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WORLD ECONOMIC FORUM

Green Hydrogen: Enabling Measures Roadmap for Adoption in India

INSIGHT REPORT

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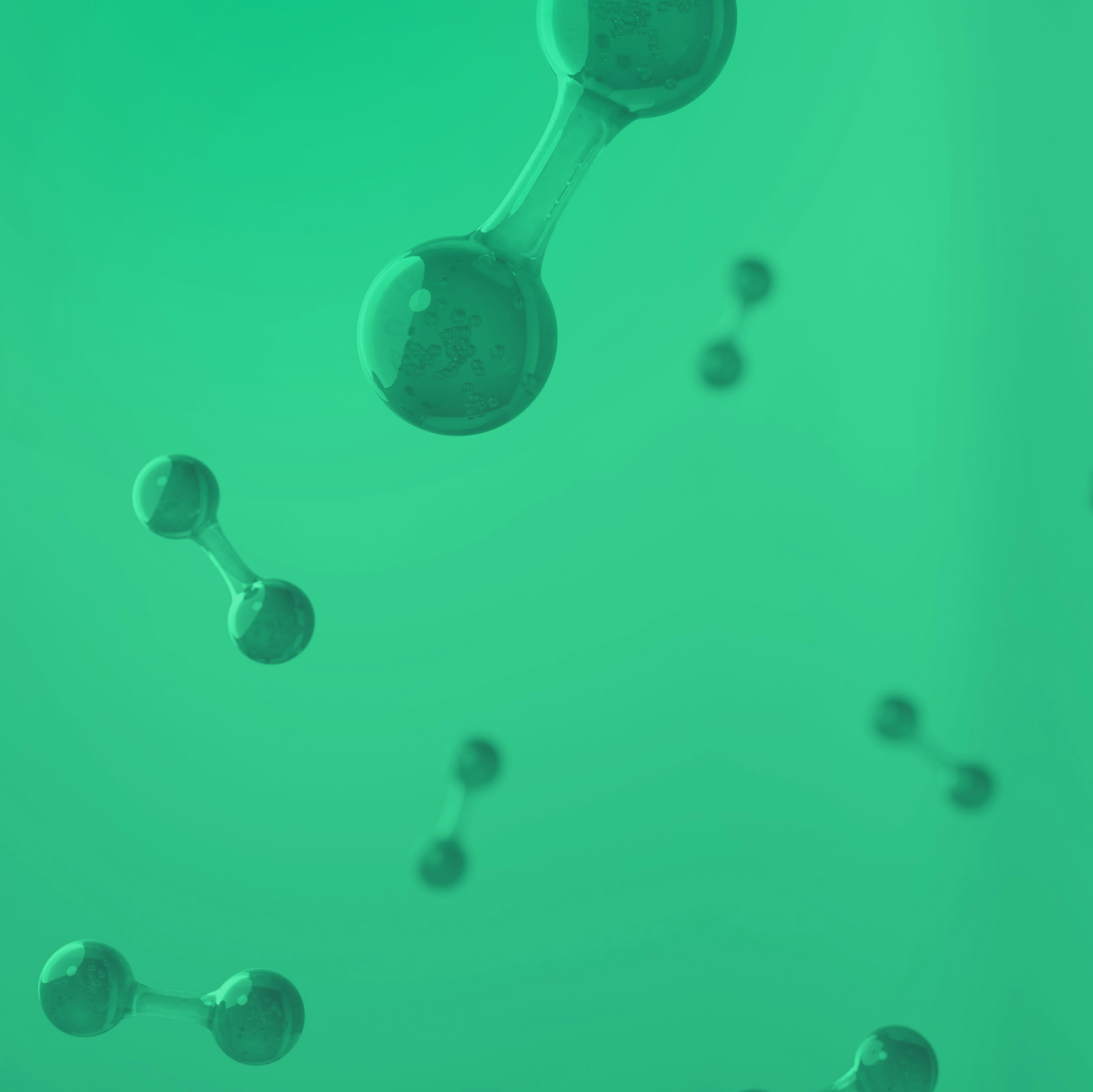

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Foreword

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Greener energy pathways are needed if India hopes to reduce its carbon emissions and achieve its net-zero goals for the future. Recently, green hydrogen has emerged as one of the country's most viable clean energy alternatives.

Green hydrogen is produced through the electrolysis of water. Unlike grey hydrogen production, which typically involves the combustion of carbon, green hydrogen production creates no harmful greenhouse gas (GHG) emissions. It uses renewable energy sources, such as solar and wind power, to supply its energy demands, making it a cleaner alternative at every stage of production.

A novel, innovative source of clean energy, green hydrogen can be harnessed to run industrial processes, charge municipal power grids and provide clean fuel sources for various modes of transport, including aviation and marine shipping.

Recognizing green hydrogen's potential, India has embarked on an ambitious goal to produce at least 5 million tonnes of green hydrogen by 2030 through its National Green Hydrogen Mission, launched in 2022.

Developing a green hydrogen ecosystem over the next few years presents a once-in-a-lifetime opportunity for India to address its growing energy needs, meet its goals for decarbonization and set the foundation for a potential energy export market. Widespread adoption of green hydrogen can be encouraged through timely early-stage interventions.

A crucial element in harnessing hydrogen's potential lies in ensuring substantial renewable energy production. India possesses abundant renewable energy resources, especially solar. The country can work to develop a thriving green hydrogen ecosystem by building this renewable energy capacity at the right speed.

To accelerate large-scale green hydrogen adoption, Indian stakeholders can also work to control the operational costs, including those related to the necessary renewable energy and electrolyser technology. Furthermore, they can promote incentives, both to support infrastructure for green hydrogen storage, transmission and conversion, and to encourage demand for green hydrogen.

This report provides a comprehensive roadmap for India's green hydrogen economy. Drawing inspiration from green hydrogen efforts already under way in the European Union, Japan and China, India can adapt best practices that are ideally suited to its unique national context.

Written as a collaborative effort between the World Economic Forum and Bain & Company, the findings in this report are informed by extensive interactions with stakeholders and experts, who provided on-the-ground insights into the current status of India's burgeoning green hydrogen economy. Information included in this report is current as of October 2023 and may not reflect developments that occurred after that time.

Executive summary

Green hydrogen can enable energy transition as India takes its net-zero journey towards 2070, while supporting its growing energy needs.

India is currently the third-largest economy in the world in terms of energy needs, and the country's demand for energy is set to surge – demand is estimated to grow 35% by 2030.[1] In 2022, India's energy import bill was $185 billion,[2] a figure that is sure to rise if the country continues to supply its growing energy demand through traditional methods.

At the same time, India set a commitment to achieve net zero by 2070 at the United Nations Climate Change Conference in Glasgow (COP26), held in 2021. At the Glasgow summit, India's prime minister, Narendra Modi, said: "Today the whole world believes that India is the only big economy which has delivered both in letter and spirit on the Paris commitment. We are making every effort with determination."[3]

Green hydrogen is critical to help meet India's energy security needs while reducing emissions in hard-to-abate sectors on the path to net zero. Recognizing this, the Indian government launched the National Green Hydrogen Mission in early 2022. The aim is to spur green hydrogen production and consumption through roughly $2.3 billion in incentive funding, to be distributed between 2022 and 2030.[4]

Currently, India produces 6.5 million metric tonnes per annum (MMTPA) of hydrogen, predominantly for use in crude-oil refineries and fertilizer production. Most of the country's current hydrogen supply is grey hydrogen, which is produced using fossil fuels in a process that creates CO_2 gas emissions.

The National Green Hydrogen Mission set a target for the production of 5 MMTPA of green hydrogen by 2030 — equivalent to roughly half of India's projected overall hydrogen demand of 11 MMTPA at that time. Green hydrogen production requires an ample supply of renewable energy for the electrolysis process. Fortunately, India's renewable energy potential can support its goals for green hydrogen growth but needs rapid capacity addition – additional capacity is required to generate green hydrogen as well as to meet the country's electricity needs. The country's solar energy potential alone is estimated at 748 gigawatts (GW) at full capacity.[5] Currently, total installed solar capacity in India sits at 70GW, or 9% of its total potential.

However, there is limited on-the-ground traction for green hydrogen in the country, and interviews with important players indicate that most are in a "wait-and-watch" phase. Many expect sizeable production of green hydrogen to take effect beginning in 2027 and after.[6]

Important constraints for the expansion of green hydrogen in India include, on the supply side, the cost of production and delivery, and, on the demand side, Indian players' readiness to consume green hydrogen in traditional industrial processes.

Supported by in-depth analysis of cost and demand drivers of green hydrogen, as well as interviews with industry players and government agencies, this report proposes five goals that, if met, can accelerate the offtake of green hydrogen in India. These goals can provide impetus to the green hydrogen demand-and-supply ecosystem by aiming to achieve the following:

- On the supply side, a cost of $2/kg of hydrogen to reach cost-parity with grey hydrogen
- On the demand side, enabling end industries to offtake green hydrogen by creating incentives for its use

Blueprint for the evolution of green hydrogen in India

Building a green hydrogen ecosystem in India requires a targeted approach, building on the National Green Hydrogen Mission.

