close attention to infrastructure readiness, cost, and operational realities.

India's target of producing 5 million metric tonnes of green hydrogen annually by 2030 is significant. As the focus now shifts from targets to implementation, the practical challenges of storage, transport, and utilisation become increasingly apparent. Transporting hydrogen from renewable-rich regions such as Tamil Nadu or Rajasthan to demand centres in Maharashtra or Gujarat involves compression, liquefaction, or conversion, each adding cost, complexity, and energy loss.

These constraints do not diminish hydrogen's strategic importance, but they do highlight the need for complementary pathways that can accelerate deployment under current conditions. There is no single fuel or technology capable of meeting India's vast and diverse energy needs on its own. A pragmatic, multi-fuel approach aligned with India's infrastructure, resource base, and industrial structure is therefore essential.

In this context, methanol emerges not as a competing solution, but as an enabling one. Methanol can function both as a hydrogen carrier and as a versatile fuel and feedstock in its own right. Its value lies in making low-carbon molecules usable at scale, sooner, and with lower system disruption. Leveraging methanol can help India advance hydrogen adoption, strengthen energy security, and support industrial competitiveness while preserving flexibility in its transition pathway.

**Prakriti Sethi**
**Chief India Representative**
Methanol Institute

## Methanol as a Bridge and Enabler

Methanol is a globally traded commodity with a diversified consumer base and mature markets. It is already a cornerstone of the chemical industry, supporting the production of downstream products such as formaldehyde, acetic acid, olefins and dimethyl ether (DME). These value chains underpin critical sectors including pharmaceuticals, construction, and manufacturing, all of which already consume methanol at scale. This existing demand base means the transition challenge is one of decarbonising supply rather than creating entirely new markets.

A key advantage of methanol lies in its physical properties. Methanol is liquid at ambient temperature, enabling storage and transport using established infrastructure with minimal modification. With supply chains operating across more than 100 ports globally and well-developed safety standards, methanol offers a level of logistical readiness that few alternative fuels can currently match.

Methanol's strategic value is reinforced by its feedstock flexibility. It can be produced from a wide range of renewable and low-carbon sources, including agricultural and forestry residues, municipal solid waste, biogas, black liquor from pulp and paper production via syngas which is composed of carbon monoxide and hydrogen, and captured carbon dioxide combined with renewable hydrogen. Depending on feedstock and production pathway, renewable methanol can achieve lifecycle greenhouse-gas reductions of up to 95 per cent compared with conventional fuels. It can also significantly reduce nitrogen oxides while virtually eliminating sulfur oxides and particulate matter.

Methanol also plays an important role in addressing renewable-energy intermittency. Power-to-liquid pathways allow surplus renewable electricity to be converted into methanol, effectively storing energy in a transportable and

dispatchable form. This improves the economics of renewable assets and reduces risk for investors, while lowering the infrastructure burden associated with long-distance hydrogen transport. In this way, methanol acts as a practical interface between renewable power generation and end-use demand, helping hydrogen function at scale in real-world systems.

## Supporting Key Sectors of Economy

Beyond its chemical role, methanol has demonstrated versatility across multiple energy applications. It is already used globally as a transportation fuel in low-, mid-, and high-blend gasoline applications, as well as in dedicated engines and as a diesel alternative in heavy-duty vehicles. Methanol's high octane rating enhances engine performance, while its clean combustion enables immediate emissions reductions when used in existing internal combustion engine platforms. This offers a near-term decarbonisation option without waiting for complete fleet turnover.

The maritime sector provides one of the clearest examples of methanol's deployment potential. International shipping accounts for approximately 3 per cent of global $CO_2$ emissions and faces limited decarbonisation options. Methanol has emerged as one of the few alternative fuels already moving from pilot projects to commercial adoption, with container shipping leading early uptake. Orders for methanol-fuelled vessels signal growing confidence in its scalability and long-term relevance.

India's shipping sector presents a particularly relevant opportunity. The Ministry of Ports, Shipping and Waterways has identified alternative fuels as a strategic priority and designated ports such as Deendayal (Kandla), Paradip, and V.O. Chidambaranar (Tuticorin) as green hydrogen hubs to support the production, storage, and bunkering of hydrogen-derived fuels.

