Harnessing GREEN HYDROGEN

OPPORTUNITIES FOR DEEP DECARBONISATION IN INDIA

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About Us

About NITI Aayog

The National Institution for Transforming India (NITI Aayog) was formed via a resolution of the Union Cabinet on 1 January 2015. NITI Aayog is the premier policy 'Think Tank' of the Government of India, providing both directional and policy inputs. While designing strategic and long-term policies and programmes for the Government of India, NITI Aayog also provides relevant technical advice to the Centre and States. The Government of India, in keeping with its reform agenda, constituted the NITI Aayog to replace the Planning Commission instituted in 1950. This was done in order to better serve the needs and aspirations of the people of India. An important evolutionary change from the past, NITI Aayog acts as the quintessential platform of the Government of India to bring States to act together in national interest, and thereby fosters Cooperative Federalism.

About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing. RMI has been supporting India's mobility and energy transformation since 2016.

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Foreword

The publication of this report cannot come at a more opportune time as the urgency to take aggressive action to fight climate change has never been greater. The COP26 conference in Glasgow signalled India's willingness to show leadership in fighting climate change. Prime Minister Narendra Modi put forth India's vision to achieve net zero by 2070, in addition to achieving aggressive near-term targets such as 500 GW of renewables capacity, 50 percent of requirements to be met with renewables, one billion tonne reduction in cumulative emissions by 2030, and 45 percent lower emissions intensity of gross domestic product (GDP) by 2030.

Addressing the nation on the 75th Independence Day, Prime Minister Narendra Modi announced the National Hydrogen Mission with an aim of making India a hub for the production and export of green hydrogen. This is geared to make India energy independent before the country completes 100 years of its independence in 2047. Currently, India spends over $160 billion of foreign exchange every year for energy imports. These imports are likely to double in the next 15 years without remedial action. This report intends to highlight the unique ecosystem advantages India has and how the stage is set for the country to become a global champion in green hydrogen. The report works towards a hydrogen strategy that is designed to construct a high-tech and low-carbon Indian brand. If right steps are taken, the following targets can be achieved by India:

1. The world's largest electrolysis (green hydrogen generation) capacity of over 60 GW/5 million tonnes by 2030 for domestic consumption. This will help India meet the 500 GW renewable energy target.
2. The world's largest production of green steel at 15-20million tonnes by 2030 — a pioneering effort to make green steel mainstream for the world.

3. The world's largest electrolyser annual manufacturing capacity of 25 GW by 2028 delivering affordable ones for India and the world.
4. The world's largest production of green ammonia for exports by 2030 helping India's allies to decarbonise. This may require up to 100 GW of green hydrogen.
5. $1 billion investment into hydrogen research and development to enable breakthrough technologies for the world at scale and the speed that is required.

With proactive collaboration among innovators, entrepreneurs and government, green hydrogen has the potential to drastically reduce CO_2 emissions, fight climate change, and put India on a path towards net-zero energy imports. It will also help India export high-value green products making it one of the first major economies to industrialise without the need to 'carbonise'. This report is a result of 12 months of intensive consultative analysis by NITI Aayog and complemented by independent techno-economic modelling of RMI.

Amitabh Kant, CEO (NITI Aayog)

Foreword

India is undertaking a resolute march towards a sustainable energy future. Prime Minister Narendra Modi's pledge at COP26 towards a net-zero India by 2070 promises to accelerate this momentum. Much action will be required to fulfil these pledges.

Central to a decarbonised India will be a widespread adoption of renewable power and vehicle electrification. Targets and policies such as the 500 GW non-fossil fuel electricity capacity by 2030, scheme for Faster Adoption and Manufacturing of Electric Vehicles- Phase II (FAME II), and ₹18,100 crore production-linked incentives for encouraging manufacturing of advanced cell chemistry (ACC) batteries in the country, represent a concrete policy push towards fulfilling these ambitions.

To further complement these ongoing efforts, India is prioritising green hydrogen as a potential solution to decarbonise hard-to-abate sectors such as refinery, ammonia, methanol, iron and steel and heavy-duty trucking. Prime Minister Modi recently announced the National Hydrogen Mission with the aim of making India the world's largest hydrogen hub. The efforts of the Mission has resulted in the recently approved Green Hydrogen Policy.

India's distinct advantage in terms of low-cost renewable electricity, complemented by rapidly falling electrolyser prices, can enable green hydrogen to be not just economical compared to fossil-fuel based hydrogen but also compared to the green hydrogen being produced around the globe.

Adoption of green hydrogen can enable India to abate 3.6 gigatonnes of CO_2 emissions cumulatively between now and 2050. This can be a significant lever for the nation to contribute towards its recently announced climate targets and net-zero vision.

As highlighted in this report, India can target the following areas to make a successful transition to green hydrogen.

- Both near-term and long-term policy pathways to reduce the cost of green hydrogen need to be encouraged to enable cost competitiveness against alternatives.
- A cost-competitive green hydrogen is bound to lead to market creation. But the government can also encourage near-term market development by identifying industrial clusters and enacting associated viability gap funding and mandates.
- An emerging green hydrogen economy means opportunities around research and development and manufacturing of components such as electrolysers and fuel cells, crucial to enabling the industry to develop and scale.
- A globally competitive green hydrogen industry also leads to prospects of exports of green hydrogen and hydrogen-embedded low-carbon products such as green ammonia and green steel.

India is at a crucial juncture in terms of its energy landscape and green hydrogen has a critical role to play to make the nation self-reliant and energy-independent. Hydrogen can be an energy molecule that is truly 'made-in-India' and that can contribute to the country's energy security and long-term economic competitiveness. India has the unique opportunity to capitalise on this new technology and become a world leader in green hydrogen production and its applications.

We would like to congratulate NITI Aayog for its leadership and partnership in the development of this report and for laying out a green hydrogen roadmap. We hope this report will provide useful inputs for the National Hydrogen Mission and its planning and implementation.

Clay Stranger (Managing Director, RMI)

Preface

The Ministry of Power (MoP) recently unveiled the first part of India's much awaited Green Hydrogen Policy on February 17, 2022. The policy is one of the key outcomes of the National Hydrogen Mission which was launched by the Hon'ble Prime Minister, Shri Narendra Modi, on India's 75th Independence Day last year. It marks the culmination of months of efforts across multiple ministries and stakeholder groups, and affirms India's intent to be a global green hydrogen hub.

There is also an increased consensus around the world that concerted steps need to be taken to reduce global warming to levels less than 2°C and if possible to cap it at 1.5°C higher than pre-industrial levels. Various countries have pledged their Nationally Determined Contributions to ensure energy transition and reduce emissions.

This report aspires to serve as one of the key knowledge bases for the benefit of India's Green Hydrogen Policy discourse and private sector investment decisions. It was developed over the course of a year by the NITI Aayog team with RMI as the knowledge partner. Beyond primary analysis, the report takes into account views expressed during stakeholder engagements across academia, think tanks, private sector entities, and startups. The report aims at providing the much-needed direction and insight for the stakeholders to act on at this crucial juncture of industry building.

India's Green Hydrogen Policy

Most large economies including India have committed to net zero targets. Transition to Green Hydrogen and Green Ammonia is one of the major requirements for reduction of emissions, especially in the hard to abate sectors. Government of India have had under consideration a number of policy measures in order to facilitate the transition from fossil fuel I fossil fuel based feed stocks to Green Hydrogen / Green Ammonia both as energy carriers and as chemical feed stock for different sectors. After careful consideration, the Government of India have framed the policy on Green Hydrogen which provides the following:

1. Green Hydrogen / Green Ammonia shall be defined as Hydrogen / Ammonia produced by way of electrolysis of water using Renewable Energy; including Renewable Energy which has been banked and the Hydrogen/Ammonia produced from biomass.