FIGURE 1 **Key goals and recommendations to accelerate a green hydrogen ecosystem in India**

Supply

Landed cost of green hydrogen needs to be less than or equal to $2/kg (parity with grey hydrogen)

1 Landed cost of **round-the-clock** (RTC) **renewable energy** (RE) to be lower than INR 2 (~$0.02)/kWh; support rapid decrease in **electrolyser costs**

Minimize **cost of landed RTC RE**

- **Cost of storage:** Reduce through monetary incentives
- **Banking accessibility:** Make available across the country and clarify norms/processes
- **Transmission and distribution charges:** Reduce intrastate/wheeling charges across all states (only for select few currently)

Rapidly bring down **electrolyser cost**

- **Subsidies:** Increase quantum for early adopters ($50/KW insufficient)
- **Capex IRR:** Increase duration of incentives, beyond five years for the much longer capex cycle of electrolysers
- **Tech discovery:** Encourage R&D for electrolyser tech suitable for India (e.g. AEM, SOEC)

2 Eliminate or reduce the cost of **conversion/reconversion, transportation and storage**

Optimize **conversion costs**

- **R&D:** Create incentives to develop R&D/pilots for local tech

Reduce **transportation costs**

- **Pipelines:** Finance creation of hydrogen pipelines in the long term

Reduce **storage costs**

- **R&D:** Create incentives to develop R&D/pilots for local tech (e.g. type 3 and 4 cylinders)

Clusters: Encourage collaboration between peers so that production and offtake takes place in clusters; this minimizes the need for enabling infrastructure

Allow/encourage companies to form clusters and bid for PLIs/other incentive schemes

Benefits such as quick clearances for clusters

Share success stories through a national platform

Demand

Demand to be enabled by supporting industries in the short term and disincentivizing carbon-intensive alternatives in the long term

3 Enable domestic demand through a **staggered approach of supporting end-user industries**

1. **Greening existing hydrogen users** (refining, fertilizer)
   - Increase **direct subsidy** ($0.50/kg is insufficient for early adopters)
   - Institute strategic **demand-side mandates** (balance the volume of green hydrogen while factoring in economic considerations)
2. **Adoption across industrials** (steel, cement)
   - Provide **CapEx support** (e.g. faster depreciation, discounted land)
   - **Launch standards** for green hydrogen by-products (e.g. green steel)
   - Support in **energy tech migration**
3. **Greening transportation** (HDVs, maritime, aviation)
   - Launch **standards** (e.g. for fuel cell)
   - Support **R&D** and pilots
4. **Energy** (power, cement)
   - Support **R&D and pilots** for blending with existing energy

4 Capitalize on **India's export potential**

- **Standards:** Work with other countries/global organizations to develop harmonized global standards (and/or the ability to certify green hydrogen made in India according to importers' norms)
- **Export infrastructure:** Develop conversion and storage facilities at ports
- **Export economy:** Convene MoUs/bilateral agreements with potential importers to enable export from India

5 **Disincentivize carbon-intensive alternatives** such as natural gas

- **Divert subsidies for carbon-intensive fuels** to support green hydrogen
- Enable **carbon tax/ carbon credits** mechanism and use the collections to fund energy transition pathways

Source: 20+ interviews with industry players and Indian government agencies; Bain & Company analysis

Goal 1: Reduce the cost of producing green hydrogen to less than $2/kg

Green hydrogen today costs roughly $4–5/kg to produce in India, approximately double the production costs for grey hydrogen.[7] The majority of production costs for green hydrogen (50–70%) are driven by the need for round-the-clock (RTC) renewable electricity. The remaining 30–50% are electrolyser costs. Green hydrogen needs to come down to a benchmark goal of $2/kg for a green energy ecosystem to develop in India. In terms of energy production, that equates to a renewable energy cost of less than or equal to INR 2 (~$0.02)/kWh.[8]

In the future, some green hydrogen production costs could be offset by renewable energy incentives and tariffs. For example, the Solar Energy Corporation of India (SECI) – an organization under the Ministry of New and Renewable Energy that facilitates renewable energy capacity development – recently achieved a cost of INR 2.6 (~$0.03)/kWh through standalone solar and wind tender tariffs,[9] while tenders for RTC renewable energy stand at INR 4–4.5 (~$0.05–0.06/kWh).[10] Renewable energy generation costs are expected to continue to decrease as India adds more scale and as the technology continues to evolve. Additional interventions can further reduce the cost of electricity storage and intra-state distribution and wheeling (general distribution) charges.

Meanwhile, electrolyser costs can also be reduced significantly with scale and innovation. Various players have reported plans for production capacity of 8GW,[11] far below the baseline requirement of 35–40GW required to meet the 5 MMTPA green hydrogen target by 2030. To meet that target, stakeholders may wish to make several essential interventions to rapidly increase electrolyser production capacity. These include:

- Increasing direct subsidies for early adopters – for example, the USA has announced, under the Inflation Reduction Act (IRA), a tax credit of up to $3/kg of hydrogen.[12]
- Supporting long capital investment cycles for technologies with long-term clarity on policies and incentives
- Encouraging the development and testing of indigenous electrolyser technology

Goal 2: Reduce or eliminate costs related to green hydrogen conversion, storage and transport

Even with low production costs, infrastructure demands – including facility costs for conversion and reconversion, storage and transport – could have a significant impact on the landed cost[13] of green hydrogen and its derivatives.

Minimizing the costs of establishing this infrastructure, wherever possible, will reduce delivery costs and increase offtake. Essential interventions to achieve this are:

- In the short to medium term, developing green hydrogen production clusters where a collaborative environment for production and offtake occur in close proximity
- Investing in long-term infrastructure construction, including pipelines for transporting green hydrogen throughout the country – for example, the European Union's European Hydrogen Backbone programme aims to develop a pipeline network in the EU[14]

Goal 3: Support industries that are most likely to adopt green hydrogen

Certain industries are better positioned than others to embrace green hydrogen consumption. Incentives, subsidies and other support mechanisms should target likely adopters to increase India's domestic demand for green hydrogen. Chief among these are existing grey hydrogen users. Stakeholders can support domestic green energy demand among users of grey hydrogen by increasing direct subsidies. This will reduce green hydrogen costs in the short term and encourage long-term demand for the new energy source.

Stakeholders can also boost demand for green hydrogen for transportation (specifically, heavy-duty and commercial vehicles), energy and other industries through targeted initiatives, including:

- Establishing long-term policy clarity to support investment cycles – for example, the EU has set demand-side mandates until 2035 for using green hydrogen[15]

- Creating financial and administrative support for research and development (R&D) and pilot programming

- Publishing clear standards and providing targeted, measurable direction for future R&D programmes (such as those involved in green hydrogen derivative use)

Goal 4: Capitalize on India's export potential for green hydrogen derivatives

Global variance in landed green hydrogen costs provides an emerging opportunity for international trade in green hydrogen derivatives in a (currently) non-regulated trade market. In this climate, India has the potential to become a green hydrogen derivative export hub. It has relatively low-cost renewable energy, a skilled workforce and abundant land for renewable energy expansion. Indian exporters should capitalize on this natural advantage. In the short term, they can attract a high value (higher than domestic markets) for their green hydrogen derivatives through exports. This will support scale in green hydrogen infrastructure over time.

Stakeholders can further capitalize on India's export potential by:

- Creating a set of globally recognized standards for green hydrogen derivative export, which could ensure the right product quality for interested importers

- Improving export infrastructure at ports, including the creation of bunkering facilities

- Convening bilateral agreements with potential import countries

Goal 5: Disincentivize carbon-intensive alternatives

While incentivizing adoption of green hydrogen is critical, the ecosystem can also be supported by disincentivizing energy sources that are more carbon-intensive. To effectively fund a green transition in India, stakeholders could divert subsidies on high-emission energy sources while ensuring citizen's basic energy needs are met. Doing so will make the relative economics of green energies more viable. Specifically, local, regional and national governments in India might consider diverting their current spending on fossil-fuel subsidies to new projects that support green hydrogen production and infrastructure-building, while ensuring energy affordability does not change materially for the domestic population (for example, Europe has included green hydrogen under the Emissions Trading System).[16] Further, governments can consider a comprehensive carbon-tax regime with the intention of using assessed funds to support green energy transition.

If met, these goals can help develop and mature India's green hydrogen ecosystem and facilitate green hydrogen's role in helping the country meet its decarbonization targets.

The following sections take a more detailed look at the specific challenges affecting each goal and recommend strategies to overcome them.

The case for green hydrogen

Tension between energy supply and climate change presents a global problem of enormous scale and complexity. Green hydrogen can help address this tension.

Energy is fundamental to human well-being. But the largest energy sources, fossil fuels, are also the largest sources of human greenhouse gas (GHG) emissions, which cause global warming. Warming presents risks over time, such as rising sea levels and an increase in the frequency and intensity of extreme weather. Solely addressing climate considerations could jeopardize access to reliable, affordable energy in the developed and developing world. Conversely, addressing access to energy without considering the impact on the climate will worsen the adverse effects of human-induced climate change in the future. This tension between energy supply and climate change presents a global problem of enormous scale and complexity.

Hydrogen produced through the electrolysis of water, powered by renewable energy – green hydrogen – is a clean, flexible and versatile energy carrier that can help address this tension. Its properties (chemical reactiveness, heat replacement, energy storage, conversion to electricity) make it suitable for a range of applications. Some of these are:

- Industrial feedstock: chemical feedstock in industrial processes in oil refineries, ammonia and methanol production, direct reduction of iron in steel and as input in other general industries
- Transport: to power fuel cells in long-distance and heavy transport (for example, heavy-duty vehicles, buses)
- Power and heat: hydrogen's long-term potential as a source of industrial energy for heat generation for industries in need of medium-to-high heat (>250–300°C)

Given its versatility, green hydrogen is critical to address energy access and energy security needs, particularly in a nation dependent on energy imports, such as India, while at the same time helping the world achieve its decarbonization targets. Consequently, the green hydrogen economy has seen a significant impetus in the past two to five years, driven by governmental initiatives. For example, the US government has announced several incentives to accelerate the switch to clean energy projects, including green hydrogen:

- In 2023 a $7 billion grant was awarded to seven regional clean hydrogen hubs to accelerate deployment of green hydrogen in the country
- The 2022 Inflation Reduction Act (IRA) includes a climate package that provides around $369 billion in incentives to reduce the cost of clean energy projects
- In 2021 the Department of Energy introduced the Bipartisan Infrastructure Law, including $9.5 billion in clean hydrogen initiatives
- In 2020 the Department of Energy established the Hydrogen Program Plan, a strategic framework that incorporates research, development and demonstration efforts to advance the production, transport, storage and use of hydrogen in different sectors of the economy

India, too, under the National Green Hydrogen Mission 2022, has set up incentives worth $2.3 billion.

FIGURE 2 | **Key provisions in the National Green Hydrogen Mission**

Overview of National Green Hydrogen Mission

- Clearly articulated targets for production of 5 MMTPA of green hydrogen by 2030
- $2.3 billion planned outlay as part of National Green Hydrogen Mission, of which $2.1 billion is committed to SIGHT programme for incentivizing green hydrogen production

SIGHT programme ($2.1 billion)

Direct green hydrogen incentive
($1.6 billion)

Direct production incentive up to **$0.5/kg** hydrogen for three-year period

Scheme deployment period: **financial years 2026–2030**

Electrolyser production-linked incentive
($0.5 billion)

Base incentive at **$54/kW** in Year 1 to taper to $18/kW by Year 5

Scheme deployment: **financial years 2026–2030**

Other initiatives ($0.2 billion)

$0.15 billion outlay on pilot projects

$0.05 billion committed for R&D

Enabling measures

Cost reduction

25-year waiver on renewable energy interstate transmission charges

Export infrastructure

Port authorities to provide land for **storage bunker** set-up

Other incentives

Renewable energy consumed for green hydrogen production included in **RPO compliance** of consumer

Note: Strategic interventions for Green Hydrogen Transition (SIGHT) programme under the National Green Hydrogen Mission; RPO: renewable purchase obligation (RPO) is the requirement mandated by central/state regulatory commission

Source: NITI Aayog; RMI analysis; Bain & Company analysis; Indian government websites (e.g. Government of India, Ministry of Petroleum and Natural Gas – MoPNG); literature search

Using green hydrogen to meet half the country's hydrogen demand by 2030 alone can abate at least 50 MMTPA of greenhouse gases,[17] while reducing dependence on energy imports.[18] The abatement could be even higher if green hydrogen is used in new use cases. Thus, green hydrogen provides a credible pathway for India to achieve its decarbonization goals, while addressing energy access and security requirements.