Kandla and Tuticorin have begun translating policy intent into action. Kandla port has approved a Rs. 3,500-crore e-project to supply alternative fuels to vessels and awarded a contract for India's first port-based bio-methanol facility. Tuticorin has launched a pilot-scale green methanol bunkering project in collaboration with SOPAN Group, targeting emissions reductions of up to 95 per cent on a lifecycle basis.

> **Studies suggest that a 20% methanol blending mandate in transportation fuels could significantly reduce crude-oil imports, delivering substantial foreign-exchange savings**

Tuticorin has launched a pilot-scale green methanol bunkering project in collaboration with SOPAN Group, targeting emissions reductions of up to 95 per cent on a lifecycle basis

The Sagarmala Programme further supports methanol deployment in inland waterways and short-sea shipping. These routes offer predictable operating patterns and controlled environments, making them well suited for phased fuel transitions. This approach allows India to build technical expertise and infrastructure incrementally, while reducing risk and preparing for broader international deployment.

## Economic Impetus and Opportunity

Methanol also presents a meaningful economic opportunity. India currently imports over 40 per cent of its primary energy requirements, exposing the economy to price volatility and geopolitical risk. Reducing this dependency through domestic fuel production is a central energy-security objective. Studies suggest that a 20 per cent methanol blending mandate in transportation fuels could significantly reduce crude-oil imports, delivering substantial foreign-exchange savings.

India is well positioned to scale domestic methanol production using biomass, agricultural residues, and municipal solid waste. As highlighted by NITI Aayog, India generates approximately 60–65 million tonnes of municipal solid waste annually, a large share of which remains underutilised for productive energy recovery. Converting this waste into methanol can support a circular economy, reduce landfill pressure, and create decentralised value chains while contributing to energy security and emissions reduction.

Cost competitiveness is another important factor. NITI Aayog has noted that domestically produced methanol could be at least 30 per cent cheaper than conventional fuels. For households, methanol-based cooking solutions could reduce annual fuel expenditure by around 20 per cent. Across production, distribution, and end-use applications, a methanol-based ecosystem has the potential to generate significant employment, with estimates suggesting up to five million jobs over time.

## The Road Ahead

Despite these advantages, scaling methanol's contribution will require targeted policy action. The absence of comprehensive regulatory frameworks for methanol as a fuel, limited fiscal incentives, and a lack of large-scale commercial production facilities remain key constraints. Coordination across ministries, clarity on standards and safety, and long-term offtake certainty will be essential.

The foundations of a methanol economy have been outlined for several years, notably by NITI Aayog. What is now required is consistent implementation. The next phase—particularly upcoming budget cycles and infrastructure investment decisions—will be decisive. Choices made today regarding ports, shipping, industrial demand, and fuel standards will shape India's position in the global energy transition.

India has the resources, technical capability, and market scale to become a leader in low-carbon fuels. Realising this potential depends on policy certainty and a recognition that methanol is not a diversion from hydrogen, but a practical pathway that enables hydrogen ambition to translate into commercial reality. With timely and coordinated action, methanol can play a central role in making India's energy transition both achievable and economically sustainable

ICN
INDIAN CHEMICAL NEWS

# SPECIAL INITIATIVES 2026-27

| MONTH | EVENT/COMPENDIUM | CITY |
|---|---|---|
| MAY | CHEMICAL INDUSTRY OUTLOOK 2026 (ANNUAL COMPENDIUM) | |
| MAY 14 - 15 | GUJARAT CHEM & PETCHEM CONFERENCE 2026 | BHARUCH |
| JULY 9 - 10 | NEXTGEN CHEMICALS & PETROCHEMICALS SUMMIT 2026 | MUMBAI |
| SEP 10 - 11 | CHEMICAL & PHARMA R&D SUMMIT 2026 | MUMBAI |
| NOV 20 | AGROCHEM SUMMIT 2026 | NEW DELHI |
| DEC | HYDROGEN INDUSTRY OUTLOOK 2027 (ANNUAL COMPENDIUM) | |

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# GREEN HYDROGEN: BOON OR BANE — INDIA'S HIGH-STAKES CLEAN ENERGY

Big promises, bold investments, and the hard realities of cost, scale, and market demand

TEAM ICN

India's energy transition is at an inflection point. As global climate urgency accelerates and domestic energy security concerns mount, green hydrogen has emerged as a central pillar of the country's aspirations to decarbonise hard-to-abate sectors, reduce dependence on fossil fuel imports, and claim a place in the future global clean-energy economy. The government's National Green Hydrogen Mission (NGHM) has set an ambitious target of producing 5 million tonnes annually by 2030, positioning India as a potential global leader in this segment.