2. The waiver of inter-state transmission charges shall be granted for a period of 25 years to the producer of Green Hydrogen and Green Ammonia from the projects commissioned before 30th June 2025.
3. Green Hydrogen / Green Ammonia can be manufactured by a developer by using Renewable Energy from a co-located Renewable Energy plant, or sourced from a remotely located Renewable Energy plants, whether set up by the same developer, or a third party or procured renewable energy from the Power Exchange. Green Hydrogen/Green Ammonia plants will be granted Open Access for sourcing of Renewable Energy within 15 days of receipt of application complete in all respects. The Open Access charges shall be in accordance with Rules as laid down.
4. Banking shall be permitted for a period of 30 days for Renewable Energy used for making Green Hydrogen / Green Ammonia.
5. The charges for banking shall be as fixed by the State Commission which shall not be more than the cost differential between the average tariff of renewable energy bought by the distribution licensee during the previous year and the average market clearing price (MCP) in the Day Ahead Market (DAM) during the month in which the Renewable Energy has been banked.
6. Connectivity, at the generation end and the Green Hydrogen / Green Ammonia manufacturing end, to the ISTS for Renewable Energy capacity set up for the purpose of manufacturing Green Hydrogen / Green Ammonia shall be granted on priority under the Electricity (Transmission system planning, development and recovery of Inter State Transmission charges) Rules 2021.
7. Land in Renewable Energy Parks can be allotted for the manufacture of Green Hydrogen / Green Ammonia.
8. The Government of India proposes to set up Manufacturing Zones. Green Hydrogen / Green Ammonia production plant can be set up in any of the Manufacturing Zones.
9. Manufacturers of Green Hydrogen / Green Ammonia shall be allowed to set up bunkers near Ports for storage of Green Ammonia for export / use by shipping. The land for the storage purpose shall be provided by the respective Port Authorities at applicable charges.
10. Renewable Energy consumed for the production of Green Hydrogen / Green Ammonia shall count towards RPO compliance of the consuming entity. The renewable energy consumed beyond obligation of the producer shall count towards RPO compliance of the DISCOM in whose area the project is located.
11. Distribution licensees may also procure and supply Renewable Energy to the manufacturers of Green Hydrogen / Green Ammonia in their States. In such cases, the Distribution licensee shall only charge the cost of procurement as well as the wheeling charges and a small margin as determined by the State Commission.
12. Ministry of New and Renewable Energy (MNRE) will establish a single portal for all statutory clearances and permissions required for manufacture, transportation, storage and distribution of Green Hydrogen / Green Ammonia. The concerned agencies/authorities will be requested to provide the clearances and permissions in a time-bound manner, preferably within a period of 30 days from the date of application.
13. In order to achieve competitive prices, MNRE may aggregate demand from different sectors and have consolidated bids conducted for procurement of Green Hydrogen/Green Ammonia through any of the designated implementing agencies.

Executive Summary

Executive Summary

Hydrogen, as an energy carrier, is becoming crucial for achieving decarbonization of hard-to-abate sectors. Many sectors such as iron ore and steel, fertilizers, refining, methanol, and maritime shipping emit major amounts of CO_2, and carbon-free hydrogen will play a critical role in enabling deep decarbonization. For other high-emitting sectors, such as heavy-duty trucking and aviation, hydrogen is among the main options being explored with an outlook to be the preferred solution for several applications.

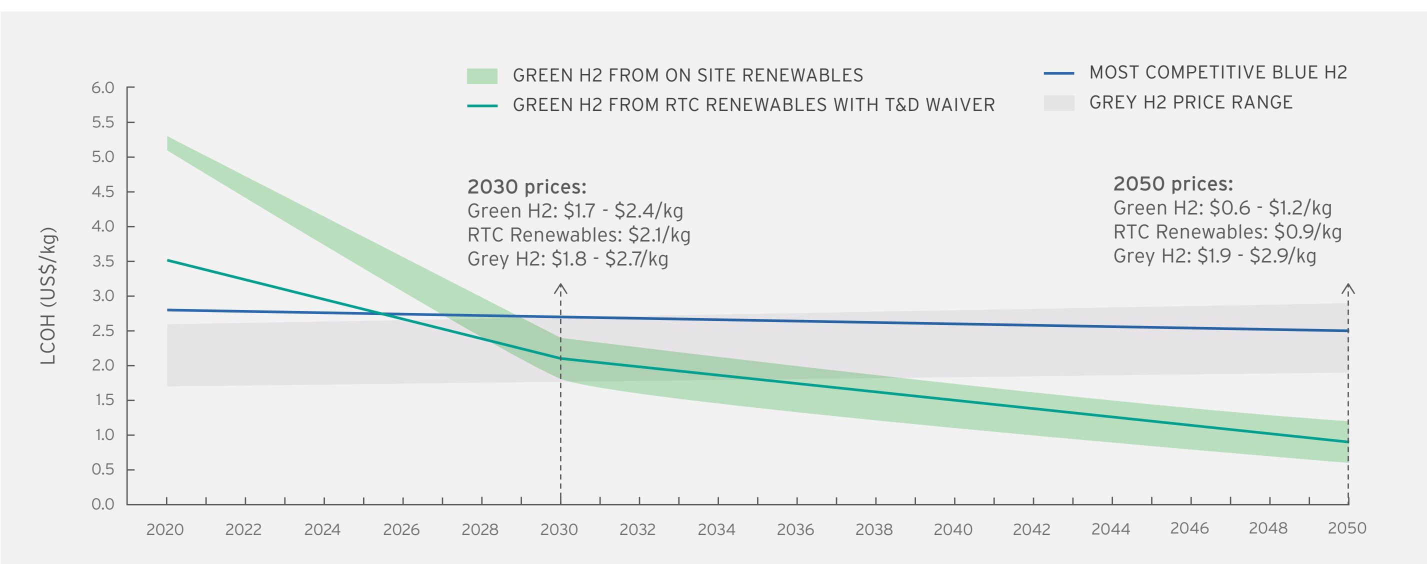
This has resulted in growing global momentum towards hydrogen in general, and green hydrogen—hydrogen produced through electrolysis of water using electricity from renewable sources—in particular. Declining prices of hydrogen, coupled with growing urgency for decarbonization means the global demand for hydrogen could grow by almost 400 percent by 2050, led by industry and transportation.[1]

A new growth momentum is emerging among various nations. At least 43 countries have now set up or are setting up strategies or roadmaps for a hydrogen economy,[2] including financial incentives to accelerate the transition. For India, this current impetus surrounding the hydrogen transition fits well within the context of a low-carbon economy, energy security, and the larger economic development ambition of the nation.

The Prime Minister's Independence Day speech on August 15th, 2021, signalling the launch of the National Hydrogen Mission, attests to India's intent to be a global hub for green hydrogen. As PM Modi's speech outlines, "not only will green hydrogen be the basis of green growth through green jobs, but it will also set an example for the world towards clean energy transition."[3]

India's distinct advantage in low-cost renewable energy generation makes green hydrogen the most competitive form of hydrogen in the long run (Exhibit 1). This enables India to potentially be one of the most competitive producers of green hydrogen in the world. Green hydrogen can achieve cost parity with natural gas-based hydrogen (grey hydrogen) by 2030, if not before. Beyond cost, since hydrogen is only as clean as its source of generation, green hydrogen will be necessary to achieve a truly low-carbon economy. It will also enable the emergence of a domestically produced energy carrier that can reduce the dependence on imports for key commodities like natural gas and petroleum.