Goal 1

Reduce green hydrogen production costs

Reducing renewable energy and electrolyser costs can help make green hydrogen production cost-effective.

Green hydrogen currently costs about $4–5/kg to produce in India. That is at least twice as much as the cost of producing grey hydrogen. The Indian government currently provides subsidies of up to $0.50/kg to help offset the higher cost of green hydrogen[19] (additional subsidy of $54/kW also provided for manufacturing electrolyser). In spite of the subsidy, however, high production costs are limiting green hydrogen's adoption potential in India. To achieve effective scale and widespread adoption, green hydrogen needs to reach a net price of $2/kg or lower.

Green hydrogen production costs are expected to decline naturally as adoption increases, thanks to both economies of scale and efficiencies gained from technological improvements. Until the benchmark price target of $2/kg is achieved, however, policy support will be essential to encourage adoption.

Currently, two main drivers dictate green hydrogen production costs:

– Landed RTC renewable energy electricity costs, which account for approximately 50–70% of green hydrogen costs

– Electrolyser costs, which constitute 30–50% of total green hydrogen production costs

In India, the lowest discovered price for landed RTC renewable energy is at least INR 4–4.5 (~$0.05–0.06)/kWh. The price can go much higher, though, depending on the operating parameters of the renewable energy power plant, such as storage technology, location, etc.

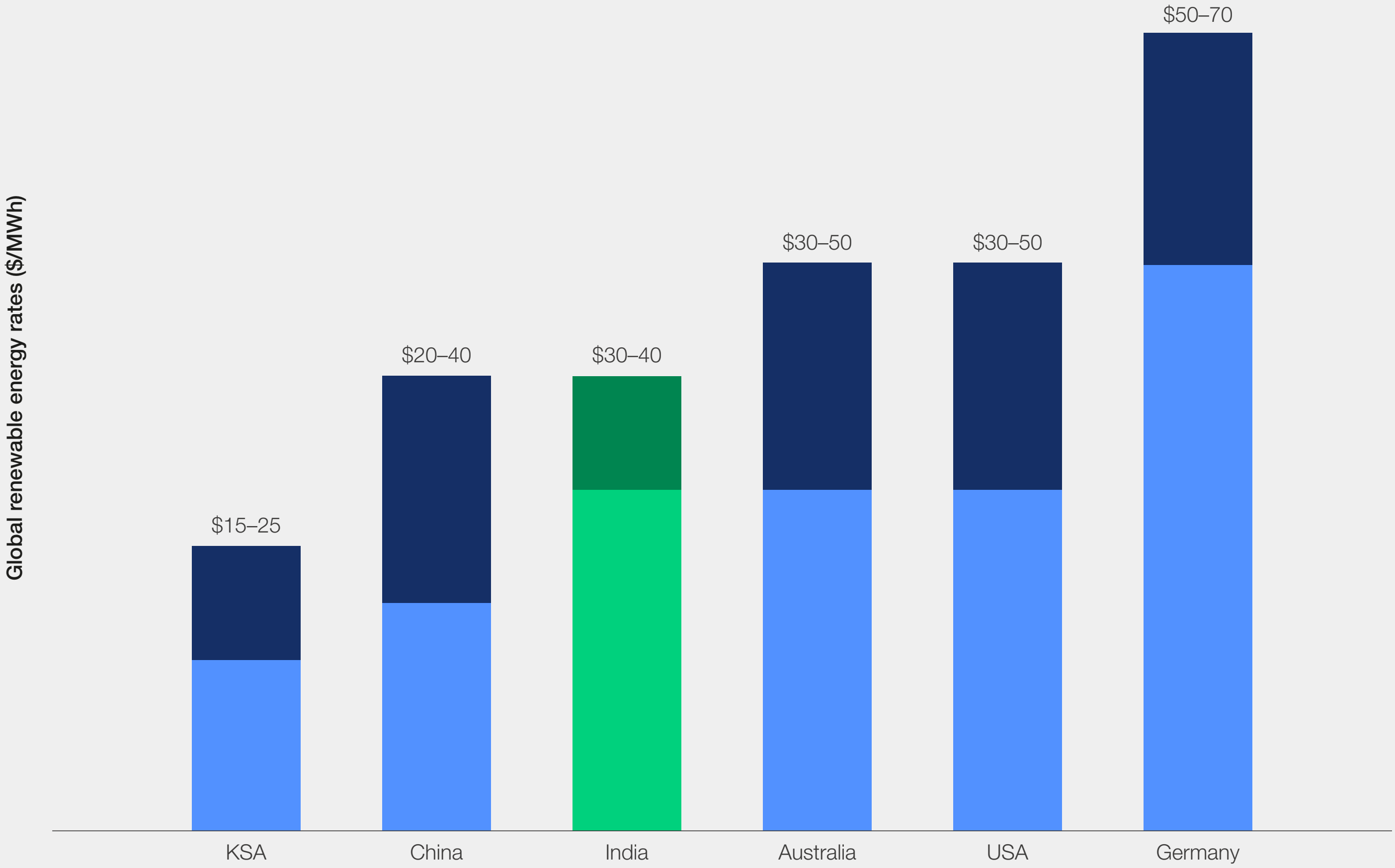
Essentially, renewable energy costs are driven by three main factors: generation, transmission and distribution (T&D) and storage.

Generation costs

Generation accounts for roughly 40% of total renewable energy costs and is the largest single driver of expense when considering green energy alternatives.[20] India already enjoys an average renewable energy cost that is below several other leading international producers, including Germany, the USA and Australia (Figure 3). As it works towards its bold 2030 target, India's renewable energy production costs are likely to fall even lower.

FIGURE 3 **Average renewable energy costs for leading international producers**

India is relatively cost-competitive globally in renewable energy



Note: Benchmarks indicate average renewable energy costs across countries as per various interviews with industry experts.

Source: International Energy Agency, *India Energy Outlook 2021*; expert interviews

Over the past decade, India's renewable energy generation costs have declined significantly. For example, in 2010, it cost roughly INR 11 (~$0.1)/kWh to produce electricity from solar energy in the country. As of 2023 that price has fallen to INR 2.6 (~$0.03)/kWh. This marked decrease can be credited to multiple interventions, such as a demand-side mandate in the form of renewable power obligations (RPOs) and advances towards a nationalized, connected energy grid.[21] To bring these costs down to the target of INR 2 (~$0.02)/kWh, stakeholders might consider interventions to reduce the capital costs associated with setting up renewable energy plants. Capital expenditure costs account for at least 90% of wind and solar energy generation costs currently.[22] Interventions that can effectively reduce capital costs include direct capital cost subsidies, goods and services tax (GST) waivers, reduced land fees and stamp duty waivers, among others. For example, GST exemptions on solar panels (currently taxed at 12%) can reduce the cost of electricity generation by 10%.

Storage costs

Storage accounts for roughly 30–40% of total RTC renewable energy costs. In India, best-in-class renewable energy plant load factors are 40%. Production of energy through renewable sources is intermittent and varies due to weather conditions, topography of the location and many other factors. Green hydrogen production requires a steady source of energy – storage systems such as batteries and pumped hydro can alleviate these intermittency issues and enable green hydrogen production. However, these facilities are not currently operating at scale, and their costs are not optimal. Interventions are needed to increase capacity and reduce costs.

Transmission and distribution costs

Transmission and distribution demands account for the final 20–30% of renewable energy costs. Renewable energy-rich states in India are often located far away from industries. For example, in northern India, Rajasthan has the highest installed capacity of solar power, but it is relatively distant from important manufacturing centres such as the Mumbai–Pune industrial hub.

Transmitting power is easier and more cost-effective than transporting hydrogen over long distances. Thus, most hydrogen plants are being planned near offtake locations, such as refineries and steel plants. To power them, industry leaders are transmitting renewable energy from other parts of the country. As a result, the transmission and distribution costs associated with renewable energy can add up to as much as 60% of the generation costs. These costs also vary widely. They are determined by factors such as the frequency of transmission loss, the cost of using state grids and fixed fees from state distribution companies. Interventions are needed to reduce and streamline these costs throughout the country.

1.1 High cost of RTC renewable energy

Due to the intermittent nature of renewable energy, green hydrogen production plants need energy storage systems (ESS) to ensure a stable power supply for their operations. Existing ESS are costly and drive up the cost of RTC renewable energy, as is evident from costs discovered in the most recently launched national tenders, including ESS (Figure 4).

FIGURE 4 **RE + ESS costs of various energy tenders**

Parameters	SJVN	SECI Peak Power-1	SECI Peak Power-2	RUVNL Peak Power 2
Project capacity	1,500 MW	1,200 MW	1,200 MW	1,200 MW
Technology mix	RE + ESS	RE + ESS	RE + ESS	Solar + ESS
Lowest tariff discovered (INR/kWh)	4.38	6.12/4.04	4.64	6.68
Present status (as of November 2023)	Bidding complete	PSA signed	Awarded	Awarded

Notes: PSA = power sale agreement; the two prices are peak and average – for example, for SECI Peak Power-1 contract, peak hourly tariff was INR 6.12/kWh, while off-peak was INR 2.88/kWh. The average tariff was INR 4.04/kWh.

Sources: Public filings of government agencies, including NTPC, formerly known as National Thermal Power Corporation; SECI, Solar Energy Corporation of India; SJVN, formerly known as Satluj Jal Vidyut Nigam; MSEDCL, Maharashtra State Energy Distribution Company Limited; GUVNL, Gujarat Urja Vikas Nikat Limited

Enabling measure: Reduce the cost of energy storage systems rapidly

To address this added expense, stakeholders could invest in incentives to reduce the cost to build and use ESS throughout the country. This can be achieved with interventions that target the three most widely used storage technologies: 1) banking; 2) battery energy storage systems (BESS); and 3) pumped storage hydropower (PSH).