But beneath the enthusiasm lies a complex mix of opportunity and risk. Green hydrogen's promise is vast: it could transform industrial processes, power heavy transport, and anchor a new export economy. Yet the path to that future is steeped in technological, economic, and infrastructural challenges. As India bets big on green hydrogen, the key question is whether it will be a boon that reshapes the country's energy and industrial landscape, or a bane that absorbs capital with limited returns.

## Weighing the Benefits

The global green hydrogen market is projected to expand significantly over the next decade. Estimates suggest that the market could be worth over US$ 400 billion by 2035, up sharply from estimated valuations of US$ ~12–13 billion in 2025, reflecting broad industrial and policy demand for decarbonised fuels and feedstocks.

India's own hydrogen demand, currently dominated by grey hydrogen used in fertilizers and refining, is forecast to nearly double to about 12 million tonnes per year by 2030, driven by growth in fertilisers, petrochemicals, and steel sectors. If green hydrogen substitutes even a portion of this demand, domestic markets could emerge rapidly. Moreover, export demand, particularly to Europe, Japan, and South Korea, could create additional revenue streams for India. Green hydrogen derivatives such as ammonia and methanol are seen as attractive carriers for transporting decarbonised hydrogen to long-haul markets with limited renewable resources.

The benefits of green hydrogen are compelling in several hard-to-abate sectors where direct electrification is either inefficient or impractical. These include heavy industry like steel and fertilizer production, shipping and aviation fuels, long-haul road transport, and high-temperature industrial heat. In contexts where alternatives do not currently exist at scale, green hydrogen offers a technically feasible path to deep decarbonisation.

From a strategic standpoint, expanding renewable energy utilisation into hydrogen allows countries to better absorb and valorise surplus solar and wind generation, particularly in regions where grid storage or additional load is limited. India's achievement of more than 50% non-fossil fuel installed power capacity, led by solar and wind, provides a strong foundation for green hydrogen scaling.

Job creation is another touted advantage. Estimates suggest that India could generate up to 600,000 jobs by 2030 across manufacturing, renewable deployment, hydrogen production, and associated services, underpinning the socio-economic case for green hydrogen development.

Energy security is equally significant. India imports more than 80% of its crude oil needs, a dependence that costs the economy hundreds of thousands of crores annually. Green hydrogen and its derivatives could substitute imported fuels in certain sectors, lowering trade imbalances and enhancing resilience to global price shocks.

### Scale of Ambition

India's National Green Hydrogen Mission targets 5 million tonnes of green hydrogen production by 2030, backed by an estimated Rs 8 trillion in cumulative investment across renewables, electrolyzers and downstream infrastructure. The scale of this ambition underscores hydrogen's potential, and the execution risk.

## The Economic and

## Technical Challenges

Despite the optimism, green hydrogen's path to competitiveness and scale is fraught with challenges that temper the unbridled enthusiasm. The primary hurdle remains cost. Currently, green hydrogen production in India, principally driven by electrolyser and renewable power costs, is significantly more expensive than conventional grey hydrogen derived from fossil fuels. Estimates put green hydrogen prices at nearly twice or more than those of grey hydrogen, and at several times the cost of hydrogen derived from steam methane reforming.

Electrolyser technology, which is core to green hydrogen, still relies heavily on imported components, advanced materials and proprietary systems, leaving India's nascent manufacturing ecosystem vulnerable to global supply chain dynamics. Although the government has awarded domestic electrolysis manufacturing capacity, large-scale industrial localisation will take time and capital to mature. Infrastructure presents another major hurdle. Unlike electricity, hydrogen requires specialised storage, transport and refuelling networks. Pipelines, cryogenic facilities, and safety-verified distribution systems remain largely absent at commercial scale. Building these systems requires massive upfront investment and regulatory frameworks that are still under development.