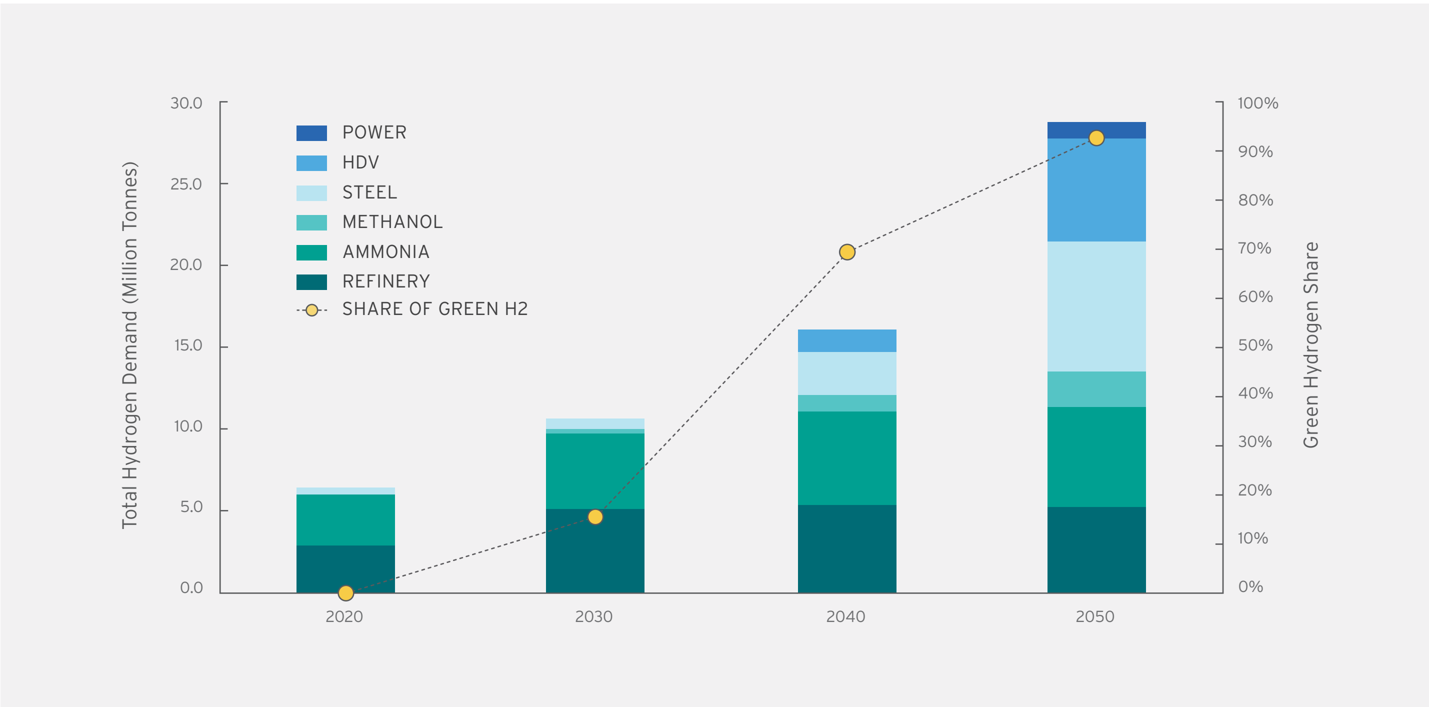
Exhibit 1 Projected price trajectory of solar-green hydrogen production based on decline in electrolyser and renewable costs



Source: IEA, BNEF, TERI, SECI, RMI Analysis | **Currency conversion:** $1 = ₹72

Hydrogen demand in India could grow more than fourfold by 2050, representing almost 10% of global hydrogen demand.[4] Initial demand growth is expected from mature markets like refinery, ammonia, and methanol, which are already using hydrogen as industrial feedstock and in chemical processes. In the longer term, steel and heavy-duty trucking are likely to drive the majority of demand growth, accounting for almost 52% of total demand by 2050.[5]

Exhibit 2 Hydrogen demand outlook and potential green hydrogen share at cost parity (without policy intervention)



Source: MoS, MoC&F, MoPNG, IEA, TERI, BCG, World Bank, RMI Analysis

From a price parity basis alone, green hydrogen's share of this demand could grow from 16% in 2030 to almost 94% by 2050. This translates to an implied cumulative electrolyser capacity demand of 20 GW by 2030 and 226 GW by 2050, promising a sizeable opportunity for indigenous manufacturing of a global emerging energy technology. The cumulative value of the green hydrogen market in India could be $8 billion by 2030 and $340 billion by 2050. Electrolyser market size could be approximately $5 billion by 2030 and $31 billion by 2050.

Adoption of green hydrogen will also result in 3.6 giga tonnes of cumulative CO_2 emissions reductions between 2020 and 2050.[6] Energy import savings from green hydrogen can range from $246 billion to $358 billion within the same period.[7] Beyond the financial savings, the energy security that green hydrogen provides will translate to less volatile price inputs for India's industries as well as strengthen India's foreign exchange situation in the long run.

While the prospects for domestic demand and exports are enticing, it's also important to achieve the expected decline in price. In the near-term, it's crucial to focus on domestic demand creation efforts, cost reduction pathways, and early pilots, as well as to learn by doing in competitive manufacturing of electrolysers. Limitation of storage and the high cost of transportation means that early market development should centre on identifying clusters of industrial demand that could be served by localized generation of hydrogen.

The government can reduce costs through preferential electricity tariffs. And it can develop the market through incentives and mandates for existing hydrogen-consuming sectors like refinery and ammonia/fertilizer, which will require comparatively lower transition support.

Such favourable policies can greatly increase demand for hydrogen and the accompanying electrolyser capacity required. It can provide a degree of near-term demand certainty for the private sector, given the risks associated with investment in early-stage energy technologies like hydrogen. This demand certainty can set the stage for green hydrogen to ride the cost reduction curve and achieve scaled adoption in the long term. And in the process it can lead to decarbonization, energy and economic security, and indigenous manufacturing.

A truly domestic energy carrier that is competitive globally can also provide a unique opportunity to participate in the energy and commodities trade. Given the expected growth in global demand and the disparity between producing and consuming nations, the need for hydrogen trade is bound to emerge eventually. If volume growth and price decline expectations can be met, this hydrogen transition can enable industries to shape up in India around exports of green hydrogen and hydrogen-embedded low-carbon commodities like green ammonia and green steel.

Towards a National Action Plan on Green Hydrogen

Given the prospects that green hydrogen presents for India, real action is required for the country to truly benefit from the opportunities. This report provides ten actionable steps that can guide a National Action Plan on Green Hydrogen.

1. A detailed roadmap focused on all aspects of 'Green Hydrogen'

The recent announcement of the National Hydrogen Mission needs to be complemented with further policy direction in the form of a national roadmap/strategy.[8] A long-term roadmap focused on green hydrogen will improve investors' confidence and will converge the entire value chain and the various government agencies towards a singular vision.

2. Intervene on the supply-side to reduce the cost of green hydrogen to $1/kg

Similar to other technology deployment and scaling efforts, government can encourage the cost economics of early producers. The current Green Hydrogen policy already focuses on measures like waiver of inter-state transmission (ISTS) charges and granting of open access for green hydrogen and green ammonia production. Other measures could include reduction in taxes and surcharges, preferential dollar-based electricity tariff, revenue recycling of any carbon tax, low-emission power purchase agreements (PPAs), and avenues for firming electricity supply including discounted grid electricity to complement variable renewable energy (VRE) generation.

3. Establish mandates and provide incentives to achieve a green hydrogen production capacity of 160 GW

The government can propose **clear mandates** around hydrogen blending in existing (refinery and ammonia) and potentially future consumption sectors (steel and heavy-duty vehicles). This will provide demand certainty for early green hydrogen projects and encourage market development. For new applications, where the viability of using green hydrogen is still nascent, the government can provide incentives such as a production linked incentive (PLI) scheme for green steel targeting export markets.