Banking

"Banking" allows a renewable energy source to bank, or store, surplus power with the grid during the day and withdraw power from the grid at night at no additional cost. This process enables grids to reduce thermal plant use in the day, which reduces GHG emissions. The grid then supplies thermal power at night in exchange for the renewable power supplied to the grid during the day.

Banking does not incur additional capital costs. States such as Maharashtra and Gujarat, which receive surplus solar and wind energy, have developed systems for banking renewable energy.[23] However, these facilities are not available throughout the country. "While banking facilities are provided in policy, there is lack of clarity on the mechanism of banking about cost, physical infrastructure and capacity," a leading steel manufacturing executive said. To make banking available in every state throughout the country, greater clarity on the banking process is needed, including precise details on facility and ownership costs, banking capacity, award mechanisms and the processes for renewable energy certification, among other issues.[24]

Battery energy storage system (BESS)

India projected its BESS capacity to be roughly 42 GW by 2030. This implies approximately 6 GW of yearly BESS capacity deployment over the next seven years.[25] While the cost of standalone lithium-ion battery packs globally fell from $1,220/kWh in 2010 to $151/kWh in 2022, the costs are still too high for utility-scale adoption.[26]

The government recently approved INR 3,760 crore (~$450 million) in funding to cover up to 40% of capital costs incurred in building BESS, with the target of achieving battery costs of INR 5.5–6.6 (~$0.07–0.08)/kWh.[27] Additional interventions can be considered to reduce the battery cost to the target price of INR 2 (~$0.02)/kWh for viable green hydrogen production.

Indirect cost subsidies in the form of GST and custom-duty exemptions[28] can be effective in lowering BESS operational costs. For example, as part of its 2023 Union Budget, India exempted custom duties on imported lithium-ion batteries for use in electric vehicles, effectively reducing their cost by as much as 20%.[29] Similar exemptions can be considered on the import of BESS components used to provide RTC renewable energy for green hydrogen production.

Pumped storage hydropower (PSH)

India's on-river pumped storage potential is estimated to be 103 GW, while the off-river potential is still being estimated. As of April 2023, however, only 4.7 GW was in operation.[30] Clearly, pumped storage hydropower (PSH) is ripe for further development.

Current estimates predict India will require 18.9 GW of pumped hydro-produced electricity in its energy mix by 2029–2030.[31] The government has issued guidelines for developing pumped hydro,[32] including budgetary support that includes cost credit (INR 1.5 crore [~$180,000]/MW up to 200 MW and up to INR 1 crore [~$120,000]/MW above 200 MW).[33]

An important challenge in scaling PSH is increasing its attractiveness for industry players. To achieve this, stakeholders could consider removing cumbersome clearance processes that have deterred private-sector contributions. Some suggested measures are:

- Encouraging private players to participate by expediting environmental clearances and defining delivery timelines that encourage private investment. For example, drawn-out clearance processes have delayed timelines and restricted private-sector contributions to only about 8% of the total installed hydro capacity today.[34]

- Environmental stipulations and other land acquisition hurdles can make PSH development difficult. Industry players may want to prioritize nationwide surveys to search for sites that could be appropriate for PSH development while meeting environmental and social stipulations.

1.2 T&D charges

When energy is transmitted from a production facility to an end user, it is subject to T&D charges, including interstate transmission charges, intra-state transmission charges and wheeling charges. These typically account for 30–60% of energy generation tariffs and drive the total landed cost for renewable energy to INR 4 (~$0.05)/kWh or more.

To ease the burden of transmission fees, India's central government has offered waivers. These include a 25-year waiver of renewable energy interstate transmission charges for green hydrogen projects commissioned on or before 31 December 2030.[35] Additionally, India's "Green Energy Open Access" plan allows generating companies to sell electricity directly to consumers cross-country through independent mutual agreements. These initiatives have successfully alleviated issues such as power evacuation and infrastructure constraints related to T&D charges. As such, they have enabled wider green energy adoption throughout the country.

In addition to interstate charges, additional intra-state, distribution and wheeling charges are also incurred, which are dictated by state government policies and so vary between states. For example, recent open-access wheeling charges for a 11 kV supply in the state of Gujarat were set at INR 0.18 (~$0.002)/kWh, while in the state of Uttar Pradesh the same charges reached INR 0.94 (~$0.01)/kWh.[36]

Some state governments, including the government of Maharashtra, have allowed a 50% concession on transmission charges and a 60% concession on wheeling charges for green hydrogen projects over the next 10 years.[37] These measures bring the effective T&D costs down from INR 1.5 (~$0.02)/kWh to INR 0.4 (~$0.005)/kWh in states such as Maharashtra (assuming a full waiver on interstate charges and a 50% exemption on intra-state charges).

However, variance leads to particularly high costs in states where policies do not exist. Further, the variability of policies among states leads to uncertainty for players as they look to transmit electricity to other parts of the country, where they have or plan to develop green hydrogen plants.

Enabling measure: Establish consistency in state T&D charges

To effectively reduce energy T&D costs and provide parity among states, industry players could work towards greater consistency in intra-state T&D changes by creating:

- Waivers for all state-driven T&D charges for green hydrogen projects, especially for early adopters
- Extending all such waivers long term (at least five or more years) to facilitate measurable progress towards developing green hydrogen plants

1.3 Electrolyser costs

An electrolyser uses electricity to split water into hydrogen and oxygen. Electrolyser costs account for approximately 30–50% of total green hydrogen production costs in India. As with any new technology, the price of electrolysers is expected to decrease as scale improves and production processes evolve.

A significant decrease in costs has been observed historically in other climate technologies. For example, as production capacity doubled, the cost of a lithium battery (LiB) pack declined by 44%, photovoltaic (PV) module costs declined by ~34%, and the average wind levelized cost of electricity (LCOE) reduced by ~23%.

Electrolyser costs will probably follow the same downward trajectory as the green hydrogen industry grows globally. To accelerate this cost decline, stakeholders can make targeted interventions to reduce the costs to acquire and use electrolysers for energy production.

Enabling measure: Award subsidies to early adopters

The Indian government provides a subsidy of $54/kW during the first year of electrolyser production through a production-linked incentive (PLI) scheme.[38] Tranche 1 was live between July and October 2023.[39] This subsidy reduces the cost of green hydrogen production by only $0.1/kg.[40] Additional interventions, including increasing subsidy support through the PLI scheme, would further reduce the cost of electrolysers and, thus, green hydrogen. Such steps would encourage early development of a critical mass of electrolysis capacity.

Enabling measure: Implement long-term policy views to reduce the risks to capital investment

India's current electrolyser PLI scheme has a five-year deployment period (financial years 2026–2030). However, typical electrolyser manufacturing units have a much longer life cycle. Therefore, stakeholders could adopt at least a 10-year view on electrolyser capital cost-related incentives to encourage private investments in this technology. Such initiatives could help adopters feel less apprehensive about the capital costs. "Given the technology is still evolving, electrolyser capital investment will only make economic sense after five years. We will likely make that investment decision in the future, instead of now," a leading energy producer said.

> It is necessary to adopt at least a 10-year view on electrolyser capital cost-related incentives to encourage private investments in this technology.

In addition to cost-reduction strategies, scaling of the correct technology is critical. Multiple technologies exist for electrolysers today, each with different specifications and use cases.

Enabling measure: Leverage R&D to support electrolyser technologies that are attuned to India's needs

Alkaline (ALK) electrolysers are the most cost-effective.[41] However, ALK electrolysers are primarily used for hydrogen production through grid-supplied electricity, as they are inefficient with intermittent power sources such as renewable energy power.

While expensive,[42] proton exchange membrane (PEM) electrolysers have better operational flexibility and reaction efficiency. They are also able to achieve the required purity for hydrogen for use in a fuel cell, unlike ALK. However, these electrolysers consist of rare-earth metals such as platinum and iridium,[43] which need to be imported into India.

Stakeholders can spur innovation in Indian electrolyser production and electrolysis capacity by making interventions such as:

- **Prioritizing the development of electrolyser technologies that operate on a flexible energy supply and without reliance on rare-earth metals**. Examples include anion exchange membranes (AEM) or solid oxide electrolyser cells (SOEC). Given the evolving nature of the industry, it is also critical to monitor the right technologies continuously. Stakeholders could consider increasing central government's R&D budget for indigenous technology to further innovation using these types of electrolysers. Also, government and industry players could build partnerships with international agencies working in the green hydrogen sector to import technology and establish mutually beneficial operations within India.

- **Facilitating collaboration between private players and academic research institutes on test and pilot programmes**. Often industry players are unaware of technology developments that occur in different parts of the country. Recently, companies in Pune formed the Pune Hydrogen Consortium to share knowledge throughout the industry and academia. Similar initiatives at a countrywide level could benefit industry players, while building a more cohesive, national understanding of this new sector.

Goal 2

Optimize green hydrogen delivery costs

Infrastructure development and clustering initiatives can reduce the costs associated with green hydrogen delivery.

Hydrogen is a volatile, small-molecule chemical with a low volumetric energy density, requiring dedicated (or adjusted) infrastructure for storage and transportation, which is expensive, especially when the scale is low. Thus, in addition to production costs, the long-term costs of building transport and storage infrastructure for this technology should also be considered.

From a logistics standpoint, hydrogen-enabling infrastructure connects the sources of production with places of offtake (that is, where it will be used). It supports several stages in the green hydrogen life cycle, including transportation, conversion (or reconversion) and storage.

Transportation and conversion/ reconversion

Transporting hydrogen in its gaseous state is very expensive (given that it requires a pipeline network to be built) compared to some of its derivatives such as ammonia or e-methanol. Infrastructure is needed to convert hydrogen into a derivative at the point of production and then back to hydrogen at the point of consumption, especially for long-distance transportation, such as when exporting it.

Given the nascency of India's hydrogen ecosystem, the country currently lacks the technology and the infrastructure for adequate transportation. These logistical gaps are hindering the country's access to green hydrogen and impeding widespread adoption. Stakeholders can establish incentives for the development of infrastructure as well as scaled green hydrogen technology to address these issues.

Storage

Given hydrogen's volatility, its storage is also challenging and potentially hazardous if not done correctly. Interventions to identify novel ways to store hydrogen and develop enabling infrastructure can spur the development of storage infrastructure.