Water scarcity is an often-overlooked constraint. Producing green hydrogen with electrolysis consumes large volumes of ultra-pure water, straining resources in water-stressed regions such as Rajasthan and Gujarat, which are also prime locations for renewable energy generation. Financing remains another sticking point. High capital costs and uncertain long-term demand reduce bankability. Offtake agreements are typically shorter (five to seven years) than the expected asset life of hydrogen infrastructure (20–30 years), creating risk mismatches for investors. Without stronger demand signals, such as mandated utilisation quotas or carbon pricing, project financiers remain cautious. Indian solar and wind capacity utilisation, measured by plant load factors, also lags behind global leaders, reducing electrolysers' effective operating hours and increasing the cost per kilogram of hydrogen produced.

### Cost Reality Check

Green hydrogen in India currently costs around \$3–4 per kg, compared with \$1–1.5 per kg for fossil-based hydrogen. While falling renewable and electrolyzer costs could narrow the gap by the end of the decade, economics remain highly sensitive to policy support and utilisation rates.

| Strategic Upside | Structural Challenge |
|---|---|
| **Leverages India's low-cost solar and wind power to produce competitive green hydrogen** | **High capital costs for electrolyzers and associated infrastructure slow early adoption** |
| **Reduces dependence on imported fossil fuels and grey hydrogen** | **Green hydrogen remains costlier than fossil-based alternatives without policy support** |
| **Enables decarbonisation of hard-to-abate sectors such as steel, fertilizers, and refining** | **Demand creation is policy-led and may weaken if incentives are withdrawn** |
| **Positions India as a potential exporter of green hydrogen derivatives like ammonia and methanol** | **Global markets are uncertain and shaped by subsidies in the US and Europe** |
| **Catalyses domestic manufacturing of electrolyzers under Make in India and PLI frameworks** | **Strong competition from low-cost Chinese electrolyzer manufacturers** |

## Long-Term Implications

If India successfully navigates the above challenges, the long-term implications are profound. Meeting or exceeding the 5 MMT target could position India as a major international hydrogen supplier, capturing a share of the growing global market. Beyond exports, decarbonising domestic heavy industry could reduce emissions significantly and help India meet its long-term climate commitments under the net-zero by 2070 objective.

A mature green hydrogen ecosystem could also stimulate technology innovation and industrial capability, fostering new centres of excellence in electrolyser manufacturing, fuel cell systems, and hydrogen logistics. This industrial development could spill over into adjacent technologies such as battery storage, carbon capture, and advanced renewables. There are geopolitical implications too. Energy independence offers strategic autonomy in international dealings, reducing vulnerability to volatile oil and gas markets. Exporting green hydrogen or derivatives would enhance India's economic partnerships with energy-importing countries in Europe and East Asia.

However, failing to scale economically sound green hydrogen could also have repercussions. Overinvestment in green hydrogen without robust demand or competitive cost structures could divert capital from other effective decarbonisation strategies such as direct electrification, energy efficiency, or bioenergy, approaches that currently deliver greater emissions abatement per rupee spent.

## Way Forward

Green hydrogen in India stands at the crossroads of ambition and realism. The country's strategic policy framework, renewable energy base, and industrial drive offer a fertile environment to pioneer new energy solutions. Industry, capital and global partnerships have begun to rally behind this vision, setting in motion projects that could reshape India's energy and industrial landscape.

Yet significant economic, technical and infrastructural hurdles remain. The high cost of production, reliance on imported technology inputs, nascent infrastructure and financing gaps present real risks that could slow progress or constrain the impact of investments.