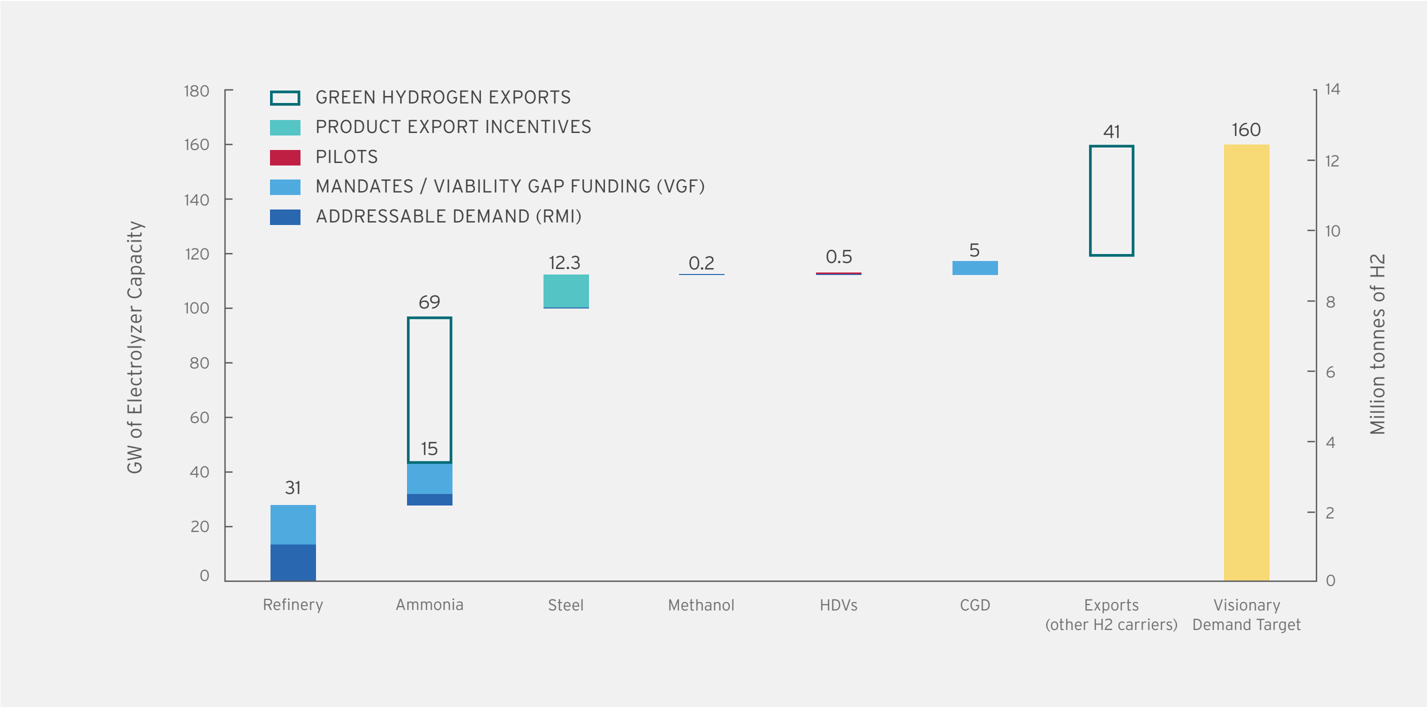
4. Build manufacturing capacity totalling 25GW by 2030 coupled with supportive manufacturing and R&D investments

The roadmap should also identify a timeline and scale of manufacturing support for electrolysers. India may aim for 25 GW of electrolysers by 2030, while also investing $1 billion in R&D to catalyse the development of commercial green hydrogen technologies across the value chain. Radically improving the speed of regulatory clearances coupled with preferential treatment in public tenders will help catalyse local manufacturing. Grand challenges, public-private venture capital and financing test bench infrastructure could be part of the R&D investments.

5. Initiate green hydrogen standards and a labelling programme

Immediate action should be undertaken to further develop standards and a green hydrogen labelling programme.

Exhibit 3 Visionary 2030 electrolyzer target for green hydrogen production



Source: NITI Aayog

* Note 1: 1 million tonnes of green hydrogen corresponds to around 11-13 GW of electrolyser capacity.
* Note 2: Additional demand could arise from electric fuels and 24X7 power storage depending on tech and policy evolution
* Note 3: Exports (other H2 carriers) refers to a possible development of new H2 carriers. If new carriers are not realised, Ammonia is likely to fulfil this portion of demand (41 GW).

6. Promotion of exports of green hydrogen and green hydrogen-embedded products through a global hydrogen alliance

The government must explore integrating hydrogen into existing energy and industrial partnerships globally. This should include developing collective frameworks and creating labelling and standards around green hydrogen and hydrogen-embedded products like green steel and green ammonia. The government should explore specific near-term incentives around green ammonia and green steel production.

7. Facilitate investment through demand aggregation and dollar-based bidding for green hydrogen

The government can provide financial certainty to early adopters through investment facilitation measures like demand aggregation, ensuring availability of long-tenor and low interest finance and initiation of a functioning carbon market.

8. Encourage state-level action and policy making related to Green Hydrogen

States should be encouraged to launch their own green hydrogen-based policies in order to complement efforts at the national-level. This way the champion green hydrogen states could also be identified.

9. Encourage capacity building and skill development

Initiate appropriate and rapid skills development across the ecosystem including government, industry, and academia addressing technologies, business models, policies, and geopolitics.

10. Construct an inter-ministerial governance structure

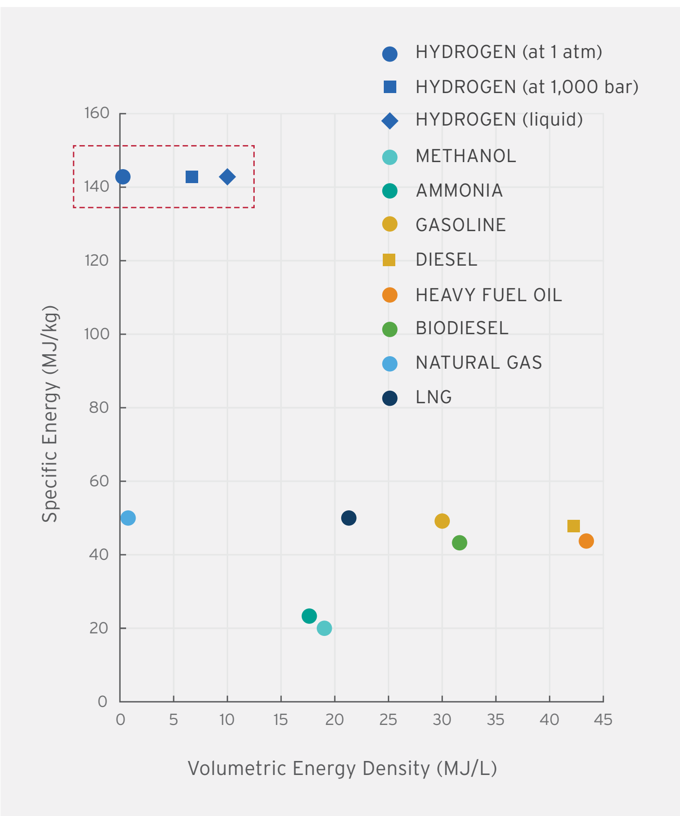
The government should create an interdisciplinary Project Management Unit (PMU) with globally trained experts. The PMU should dedicate fulltime resources to effectively implement the mission. At the policy level, an inter-ministerial mechanism should be instituted to coordinate across the efforts of the various ministries and departments required to achieve the target of the mission.

Introduction

Introduction

The world is in a unique and necessary phase of energy transition, where emerging low-carbon technologies are replacing existing fossil fuel assets and are shaping a new energy paradigm. Rise of technologies such as solar and wind, lithium-ion batteries, and alternative fuels have paved the way for decarbonization in various end-use sectors. However, there are certain sectors like industry and heavy transport that are hard to decarbonize using the current low- or zero-carbon technologies. Hydrogen promises to address those challenges and contribute to the decarbonization of these hard-to-abate sectors.

Exhibit 4 Energy density profile of different fuels compared with Hydrogen



Source: World Bank ESMAP

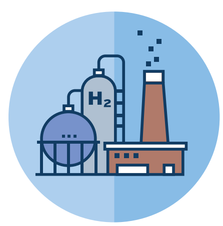
Hydrogen fundamentals

Hydrogen is an energy carrier and can be used for a wide array of energy and industrial applications. It can also be stored for long time. The opportunities and challenges of hydrogen emerge from its energy characteristics (see Exhibit 4[9]). Hydrogen's specific energy (i.e.,energy content per unit of mass) is higher than most hydrocarbon fuels. But its volumetric energy density is the lowest. That means pressurization or liquefaction is required for hydrogen to be useful as a fuel. These two properties drive the value as well as the applicability of hydrogen for the various possible end-use cases.

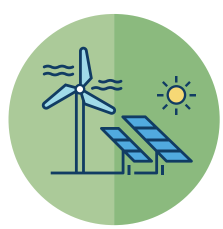
Production

Although hydrogen is the lightest and most abundant element in the universe, it is rarely found in nature in its elemental form and always must be extracted from other hydrogen-containing compounds. It also means that how well hydrogen contributes decarbonization depends on how clean and green the method of production is. Based on the sources and processes, hydrogen can be classified into various colours:

- **Black / Brown / Grey hydrogen** is produced via coal or lignite gasification (black or brown), or via a process called steam methane reformation (SMR) of natural gas or methane (grey). These tend to be mostly carbon-intensive processes.



- **Blue hydrogen** is produced via natural gas or coal gasification combined with carbon capture storage (CCS) or carbon capture use (CCU) technologies to reduce carbon emissions.