2.1 High cost of green hydrogen transportation

Currently, hydrogen is transported using three main methods:

1. Shipping of hydrogen or its derivatives over long distances (cross-continent)
2. Transporting of gaseous or liquefied hydrogen (or its derivates) using trailers
3. Transporting of gaseous hydrogen through pipelines

When the volumes are substantial and the distances are relatively small, a pipeline is an effective way to transport hydrogen.

Three types of pipeline can be used for this purpose. The first, dedicated hydrogen pipelines, are specialized pipelines made with materials designed for hydrogen dissemination. (Hydrogen can cause steel and other standard pipeline materials to become brittle.) Using the second type, converted natural gas pipelines, involves making slight modifications to existing pipelines to enable them to carry a blend of natural gas and hydrogen. The third method involves blending small amounts of green hydrogen (limited to 5–10%) with natural gas, using existing natural gas pipelines.

Enabling measure: Scale transportation and conversion/reconversion infrastructure

Because India's green hydrogen industry is still evolving, a dedicated nationwide interconnected hydrogen pipeline network does not currently exist. Building such a network will require massive upfront capital investment as well as a prolonged construction timeline. In the short term, therefore, officials can encourage the use of modified existing natural gas pipelines for hydrogen dissemination or blending of green hydrogen with natural gas. In the long term, India can look to Europe's example of laying down a dedicated hydrogen transport network using its pre-existing gas network as a foundation (the European Hydrogen Backbone project).

FIGURE 5

Case study: EU repurposes natural gas pipelines as part of the European Hydrogen Backbone programme

Situation	Anticipated large-scale hydrogen consumption in EU (40 GW) will require a well-developed hydrogen transportation infrastructure
Vision	Connecting hydrogen supply and demand across the region, labelled "the European Hydrogen Backbone" – Also connected to wind and solar-photovoltaic supply as well as hydrogen imports from outside EU
Description and anticipated progress	Dedicated hydrogen pipeline across Europe, mainly created by converting existing pipelines – Initial 6,800 km pipeline network by 2030 (initiated by early 2020s) – Expand to 23,000 km by 2040 (Phases 2 & 3) Estimated cost: €27–64 (~$29–69) billion (2020–2040)
Countries involved	

Source: European Hydrogen Backbone, 2020

In order to explore other mediums of transporting hydrogen – such as ammonia – appropriate technology and scale related to conversion/reconversion facilities are needed.

Until the required scale is achieved, uptake should be encouraged in one of two ways:

– **Engage in captive production:** Many early adopters are planning to set up captive green hydrogen plants to eliminate the cost of transport and storage. For example, Indian Oil has plans to set up a commercial-scale green hydrogen plant at its Panipat refinery,[44] and HPCL is setting up a 370 tonne-per-annum (TPA) green hydrogen plant at the Vishakhapatnam refinery in Andhra Pradesh.[45]

– **Consume within a closely held cluster:** Alternatively, some adopters have plans to establish green hydrogen clusters. For example, Adani Enterprises is setting up a cluster at Khavda with 20 GW+ renewable energy and green hydrogen production. Consumption there is driven by the nearby Mundra industrial hub.[46]

The creation of clusters for both hydrogen production and offtake can significantly reduce the cost of infrastructure for transportation and storage. The formation of clusters can be encouraged by:

– Allowing companies to bid for PLI/other incentive schemes as part of a cluster

– Enabling faster clearances for clusters compared to single entities

– Sharing success stories of clusters on national platforms to encourage collaboration

FIGURE 6 | **Global examples of hydrogen cluster projects**

	Project name	Country	Production start year	Description	Electrolyser size/KTPA
Supply-led cluster	H2opZee Hydrogen Project	Netherlands	2030	Neptune Energy and RWE are collaborating to develop the H2opZee offshore green hydrogen project, which aims to build 300–500 MW of electrolyser capacity in the North Sea	500 (71* KTPA)
	Enterprize Energy Thang Long Hydrogen Project	Viet Nam	2030	Enterprize Energy and the Vietnamese Institute of Energy are collaborating to develop the 3.4 GW Thang Long offshore wind farm to produce more than 330,000 tonnes of green hydrogen in Viet Nam	2,318* (330 KTPA)
Integrated hub	Hydrogen City, Texas Hub	US	2026 (Phase 1)	Green Hydrogen International (GHI) plans to develop an integrated green hydrogen production, storage and transport hub growing to 60 GW renewable capacity (solar and wind power) in Texas	2,000 (285* KTPA)
	HyDeal España	Spain	2030	HyDeal España is the first industrial implementation of the HyDeal ambition platform, which aims to achieve electrolyser capacity of 67 GW and 3.6 million tonnes of green hydrogen production by 2030	7,400 (330 KTPA)
	HyNet North West	United Kingdom	2025 (Phase 1)	HyNet plans to provide infrastructure to produce, store and transport low-carbon hydrogen across North-West UK and North Wales. This also includes infrastructure to capture, transport and lock away carbon dioxide emissions from industry. This cluster consists of ~40 organizations and is expected to deliver up to 80% of the UK's 5GW low-carbon hydrogen target by 2030.	–
	National Capital Hydrogen Centre	US	2030	National Capital Hydrogen Centre plans to produce, store and transport low-carbon hydrogen in the DMV region (District of Columbia, Maryland and Virginia) abating ~1.5% of regional carbon emissions in less than a decade.	–

Source: GlobalData; literature search

Notes: *Calculated using a fixed conversion factor; KTPA = kilotonnes per annum.

2.2 High cost of green hydrogen storage

Effective hydrogen transport can occur only when systems for hydrogen storage – both before and after transportation – are in place. Thus, a viable storage infrastructure is critical for the green hydrogen industry to thrive. Given the fact that hydrogen storage also plays a role in potential use cases, including for grid balancing and power generation, the demand for effective storage facilities becomes even more critical.

FIGURE 7 **Global hydrogen storage capacity**

Regions	Gaseous state				Liquid state			Solid state
	Salt caverns	Depleted gas fields	Rock caverns	Pressurized containers	Liquid hydrogen	Ammonia	LOHC	Metal hydrides
Main usage (volume and cycling)	Large volumes, months–weeks	Large volumes, seasonal	Medium volumes, months–weeks	Small volumes, daily	Small–medium volumes, days–weeks	Large volumes, months–weeks	Large volumes, months–weeks	Small volumes, days–weeks
Working capacity	300–10,000 tonnes/cavern	300–100,000 tonnes/field	300–2,500 tonnes/cavern	5–1,100 kg/container	0.2–200 tonnes	1–10,000 tonnes	0.18–4,500 tonnes per tank	0.1–20 kg
Benchmark LCOS ($/kg H_2)	$0.23	$1.90	$0.71	$0.19	$4.57	$2.83	$4.50	Not evaluated
Possible future LCOS	$0.11	$1.07	$0.23	$0.17	$0.95	$0.87	$1.86	Not evaluated
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited	Not limited

Source: Bloomberg New Energy Finance

Notes: LCOS = levelized cost of storage; LOHC = liquid organic hydrogen carriers.

Enabling measure: Build technology and infrastructure for green hydrogen storage

Storing hydrogen in its liquid state is very expensive and energy intensive, while storage in its solid state is yet to be adopted. Consequently, storing hydrogen in its gaseous state is currently the most cost-effective medium.

For large-volume gaseous hydrogen storage, salt caverns, depleted gas fields and rock caverns are needed, and this can happen only at naturally occurring geological sites. India is still at the feasibility-study stage when it comes to large-scale underground storage. An exploratory study is currently under way at a site in Bikaner,[47] and the India Hydrogen Alliance (IH_2A) is also conducting R&D on salt cavern-based hydrogen storage.

Storing gaseous hydrogen in pressurized containers (sometimes called cylinders) – since it does not rely on naturally occurring geological sites – represents the most easily controllable storage technology currently available in India, albeit only for short-term/low-volume storage. There are four types of cylinders for storing gases, made according to a specific standard and process. Type 3 and 4 composite cylinders are better suited for hydrogen storage than types 1 or 2, due to the former's ability to withstand very high pressures. But type 3 and 4 cylinders are currently still in development and very expensive for industrial use. Presently, Indian Oil is working with IIT Kharagpur to develop a type 3 composite cylinder for use with compressed hydrogen gas.[48]

Developing type 4 cylinder technology will follow type 3 cylinder adoption. In the short term, stakeholders could encourage the development of type 3 cylinders to reduce hydrogen storage costs. This could be done by setting up testing facilities for type 3 composite cylinders as per International Organization for Standardization (ISO) standards and by offering incentives for R&D on other innovative, commercial-scale storage technologies. Until credible technologies for storage are widespread in India, creating hydrogen clusters should be prioritized to reduce or eliminate the need for hydrogen storage.

Goal 3

Drive domestic uptake

Creating pull for green hydrogen through demand-side interventions within India's borders will boost its development.

In addition to supply-side interventions, the demand side can also encourage industries to consume green hydrogen rather than fossil-fuel-based energy sources.

Four important categories of users will likely drive the adoption of green hydrogen throughout India: existing grey hydrogen users, transportation providers, power suppliers and other major industries (Figure 8). Interventions can be tailored for each category to support widespread green hydrogen adoption.

FIGURE 8 **Key sectors driving green hydrogen adoption in India**

Category	Greening existing grey hydrogen users	Wider adoption across industrial processes	Greening transportation	Power and heat
Industry examples	Refinery, fertilizer	Steel, cement, chemicals	Heavy-duty vehicles, maritime, aviation	Power, grid balancing

Source: Bain & Company analysis

3.1 Greening existing grey hydrogen users

Refineries and fertilizers are the two biggest consumers of grey hydrogen in India. Together they make up more than 90% of the country's total hydrogen demand.[49] In refineries, hydrogen is used for the desulphurization of petrol and diesel. The fertilizer industry, meanwhile, uses hydrogen to produce fertilizers such as urea. Currently, on-the-ground traction for green hydrogen implementation is limited in both sectors.

To date, only a few players have clear targets for integrating green hydrogen into their refineries or fertilizer production operations. A prominent example is Indian Oil, which has expressed plans to use green hydrogen for 50% of its total hydrogen used by 2030.[50] While these sectors could easily adopt green hydrogen into their operational processes, their transition is limited by cost barriers. Green hydrogen costs roughly $4–5/kg, while grey hydrogen costs less than $2/kg today. The significant price differential is, for now, a critical obstacle to widespread adoption.

Enabling measure: Reduce the cost/drive uptake of green hydrogen for existing grey hydrogen users

Encouraging green hydrogen adoption among existing grey hydrogen users in India will require both cost interventions on the supply side and mandates on the demand side.