Whether green hydrogen proves to be a boon or bane for India will depend not just on technologies and policies, but on the ability of the government, industry and capital markets to align incentives, create durable demand and build the ecosystems necessary for long-term viability. If India successfully surmounts these challenges, it could emerge as a global green hydrogen powerhouse. If not, it risks a high-stakes gamble with limited returns, a cautionary tale for other emerging economies chasing the same clean energy dream

# IMPORTANCE OF HYDROGEN AS A FUEL FOR DECARBONISING THE STEEL INDUSTRY

Hydrogen and green electricity have emerged as the most viable and scalable alternatives for deep decarbonisation of steelmaking

The steel industry is one of the largest industrial sources of global $CO_2$ emissions. It is estimated that more than 7 per cent of global $CO_2$ emissions originate from steel production, primarily due to the manufacture of steel from virgin raw materials using carbon-intensive processes. Traditionally, ironmaking relies on coke, coal, natural gas, and other fossil fuels, which serve both as a source of energy and as chemical reducing agents..

As a result, conventional steelmaking routes generate substantial carbon dioxide emissions, typically in the range of 2.2 to 3.0 tons of $CO_2$ per ton of crude steel, depending on plant configuration, fuel mix, and operating efficiency.

The global steel industry is now actively exploring ways to significantly reduce $CO_2$ emissions while maintaining production efficiency, product quality, and cost competitiveness. At present, most primary steel production is carried out through the Blast Furnace–Basic Oxygen Furnace (BF–BOF) route, which is inherently carbon intensive.

**V. R. Sharma**
**Vice Chairman**
Naveen Jindal Group (Jindal Steel)

> **The future competitiveness and sustainability of the steel industry will increasingly depend on its ability to adopt hydrogen-based ironmaking and green electrified production routes**

To reduce dependence on fossil fuels and free carbon, hydrogen and green electricity have emerged as the most viable and scalable alternatives for deep decarbonisation of steelmaking.

## Role of Hydrogen and Green Energy in Steelmaking

### Role of Hydrogen

Hydrogen can act as a clean and effective reducing agent in ironmaking. When hydrogen is used to reduce iron ore, the by-product is water vapour instead of carbon dioxide, making the process inherently low-carbon. This principle forms the basis of Hydrogen-based Direct Reduced Iron ($H_2$-DRI) technology, which is gaining global momentum.

Currently, two major commercial DRI technologies are leading this transition: MIDREX DRI Technology and Tenova-Danieli Energiron DRI Technology.

Both technologies are capable of operating with high hydrogen concentrations and, ultimately, 100 per cent hydrogen, and claim high metallisation rates, operational flexibility, and improved energy efficiency.

### Role of Green Electricity

Green electricity, generated from renewable sources such as solar, wind, and hydropower, plays a critical role in hydrogen-based steelmaking by:

- Producing green hydrogen through

> When hydrogen is used to reduce iron ore, the by-product is water vapour instead of carbon dioxide, making the process inherently low-carbon

water electrolysis
- Supplying clean power to Electric Arc Furnaces (EAFs), where green or low-emission DRI is melted
- Electrifying downstream processes such as rolling mills, finishing lines, and auxiliary systems

The availability of low-cost renewable electricity is therefore a key enabler for large-scale steel decarbonisation.

## Decarbonisation Potential

By adopting hydrogen as the primary reducing agent and replacing fossil-fuel-based energy with green electricity, the steel industry can:
- Eliminate up to 80% or more of fossil-fuel-derived carbon usage
- Achieve deep reductions in CO2 emissions
- Move closer to net-zero steel production, with CO2 emissions reduced to below 0.50 tons of CO2 per ton of finished steel.

## Conclusion

Hydrogen, supported by renewable electricity, represents a transformational solution for decarbonising the steel industry. While challenges remain related to cost, infrastructure development, and large-scale hydrogen availability, the transition away from fossil fuels is both technically feasible and environmentally imperative.

The future competitiveness and sustainability of the steel industry will increasingly depend on its ability to adopt hydrogen-based ironmaking and green electrified production routes.

Several large-scale projects currently under installation worldwide are expected to establish clear and replicable decarbonisation pathways for the global steel industry, including: Jindal Steel, Oman; Stegra (formerly H2 Green Steel), Sweden; ThyssenKrupp Steel, Germany; and Salzgitter AG, Germany.

Once commissioned, these plants will serve as benchmark projects, demonstrating the technical and commercial viability of hydrogen-based steelmaking.

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