- **Green hydrogen** is produced using electrolysis of water with electricity generated by renewable energy. The carbon intensity ultimately depends on the carbon neutrality of the source of electricity (i.e., the more renewable energy there is in the electricity fuel mix, the "greener" the hydrogen produced).

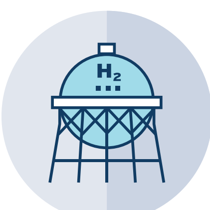
Central to the green hydrogen production process is the electrolyser technology. **Alkaline and polymer electrolyte membrane (PEM) electrolysers** are two commercially available technologies for green hydrogen production today. Advanced electrolyser technologies like solid oxide and anion exchange membrane nearing commercial deployment as well.

- Other less prevalent sources of production include bio-hydrogen which can either be produced by an SMR process around methane produced by anaerobic digestion of organic waste or through a fermentation process by bacteria.

Transportation and Storage

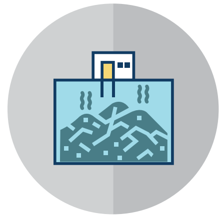
Storage and transportation of hydrogen have traditionally been difficult due to the unique characteristics of the gas–flammability, low density, ease of dispersion, and embrittlement.[i] Yet technical development and commercial impetus are increasingly enabling more economic modes of storage and transportation.

Hydrogen has three main avenues for storage, each with their own use cases and challenges:



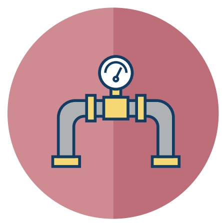
- **Storage Tanks** are the simplest and at times economical way to store and transport hydrogen–usually in the form of compressed and cryo-compressed hydrogen.[ii] The challenge for compressed hydrogen storage is that hydrogen's low-density results in the need for large containers–three times the size used for methane and ten times the size used for petrol[10]–which increases the material costs. Liquefaction of hydrogen is another way to increase density, but liquefaction also has higher energy costs–up to 30% of the energy content of the fuel compared with 4%–7% for compressed hydrogen.[11]

- **Chemical storage** in in the form of compounds such as liquified organic hydrogen carriers (LOHCs) like methanol and toluene, and hydrides such as ammonia (NH_3) are also gaining prominence given the high energy cost of liquefaction and material inefficiencies of compression. Each mode of chemical storage, however, comes with its own uses and hurdles, including energy conversion cost and chemical characteristics that require careful handling etc.[12]



- **Natural underground storage in salt caverns and salt domes** are large volume, low-cost, natural storage options, but local availability can be a challenge.

Hydrogen can be transported three main ways, depending on the distance, volume, and state in which transporting:



- **Pipelines** tend to be the cheapest way to move hydrogen over longer distances. Constructing pipelines usually requires volume and demand certainty to justify investment. Additionally, existing natural gas pipelines can be repurposed provided they meet the technical criteria to reduce the risk of embrittlement. Repurposing of existing pipelines also enables blending of hydrogen within the existing natural gas networks for end uses where blended hydrogen can accelerate demand creation.

- **Trucks** are also used to transport hydrogen in smaller volumes, both in gaseous and liquid form, for local distribution and longer journeys.

- **Tanker ships** are beginning to be used for larger volume, longer distance transport, mainly moving liquid hydrogen (LH2), LHOCs, and ammonia. Shipping of hydrogen is currently expensive due to added conversion costs (liquefaction or chemical conversion) in addition to the necessary structural design to reduce risk of embrittlement.

Challenges to a Hydrogen transition

In addition to the technical challenges discussed above, the emergence of a hydrogen economy has been challenging because of high costs, supply chain complexity, policy, and regulations.

The cost of green hydrogen production is much higher than what is produced from fossil fuels. Decreasing renewables prices and economies of scale promise to make green hydrogen economical going forward, but much work remains.

Hydrogen can be produced by a variety of process and has use in various sectors, making its sourcing and supply chain complicated when compared to oil and gas. Moreover, as discussed above, transporting and storing hydrogen remain a big challenge and will require massive investment in infrastructure upgrades.

Traditionally, hydrogen has seen minimal policy support from governments across the globe so far. Policy push has been towards other technology options and end uses, even when hydrogen can make a much bigger impact. Lastly, standards around hydrogen use either don't exist or haven't been updated.

Emerging Importance of Hydrogen

Despite all the challenges discussed, hydrogen's utility for selected use cases is increasingly providing economic value compared with alternatives. This is slowly shaping a market for hydrogen.

Hydrogen can be consumed through either direct combustion, electricity generation through fuel cells, or industrial processes to be used as chemical feedstock. Direct use includes industrial processes in iron and steel plants and refineries; transportation fuel for light duty vehicles, buses, trucks, trains, and potentially shipping and aircrafts; and power sector storage and grid balancing and for co-firing in thermal power plants. Hydrogen is essential as a chemical feedstock for the production of ammonia (used in the fertilizer industry), methane, and methanol.

Exhibit 5 Hydrogen End Use

While the use cases for hydrogen are not a new revelation, the emerging momentum is a recent phenomenon and hinges on hydrogen's role as an **energy carrier** crucial for achieving **deep decarbonization of hard-to-abate sectors.** Existing low-carbon technologies and techniques such as solar, wind, Li-ion batteries, and energy efficiency are contributing to the decarbonization of various sectors such as power generation, buildings, and light transportation.

However, carbon-free hydrogen will play a critical role in decarbonizing certain end-use sectors such as iron ore and steel, fertilizers, refining, methanol, and maritime shipping, which emit major amounts of CO_2. For other high-emitting sectors, such as heavy-duty trucking and aviation, hydrogen is among the main options being explored with an outlook to be the preferred solution for several applications.

Further, production of hydrogen through electrolysis of water can **support widespread renewable electricity generation** and can act as an energy storage mechanism. Moreover, decreasing costs of renewables will lead to a reduction in hydrogen production costs, making hydrogen more competitive.

Lastly, hydrogen can help reduce the nation's reliance on oil imports and bolster a domestic job market. Additionally, it provides the ability to participate in the ensuing global energy transition and the economic opportunity that transition presents.

A renewed momentum

With countries' and companies' growing net-zero emission targets and hydrogen's capability to decarbonize the hard-to-abate sectors, hydrogen has started witnessing new momentum among various nations. At least 43 countries have now set up or are setting up either strategies or roadmaps for a hydrogen economy.[13] Most of the government related R&D funding for hydrogen is concentrated in Europe, the United States, Japan, and China.[14]

Exhibit 6 Mapping emerging hydrogen roadmaps and strategy documents of leading countries and regions[15,16]