On the supply side, these industries can benefit from increased subsidies that accelerate uptake in consumption. This can be done by increasing the amount of direct cost incentives – in the form of tax credits or fixed subsidies, for example – to compensate for the green hydrogen cost premium. India could follow a model set by the USA, where tax credits of up to $3/kg are available for green hydrogen production under the Inflation Reduction Act.[51]

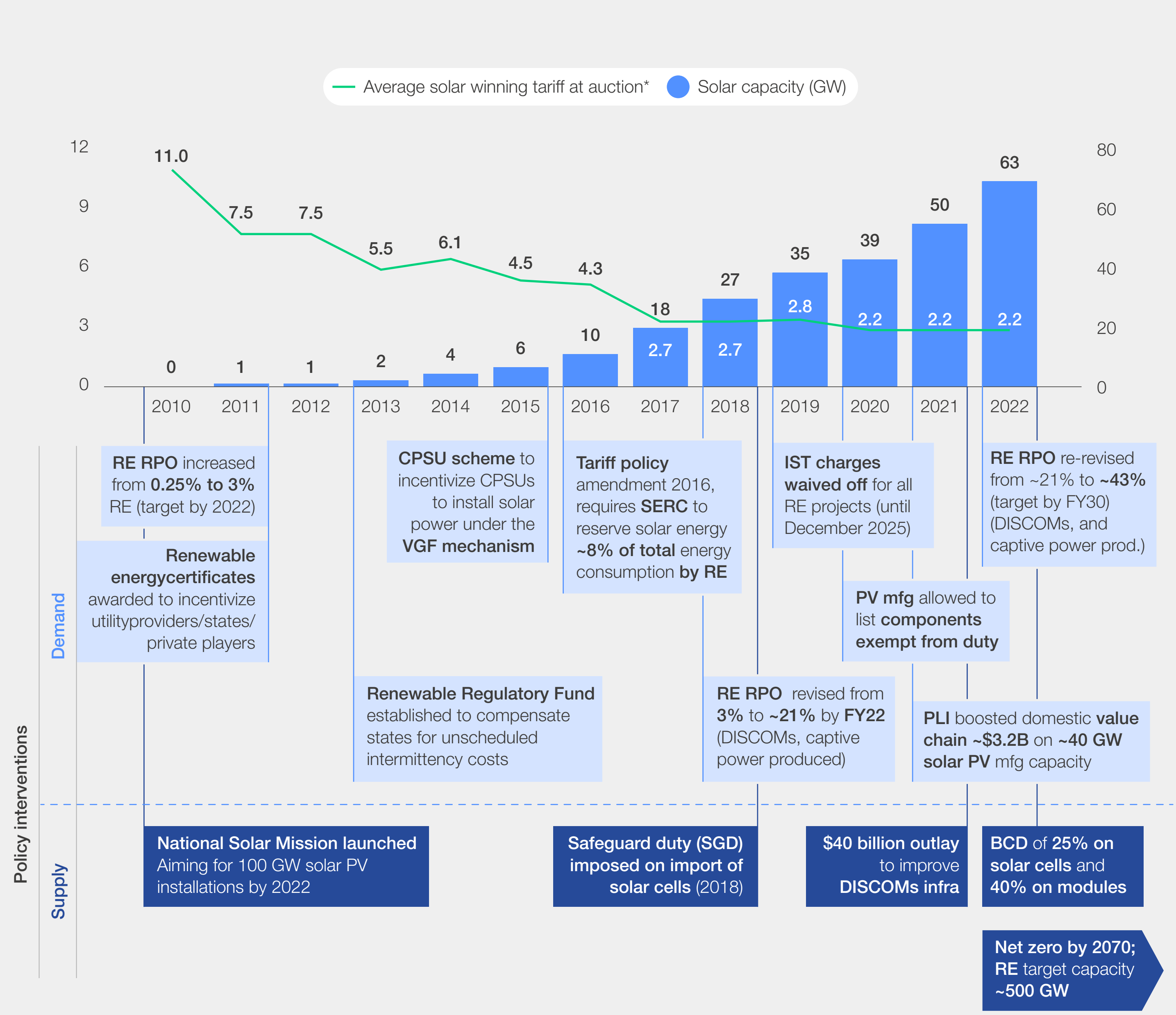
On the demand side, green energy uptake can be influenced by consumption-based interventions. One leading energy producer said: “Supply-side interventions, while helpful, are not enough without certain demand-side mandates. Adoption of green hydrogen in the short term may not be viable unless there is demand from customers.” Of course, the potential cost impact for customers should be factored in when setting these mandates.

In the short term, stakeholders could encourage the use of blended hydrogen, which combines both green and grey hydrogen, by setting demand mandates that have a minimal impact on final product costs. For example, mandates can be set that require refiners and fertilizer manufacturers to blend small quantities (5–20%) of green hydrogen into their fuel. Use of green hydrogen at such levels may not materially change the cost of the end-product, but it could nonetheless provide early impetus for more widespread adoption.

To illustrate, historically, renewable energy has achieved scale through demand-side policy interventions in the form of renewable energy purchase obligations. Since their launch in 2011, purchase obligations have led to massive capacity addition and price correction (Figure 9).

FIGURE 9

Demand-side policy interventions outweighed supply-side interventions for successful scale-up in solar renewable energy production



Notes: RPO = renewable purchase obligation, launched in 2003; VGF = viability gap funding; SERC = state electricity regulatory commissions; IST = interstate transmission charges; BCD = basic customs duty; CPSU = central public sector undertaking; RPO = renewable purchase obligation; DISCOMs infra = distribution company infrastructure; PV mfg = photovoltaic cell manufacturing; * = average of winning tariff across energy bidders each year.

Source: Literature search; Bain & Company analysis

3.2 Wider adoption in industrial processes

Adoption of green hydrogen by industries other than those already using hydrogen for fertilizer production and in oil refineries represents its own, separate challenge. Adoption in wider industrial sectors will probably require significant process adaptation or machinery retrofitting.

Importantly, green hydrogen provides pathways to decarbonize industrial processes where emissions are otherwise hard to abate. For example, green hydrogen can reduce emissions related to steel production through two critical adaptations:

– Green hydrogen can partially replace coke in a blast furnace, resulting in up to 20% reductions in CO_2 emissions

– Green hydrogen can replace natural gas in electric arc furnaces through a direct-reduced iron (DRI) process that reduces CO_2 emissions by as much as 90%[52]

To achieve long-term sustainability of steel, India will need to scale its use of green hydrogen in the DRI manufacturing process. However, there is limited DRI steel capacity in India today, and steel production is primarily driven by blast furnaces that use coal or coke. In the long run, building a green steel industry will require the replacement of blast furnaces with DRI set-ups throughout the country – a capital-intensive and potentially operating-cost expensive investment that will necessitate buy-in from industry, government and end customers.

Similarly, for other industrial sectors, such as cement, chemical production and mining, large-scale capital investments for equipment replacement and process adaption will be required.

Enabling measure: Reduce investment risk for industrial players who make long-term capital commitments

The investment cycles on these future capital commitments are very long, sometimes as much as 25 years or more. Interventions could encourage industry players to commit the required capital for green processes for these long investment cycles. This can be done by:

– **Reducing the cost of capital:** Industrial players can be encouraged to make capital commitments for new plants by offering incentives to reduce the perceived cost of the investment. These include measures such as accelerated depreciation, discounted land and tax rebates throughout the life cycle of the plant.

– **Making more funds available:** Investments can be encouraged if investment funds are readily available. Indian stakeholders could consider including green hydrogen within the Priority Sector Lending List to accelerate fund availability.

– **Adopting a long-term vision:** Extending a 25-year vision for green hydrogen investments can alleviate some long-term risks. In India, the model for such long-term policies is already in place, in the form of 20-year power-purchase agreements for renewable energy. Such plans decrease the investment risk of capital expenditures by ensuring that the technologies involved have a guaranteed long-term use.

– **Customer/demand-side mandates:** Setting demand-side mandates specific to the industry can reduce the risk of capital investments by ensuring long-term demand for green substitutes. For example, potential mandates to use a percentage of green steel in vehicle manufacturing could ensure demand for steel manufactured using green hydrogen.

Enabling measure: Set green hydrogen by-product standards

India recently launched standards for green hydrogen, defining it as hydrogen produced using renewable energy (including through electrolysis or conversion of biomass) with less than 2kg CO_2/kg hydrogen emissions over a 12-month period.[53] However, detailed methodology for measurement, reporting, monitoring and on-site verification of green hydrogen and its derivatives is yet to be specified.[54] An important next step for stakeholders will be the establishment of precise definitions, usage thresholds and carbon emissions boundaries for products made using green hydrogen to be identified as “green”; for example, “green steel” or “green cement”. Establishing such guidelines will provide clarity to both customers and producers alike.

3.3 Greening transportation

In India, road transport alone accounts for more than 10% of CO_2 emissions.[55] The country has an existing low-CO_2 emissions pathway for rail and light-duty road transport, including rail electrification and battery-powered electric vehicles. But, for other modes of transport – including road-based freight transport by heavy-duty vehicles (HDVs), aviation and maritime shipping – green hydrogen can provide a novel, much-needed green pathway. For example, in the future, a substantial share of heavy-duty road transport could be handled by hydrogen-powered fuel-cell electric vehicles (FCEVs).

Despite ongoing R&D and pilots, the operational infrastructure for such usage has not yet been established. For instance, even though fuel-cell technology to run HDVs currently exists, the technology and infrastructure required for adequate refuelling is still under development. Hence, these sectors require support in developing these technologies.

Enabling measure: Facilitate support for R&D and pilots

Various hydrogen-based technology variants are currently undergoing R&D throughout India. These include hydrogen-based internal combustion engines (ICE), hydrogen fuel cells, hydrogen-blended fuel and production of fuels using ammonia and methanol. The Ministry of New and Renewable Energy launched the *R&D Roadmap for Green Hydrogen Ecosystem in India* earlier in the year, which creates a foundation for enabling R&D.[56] Additionally, stakeholders can support the Indian transport sector's goal of reaching commercial readiness regarding green hydrogen implementation by lending support to R&D and pilot programmes. Incentives to create large-scale testing facilities, for example, could jump-start indigenous technology development for hydrogen-based transport in HDV, aviation and maritime shipping.

Apart from delivering this technological support, stakeholders could also work to develop a set of common, nationwide standards for large-scale green hydrogen adoption. Such standardization is critical if "green transport" is to grow commercially throughout India. In this pursuit, stakeholders could look to electric vehicle (EV) battery standards as a model. These standards are regularly updated to reflect regulation changes as well as revisions to testing and certification protocols, which are driven by technological advances in the EV market.[57]

Enabling measure: Establish hydrogen mobility technology standards

Currently, commonly accepted standards throughout the hydrogen-based mobility value chain are lacking in India – especially compared to the existence of such standards in other countries, including Australia, Canada, Germany, Japan, South Korea, the USA and the UK.

For example, India currently has no nationwide standards for fuel-cell modules in HDVs. To establish nationally accepted standards for hydrogen mobility technology, Indian stakeholders could work to create common protocols for all hydrogen-based technologies under pilot programmes or in R&D. This includes fuel-cell modules, hydrogen ICEs, hydrogen refuelling stations and the use of ammonia or methanol as shipping fuels. Additionally, stakeholders could invite relevant researchers and scholars from academic institutions to participate in standards creation to aid in the construction of cohesive and credible metrics. For example, in the USA, the American National Standards Institute (ANSI) and the Standards Development Organization (SDO) collaborate on hydrogen technology standards. The ANSI oversees the process and approves national standards, while the SDO, which includes academic and industry groups, sets the standards.[58]

3.4 Power and heat

Green hydrogen in auxiliary power generation is still in its early days. Current interventions are focused on encouraging the development of a thriving ecosystem backed by adoption in the three other use categories.

Developing technology to augment the use of green hydrogen in auxiliary power generation is critical for its uptake in these applications. This is an area rich for development, and stakeholders can encourage pilot projects and enhanced R&D by working to invest in cutting-edge laboratories and study facilities for Indian researchers and engineers employed in this field. Additionally, industry players could act to encourage technology-transfer agreements with representatives from international academic institutions, so that India's green hydrogen industry can grow using best practices already in use in other countries.

Goal 4

Capitalize on India's export potential

India has the potential to become a green hydrogen exporter, which could also spur domestic ecosystems.

India could emerge as a cost-competitive green hydrogen derivative exporter, thanks to its access to relatively low-cost renewable energy, a skilled workforce and a connected power grid.

The cost differential inherent in producing green hydrogen in various countries provides an emerging opportunity for international trade in its derivatives. Globally, the EU, Japan and South Korea are already exploring international agreements related to hydrogen imports driven by the high cost of local production and their net-zero aspirations. Given this climate, India could emerge as a cost-competitive green hydrogen derivative exporter, thanks to its access to relatively low-cost renewable energy, a skilled workforce and an enabling infrastructure in the form of a connected power grid.

The green hydrogen ecosystem in India is still nascent, so there is relatively little domestic demand for the product to date. Potential international importers such as the EU and Japan have, however, set long-term green hydrogen targets, which would suggest a need for imports to meet the targets. Capitalizing on this potential international demand could affect India's hydrogen ecosystem as well as its economy in the following ways:

- The export economy can positively influence domestic demand by enabling scaled production, leading to a decrease in production costs
- India's green hydrogen producers could expect a better short-term value realization through exports
- Capturing this import demand early can prove to be a strategic enabler for becoming a scaled exporter in the 2030s and 2040s, when cost curves and technologies have stabilized – this could be economically advantageous for India, which has historically relied on energy imports

To emerge as a leader in green hydrogen derivative exports, though, India will have to compete with other countries where green hydrogen production costs are expected to be low, for example, Saudi Arabia, Chile and Australia.

4.1 Enable Indian exporters to thrive by creating demand for Indian green hydrogen

The EU, Japan and Singapore are expected to be significant importers of green hydrogen, given their demand targets for 2030 and the high local costs of production. Drivers for green hydrogen demand in these markets are shown in Figure 10.

FIGURE 10 **Global green hydrogen derivatives import opportunities and key demand drivers**

Territory	2023 GH_2 cost ($/kg)	2030 Target (MMTPA)[3]	2030 Imports (MMTPA)	Demand drivers
EU	6.8[1]	20	~10	A minimum of 42% of hydrogen for industries, **to be sourced from renewable energy** by 2030. "We want to make Germany and Europe a lead market for green hydrogen. We are therefore launching a first auction procedure **for the import of green hydrogen worth €900 million.**" European Commission, 2022
Japan	8.0	0.4	*N/A*	**Japan and South Korea importing green ammonia** for co-firing power plants. **Hydrogen mobility to rise,** along with that of **fuel-cell vehicles** and **refuelling stations.** "We have positioned **hydrogen as one of the priority areas** in the Green Growth Strategy." Ministry of Economy, Trade and Industry, Japan, 2021
Singapore	6.6[2]	*N/A*	1–1.5	To be used as a low-carbon fuel across **maritime, aviation and road transport**. Green ammonia to be imported for **blending with fossils** to achieve net-zero target. "Singapore believes that low-carbon **hydrogen** has the potential to be the next frontier of our efforts to **reduce our emissions.**" Deputy Prime Minister, Singapore, 2022

Notes: 1. Prices include subsidies; 2. price for low-carbon hydrogen; 3. targets for low-carbon hydrogen consumption.

Source: Bain & Company analysis; secondary research

Enabling measure: Pursue greater participation in multilateral initiatives with potential importers

India should prioritize international cooperation and the co-development of hydrogen networks and supply chains if it hopes to establish itself as a leading international exporter of green hydrogen derivatives. Already many green hydrogen derivative producers have signed MoUs and export pacts with importers. For example, Australia has signed an export deal with Japan to export renewable hydrogen and ammonia,[59] while the Netherlands and Australia have signed MoUs for the establishment of a hydrogen network, including trade policy, port infrastructure and new technologies.[60] Although most of these MoUs are for small initial volumes, they define a precedent for increased global trade.

While India has signed an MoU with Singapore for green hydrogen derivative exports,[61] opportunities for further international engagement exist. India should work to enter into mutually beneficial MoUs with countries from multiple geographical regions in order to fully develop its capacity for green hydrogen derivative development and trade.

Enabling measure: Develop port infrastructure for green hydrogen derivative exports

To maximize demand drivers facilitated through multilateral international trade agreements, India should expand its green hydrogen export infrastructure. Exports of green hydrogen derivatives will require conversion (at the production site or at the port), storage and shipping facilities at port terminals. Recently the Indian government began permitting manufacturers of green hydrogen and green ammonia to establish storage bunkers near ports for their products.[62] In the future, port infrastructure could be optimized further to allow for green hydrogen production and conversion on site.

"India already has existing port infrastructure, but it needs to ramp up its storage to create an enabling ecosystem for global uptake," said a leading Indian energy producer. To properly develop India's port infrastructure for efficient green hydrogen derivative exports, stakeholders could work to encourage PLIs to support private investments related to port-adjacent conversion and reconversion facilities. Additionally, Indian industry and government players could partner to establish green hydrogen special economic zones (SEZs) around port regions. SEZs use tax incentives, fiscal concessions and duty benefits to support the development of specific sectors – and their implementation on land near ports could jump-start green hydrogen infrastructure.[63]

Enabling measure: Harmonize global standards and certification mechanisms

Another critical aspect of exports is establishing harmonized standards for seamless global trade. Over the years, organizations such as the ISO and the International Electrotechnical Commission (IEC) have been created to include global representation for the development of universally accepted standards in different application areas. Given green hydrogen's nascency, there are currently no such global governing bodies establishing platforms or standards for its production. Instead, each country has its own standards for green hydrogen production processes and emissions limits. For example, India includes "banked" renewable energy electricity as part of its green hydrogen definition, while the EU does not permit its inclusion.

FIGURE 11 **Disparity among renewable standards affects demand for green hydrogen (voluntary market mechanisms with published technical criteria [IRENA])**

Country	Production method	Year issued	Carbon threshold (kg CO_2e/kg H_2) to qualify as clean or green hydrogen
India	Renewable electricity (electrolysis and conversion of biomass)	2023	2.0
China	Renewable electricity; low-carbon electricity	2023	4.9 (threshold for "low-carbon" hydrogen is different)
International (Voluntary standard by Green Hydrogen Organisation)	Renewable electricity	2022	1

Note: Emissions threshold refers to the maximum permissible emissions limits for various standards to qualify as low-carbon and/or green hydrogen.

Source: Renewable Energy Institute, *Revised Basic Hydrogen Strategy Offers: No Clear Path to Carbon Neutrality*; IEA, Ministry of New and Renewable Energy, "Green Hydrogen Standard for India"

While there is disparity today between global standards, potential exporter countries have embarked on initiatives to develop a common set of guidelines. Saudi Arabia, for example, has configured its production standards to meet market requirements in both Europe and the Asia-Pacific region. In this way, it is working to position itself as a global supplier of renewable and low-carbon hydrogen.[64]

The Hydrogen Production Analysis (H_2PA) task force of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is devising ways to develop a commonly accepted methodology for estimating emissions throughout the green hydrogen life cycle. If adopted, this will facilitate international trade.[65]