	Current Hydrogen Demand	Policy Target Demand	Capital Allocated (US$)	Focused Hydrogen Source	Demand Focus: Industry	Demand Focus: Transport	Demand Focus: Others	Export/ Import Focus
European Union		6 GW capacity by 2024; 40 GW by 2030; 10 MMTPA green H_2 by 2030	609 billion	Low Carbon - Blue / Green	1. Chemical feedstock 2. Refining	1. Medium and Heavy Duty 2. Buses 3. Rail		
Germany	1.65 MMTPA	2.7-3.3 MMTPA by 2030	15-20 billion	Carbon free - Blue / Green	1. Iron and Steel 2. Chemical feedstock 3. Refining	1. Medium and Heavy Duty 2. Buses 3. Rail		Import
France	0.9 MMTPA	6.5 GW via electrolysis by 2030	> 7 billion	Low Carbon - Blue	1. Iron and Steel 2. Chemical feedstock 3. Refining 4. Others	1. Medium and Heavy Duty 2. Buses 3. Rail 4. Aviation		Export
Netherlands	1.5 MMTPA	Not Available	40-55 million/yr	Blue / Green	1. Iron and Steel 2. Chemical feedstock 3. Refining 4. Others	1. Passenger Vehicle 2. Medium and Heavy Duty 3. Buses 4. Rail	1. Heating	EU Export/ Import Hub
Hungary	160 ktpa	36 ktpa (low carbon) + 138 ktpa (grey) by 2030	450 million	Low Carbon - Grey / Blue	1. Chemical feedstock 2. Refining	1. Medium and Heavy Duty 2. Buses	1. Heating	
Portugal	~150 ktpa	2-2.5 GW via electrolysis by 2030 400 ktpa overall by 2030	No dedicated capital	Green	1. Iron and Steel 2. Chemical feedstock 3. Refining 4. Others	1. Passenger Vehicle 2. Medium and Heavy Duty 3. Buses	1. Heating	Export
Spain	0.5 MMTPA	4 GW via electrolysis by 2030	No details	Green	1. Chemical feedstock 2. Refining			Export
United Kingdom	0.7 MMTPA	5 GW/a electrolysis capacity by 2030	2 billion	Blue / Green	1. Chemical feedstock 2. Iron and Steel	1. Medium and Heavy Duty 2. Buses 3. Rail 4. Aviation 5. Shipping	1. Heating 2. Power	Export
Norway			23 million	Clean	1. Chemical feedstock	1. Maritime		
Japan	2 MMTPA	3 MMTPA by 2030 and 20 MMTPA by 2050 (5-30 by 2050)	935 million / yr	Blue		1. Passenger Vehicle	1. Heating 2. Power	Import
South Korea	220 ktpa	3.9 MMTPA by 2030 and 27 MMTPA by 2050	653 million / yr	Grey / Blue / Green		1. Passenger Vehicle 2. Medium and Heavy Duty 3. Buses	1. Power	Import
United States	10 MMTPA		> 15 billion	Low Carbon - Blue / Green / Others	1. Refining 2. Others	1. Passenger Vehicle 2. Medium and Heavy Duty 3. Buses 4. Aviation	1. Heating 2. Power 3. Energy storage	
Canada	3 MMTPA	20 MMTPA	1.2 billion	Low Carbon Intensity - Grey / Blue	1. Iron and Steel 2. Chemical feedstock 3. Refining 4. Others	1. Passenger Vehicle 2. Medium and Heavy Duty 3. Buses 4. Rail	1. Heating	Export
Australia	650 ktpa		278 million (annual support)/ yr	Clean - Blue / Green	1. Chemical feedstock	1. Medium and Heavy Duty 2. Buses	1. Heating	Export
Chile	58.5 ktpa	5 GW/a (2025) 25 GW/a (2030)	50 million	Green	1. Chemical feedstock 2. Refining	1. Medium and Heavy Duty 2. Buses	1. Heating	Export
China	22 MMTPA	35 MMTPA (by 2030); 160 MMTPA (by 2050)	13 million	Green (long-term)		1. Passenger Vehicle 2. Medium and Heavy Duty 3. Buses	1. Power	
Russia	2-3.5 MMTPA	7 MMTPA by 2035 and 33 MMTPA by 2050 (export only)	1.2 billion	Low Carbon - Blue / Nuclear	1. Refining	1. Rail		Export

Over the past decade, financial support to hydrogen by governments has increased. The amount of support depends on countries' advancement of their hydrogen agenda. While early support had focused on R&D and initial investments, much of the newer financial support aims to close the gap on the operating cost differential to existing technologies. Globally, governments are moving towards supporting commercialisation and demonstration of entire value chains, often through public-private partnerships (See Appendix for details on country strategy). Nations are increasingly using regions, cities, or industrial clusters as focal points of financing. In addition to direct support and programs, public financial institutions are being engaged to support the transition.

Currently, almost $11.4 billion per year of national government subsidies have become available for hydrogen projects directly or indirectly.[17] This signals a growing intent to spur the hydrogen economy, akin to the support the solar and wind industries received over the previous decades.

Global Hydrogen Supply and Demand – Where is hydrogen now and where it is heading?

Given this growing support, global supply and demand of hydrogen, particularly green hydrogen is expected to witness tremendous growth. Sustaining this policy momentum is the emerging economics of green hydrogen production (see Box 1). Although 98% of hydrogen is currently produced from fossil fuels (Natural gas – 71%, Coal – 27%)[18], in the last decade, number of electrolyser projects have jumped from 40 to 100, amounting to an increase in their capacity from 2 MW to over 200 MW in 2020.[19]

Box 1 What Drives the cost of Hydrogen production?[20]

GREY HYDROGEN ECONOMICS

Hydrocarbon economics (LNG / fossil fuel landed cost + transportation) + Foreign exchange (if fuel is imported) + Transportation, Storage and Others

GREEN HYDROGEN ECONOMICS

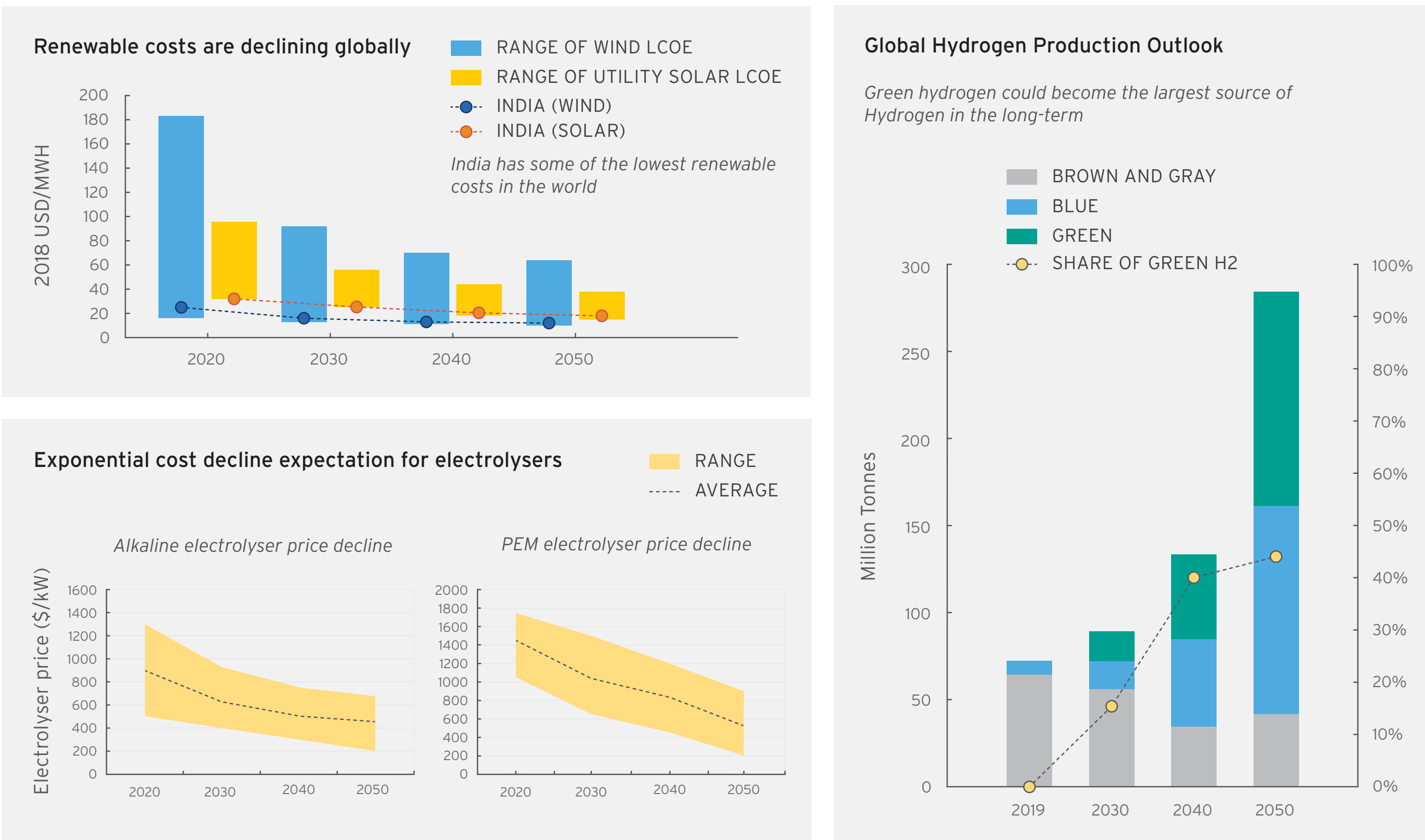
Electricity Cost (Generation cost + utilization factor + T&D cost) + Electrolyser Cost (Capex + efficiency & degradation) + Transportation, Storage and Others

For traditional fossil fuel-based grey (or even brown) hydrogen, the fossil fuel price is the biggest determinant of hydrogen cost. Other costs include for transportation and storage and any taxes or foreign exchange risk associated with fuel imports. For blue hydrogen, the cost of carbon capture and storage (CCS) will need to be included. The difference with green hydrogen is that, in the absence of fuel, the capital expenditure around electrolysers (and any other associated infrastructure) and their utilization and power costs are what ultimately decides the production economics.