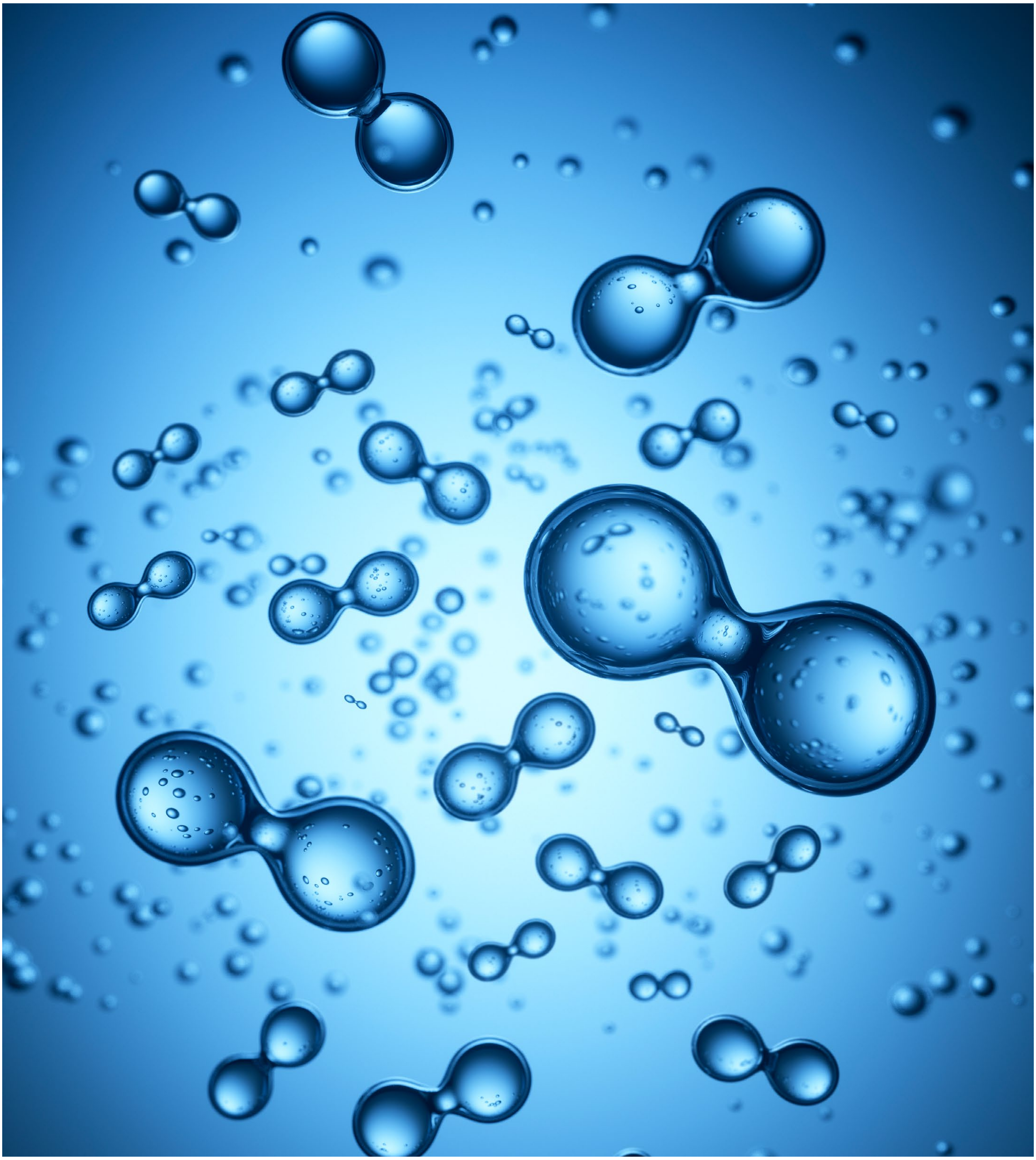
India, too, will benefit by harmonizing its standards mechanisms in line with importers' market requirements. For example, stakeholders could prioritize the development of cohesive guidelines that support the translation of Indian standards to global standards, thereby reducing potential inconsistencies that could prevent India's green hydrogen from being accepted by international markets. Additionally, work could be done to clarify current guidelines surrounding the treatment of green attributes for export-oriented units. Currently it is not clear whether such exports should be counted towards India's nationally determined contributions (NDC) or the importer's NDC.

Finally, India should follow successful models set by other countries, where clear guidelines for domestic green hydrogen certification have been established. For example, the EU has established certifications for green hydrogen – dubbed "CertifHy" – that include high-quality hydrogen certification schemes to promote the development of transparent and credible markets for green hydrogen throughout Europe. The EU has also brought in guarantees of origin (GOs) for renewable energy, which enable users to track and verify the origin and quantity of renewable energy produced anywhere in Europe.[66]

Goal 5

Disincentivize carbon-intensive alternatives

Investments in carbon-intensive alternatives should be diverted to green pathways, including green hydrogen.



Each of the previous four goals focuses on creating incentives for green hydrogen production by driving demand and making it more affordable and more efficient to use. Demand for green hydrogen can also be built through policies that disincentivize the use of carbon-emitting fuel alternatives.

Enabling measure: Introduce penalties on the use of carbon-intensive alternatives, with plans to use the funds collected to finance the green hydrogen economy and other transition pathways

India's current subsidy and tax regime encourages transition from coal to less-polluting natural gas by taxing the use of coal and providing subsidies on natural gas consumption. Specifically, India has introduced an INR 400 (~$4.80)/tonne coal tax called the National Clean Energy and Environment Fund (NCEEF)[67] as part of its strategy to fund decarbonization transition. This translates to a carbon tax of $5/tonne of CO_2 emissions. While India's tax fee has increased from INR 50 (~$0.60)/tonne in 2011,[68] it is still lower than the carbon-tax rates of other countries. (For example, both Germany and the UK have higher rates, with fees now set at $35/tonne CO_2 and $22/tonne CO_2, respectively.[69])

To further encourage the use of natural gas in India, the government has set a cap on the cost of natural gas produced or imported by nationalized oil companies, including the Oil and Natural Gas Corporation (ONGC) and Oil India.[70]

Stakeholders can build on this foundation to provide more support for the transition towards green hydrogen and away from high-carbon-emitting fuels by introducing mechanisms to establish comprehensive carbon pricing and tax frameworks. This, of course, needs to be offset against the potential impact on energy affordability for the domestic population. Some of the recommended interventions could be:

- Reallocating existing coal subsidies (for example, create incentives for electrification rather than coal usage)[71]
- Setting aside a portion of fossil-fuel revenue to establish a green hydrogen development fund
- Levying additional carbon pricing (tax or other mechanisms) on fossil fuel-based technologies, while balancing increased cost to the customer against cost reduction in green technologies
- Establishing emissions penalties for the development of carbon-intensive manufacturing processes such as blast furnace-based steel plants to encourage greener technologies (for example, direct reduction iron–electric arc furnaces [DRI–EAF] using scrap steel and renewable energy)[72]
- Encouraging companies to set internal carbon costs to better enable the transition to green energy alternatives (for example, Tata Steel has established an internal carbon pricing of $40/ton of CO_2)[73]

Roadmap

Green hydrogen is currently undergoing early-stage adoption and expansion in India. Several priorities must be met if the country hopes to grow the industry.

By reducing the cost of producing and delivering green hydrogen, increasing domestic demand and establishing its power as a global green hydrogen exporter, India can further its fledgling green hydrogen ecosystem and establish a pathway to meet its ambitious goal of creating 5 MMTPA of green hydrogen by the 2030s.

The roadmap below recommends the phasing of the recommended strategies to achieve these ambitions. While most of them should, and need, to happen quickly, a phased plan can reduce the stress on implementing agencies while balancing other decarbonization priorities (for example, the biofuels economy and the scaling of renewable energy capacity).

FIGURE 12 **Enabling measures roadmap**

Goal		Enabling measure	Near term CY24–26	Medium term CY27–30	Long term CY31–50
Reduce the cost to produce green hydrogen to less than $2/kg		Cost of energy storage system needs to reduce rapidly	↔	↔	
		Consistency can be established across state transport/distribution charges	↔	↔	↔
		Subsidies can be awarded to early adopters	↔		
		Long-term policy views can reduce the risks of capital investment	↔		
		R&D can support electrolyser technologies that are attuned to India's needs		↔	↔
Reduce or eliminate costs related to green hydrogen conversion, storage and transportation		Scaling of transportation and conversion/reconversion infrastructure is needed		↔	↔
		Build technology and infrastructure for green hydrogen storage		↔	↔
Support industries that are most likely to adopt green hydrogen	Category 1: Greening existing grey hydrogen users	Reduce the cost of green hydrogen for existing grey hydrogen users	↔	↔	
	Category 2: Wider adoption across industrial processes	Investment risk could be reduced for industrial players who make capital commitments for new plants		↔	↔
		Green hydrogen by-products standards can be set	↔	↔	
	Category 3: Greening transportation	Facilitate support for R&D/pilots		↔	↔
		Establish hydrogen mobility technology standards		↔	
Capitalize on India's export potential		Greater participation in multilateral initiatives with potential importers	↔	↔	↔
		Development of port infrastructure for green hydrogen derivative exports	↔		
		Harmonized global standards and certification mechanisms	↔		
Disincentivize carbon-intensive alternatives		Penalties on usage of carbon-intensive alternatives can be enacted, with plans to use collected funds to finance the green hydrogen economy and other transition pathways		↔	↔

Source: Expert interviews and Bain & Company analysis

Conclusion

Green hydrogen has a critical role to play in driving India's net-zero transition and securing its energy needs. The country has embarked on a bold journey through the launch of its National Green Hydrogen Mission.

To achieve its ambitious goal of producing at least 5 MMTPA of green hydrogen production by 2030, India should work to reduce the cost of green hydrogen by lowering the associated renewable electricity expenses and investing in advances in electrolyser manufacturing, infrastructure and innovative R&D.

This report proposes a roadmap defined by five development goals, focused on encouraging the integration of green hydrogen to meet India's fuel demands and on disincentivizing the use of carbon-emitting fuel sources. Facilitating exports could be another economic incentive that the green hydrogen economy could provide. Also, the incremental value being created during the process of national decarbonization could be used to further aid domestic decarbonization goals.

Green hydrogen is still in an emerging phase. As with the evolution of any new technology, measures that have a shorter time-to-impact and higher ease of implementation could have the most profound near-term effects in steering India's green hydrogen ecosystem towards maturity.

If India is to reach its goal of becoming a global leader in green hydrogen production, it is vital that its central and state governments work together with industry participants and academia. Taking such a collaborative approach will enable the country to make the necessary changes and foster the innovations required to accelerate the growth of this exciting new energy technology.

Abbreviations

AEM
Anion exchange membrane electrolyser

ALK
Alkaline electrolyser

BESS
Battery energy storage systems

BNEF
Bloomberg New Energy Finance

CPSU
Central public sector undertaking

DISCOMs
Distribution companies

ESS
Energy storage systems

GHG
Greenhouse gas

GST
Goods and services tax

GUVNL
Gujarat Urja Vikas Nigam Limited

HDV
Heavy-duty vehicles

IEA WEO
International Energy Agency *World Energy Outlook*

IRR
Internal rate of return

LCOS
Levelized cost of storage

LNG
Liquefied natural gas

LOHC
Liquid organic hydrogen carrier

LPG
Liquefied petroleum gas

MMTPA
Million metric tonnes per annum

MoPNG
Ministry of Petroleum and Natural Gas, Government of India

MSEDCL
Maharashtra State Electricity Distribution Company Limited

PEM
Proton exchange membrane electrolyser

PLI
Production-linked incentive

PSH
Pumped storage hydropower

PV
Photovoltaic cell

RE
Renewable energy

RPO
Renewable power obligations

RTC
Round-the-clock

SECI
Solar Energy Corporation of India

SEZ
Special economic zones

SOEC
Solid oxide electrolyser cells

T&D
Transmission and distribution

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