Central to global scale-up of green hydrogen, are the lowering of renewable costs and expected cost decline of electrolysers. IRENA estimates an 80% drop in green hydrogen costs if the electrolyser capital cost falls by 80% and the electricity costs drop below $20/MWh. Additional factors like higher capacity factors of renewable energy generators, increased electrolyser efficiency, and longer electrolyser lifetimes are important contributing factors that can enable the cost-competitiveness of green hydrogen.

Renewables prices have witnessed incredible declines over the past years and the economic inertia is expected to drive further decrease. When coupled with the decline in electrolyser costs, as technology matures and volume production and deployment take place, there is an emerging consensus that green hydrogen production will become economical. RMI's analysis of IEA's outlook shows that the green hydrogen market could be US$120–US$175 billion annually by 2050 based on a range of projected prices.[iii,21]

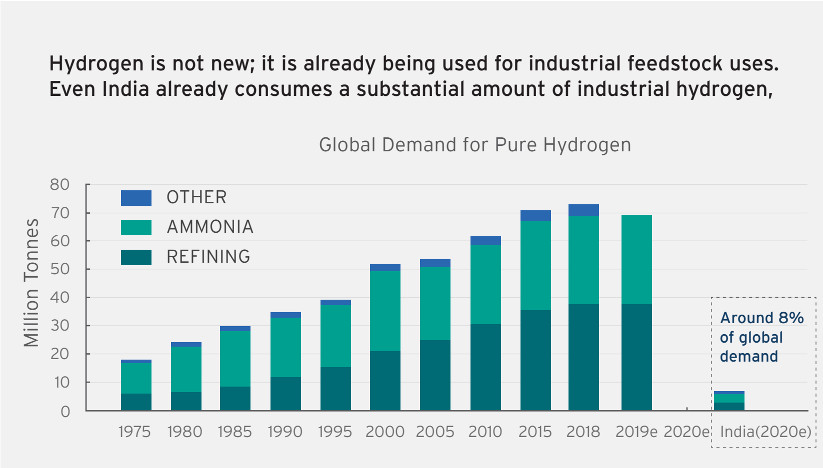
Exhibit 7 The driving forces of the emerging economics of green hydrogen

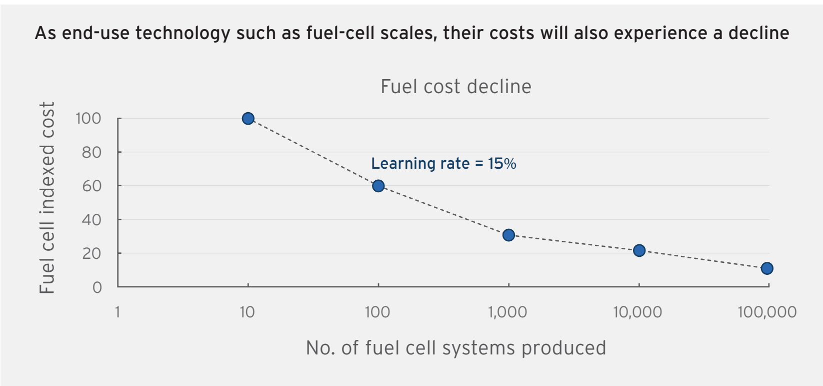


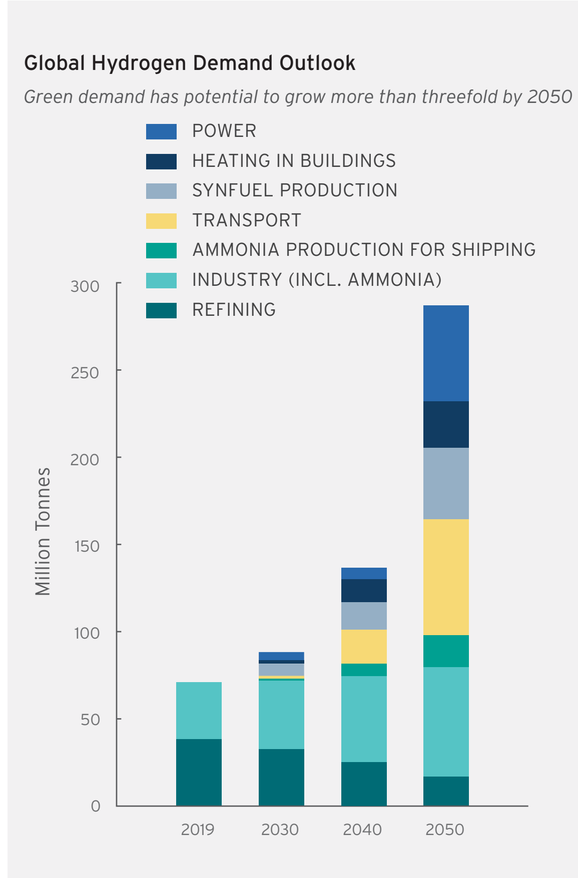
Source: IRENA, BNEF, IEA

Globally, demand for hydrogen has increased by 17% between 2010 and 2018,[22] used mostly to produce ammonia and in refineries. With the global decarbonization push, current policy momentum, and improvement in economics and durability of end-use technologies like fuels cells, hydrogen could serve 7%–18% of global final energy demand in 2050.[23] Significant upside exists if net zero targets are pursued seriously. The IEA projects potential hydrogen demand of 528 million tonnes under their net zero scenario, up from 287 million tonnes as per their sustainable development scenario.[iv] This could result in the mitigation of 1.6-3.5 giga tonnes of greenhouse gas emissions annually by 2050.[24] Industrial decarbonization (both energy and feedstock) is driving near-term hydrogen demand creation. But longer-term opportunities fall in transport, power, and even for decarbonization of the shipping and airline industry.

Exhibit 8 Hydrogen demand is expected to grow substantially







Source: IEA, S&P, Ballard, US DoE, RMI Analysis

Given the projected growth in green hydrogen, there is consequent expectation for an exponential growth in electrolyser capacity. The electrolyser market is expected to reach gigawatt-scale in 2022 spurred by increasing installation in China.[25] Almost 40 GW of electrolysers by 2030 are already proposed.[26] There could be significant increase if an aggressive green hydrogen price decline allows for the replacement of blue hydrogen with green hydrogen.

What could hydrogen mean for India?

For India, this momentum currently surrounding the hydrogen transition efforts needs to be situated within the context of a low-carbon economy, energy security, and the larger economic development ambition of the nation.

India's thrust towards a low-carbon economy currently hinges on an accelerated transition towards a higher share of renewables in the electricity grid complemented by electrification of end uses such as transportation. But there is a tacit recognition that materials critical to industrialisation and urbanization such as steel, ammonia, cement, and plastic have no substitutes and cannot be decarbonized with electricity alone.[27] Green hydrogen is a necessary lever to achieve a truly low-carbon economy.

For India, this transition can be synergistic with the scale, ambition, and economic competitiveness of its renewable industry. Unlike fossil fuels which have resource and geography constraints, green hydrogen can be produced anywhere there is ample renewable potential. India is blessed in that aspect. This will enable the emergence of an energy carrier that is domestically produced, reducing the dependence on imports for key energy commodities like natural gas and petroleum.

Given that the cost of electrolysers must decline for hydrogen to become cost-competitive, research and development and scaled manufacturing of electrolysers is becoming an area of global technology competition. India will benefit greatly from enabling domestic manufacturing of electrolysers (and relatedly fuel cells). This will allow the country to achieve technical capability, participate in an emerging global market underpinning the clean energy transition, and capture more of the economic gains of this transition.

A truly domestic energy carrier that is price competitive globally can also mean a unique opportunity to participate in an energy and commodities trade. Given the expected growth in global demand and the disparity between producing and consuming nations, the need for a hydrogen trade is bound to emerge eventually.
If volume growth and price decline expectations can be met, this hydrogen transition can enable industries to shape up in India around exports of green hydrogen and hydrogen-embedded low-carbon commodities like green ammonia and green steel.

This report is an attempt to understand this emerging opportunity in India better. The next three chapters lay out the scale of the opportunity while highlighting possible challenges. The report also touches on the role of finance in enabling this transition. Lastly, the report aims to provide useful insights and policy-relevant recommendations that can accelerate the development of a sustainable hydrogen economy in India.

Future of Hydrogen in India

The Future of Hydrogen in India

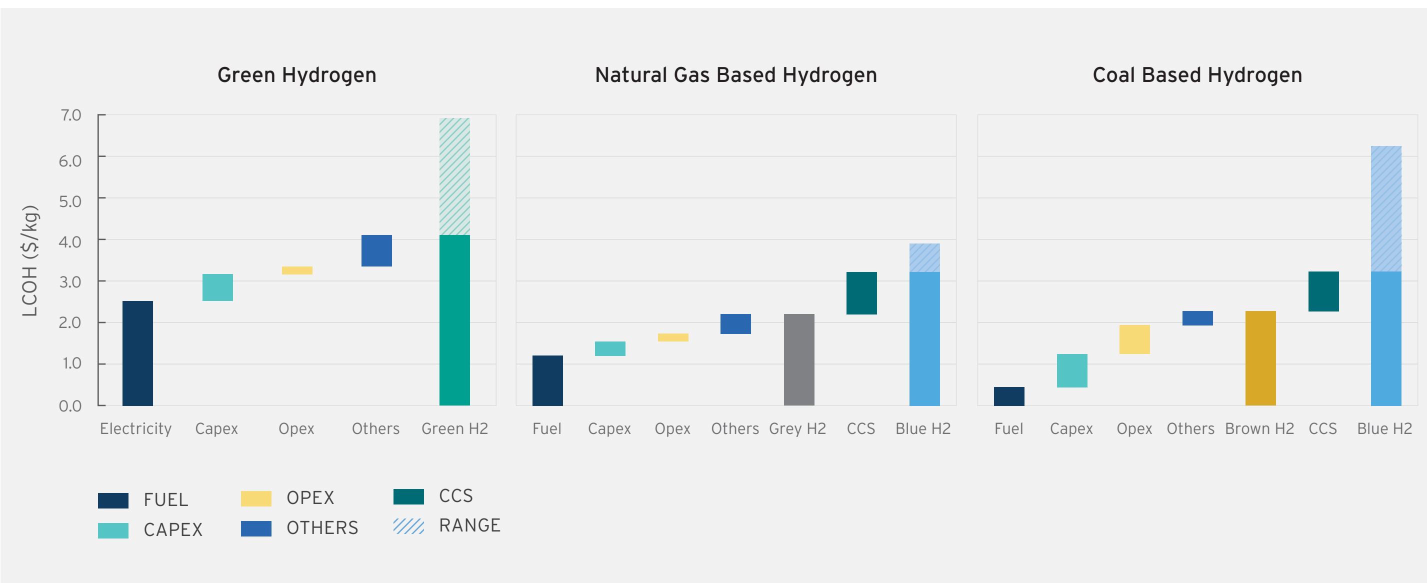
The emerging opportunity for hydrogen in India rests in the ability to produce price-competitive green hydrogen and enabling market creation for that hydrogen. This chapter will focus on the supply and demand dynamics within India.

Green Hydrogen Production in India

How competitive can it be?
As stated earlier, green hydrogen prices are determined largely by the cost of electrolysers and electricity. Beyond that, there are the operating costs, transmission and distribution (T&D) costs, and wheeling charges for electricity as well as specific local duties and taxes like the goods and services tax (GST) in India. The supply chain model, distance to demand centre, system design, and utilization factor are additional factors that strongly influence the delivered cost of hydrogen.

The cost of hydrogen from electrolysis today is relatively high, between around $7/kg and $4.10/kg depending on various technology choices and the associated soft costs (see Exhibit 9). This makes it hard to compete with the existing cost of grey or brown hydrogen. But India has some of the most competitive levelized cost of electricity (LCOE) for solar and wind in the world while remaining a net importer of natural gas. Given the promises of electrolyser cost and LCOE decline, it is more beneficial to expand green hydrogen production in India rather than production of grey or blue hydrogen.[v]

Exhibit 9 Current cost economics of green hydrogen production in India



Source: RMI Analysis for Green and Natural Gas Based Hydrogen; Coal Based Hydrogen analysis adapted from TERI and BNEF

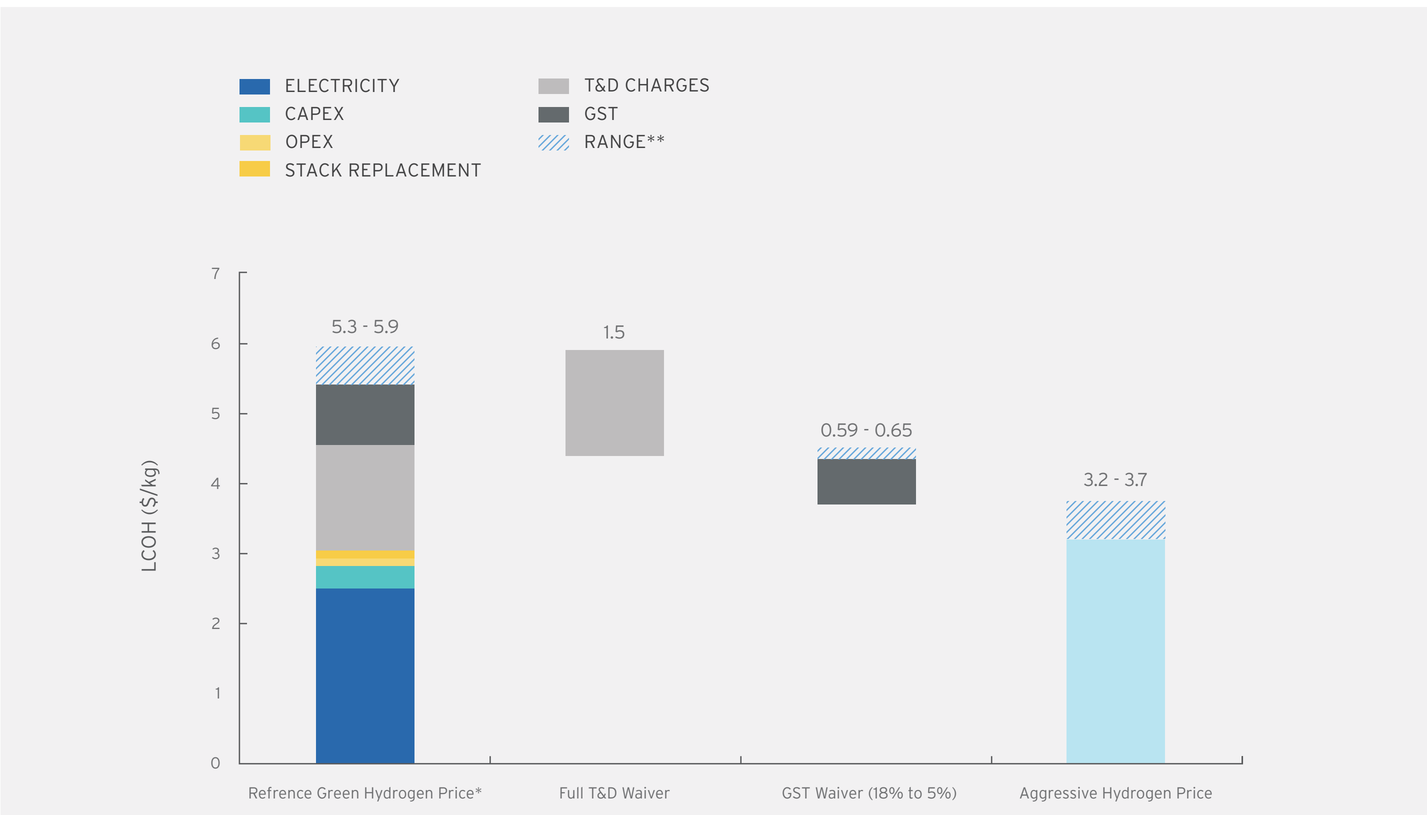
Soft-cost driven green hydrogen price reduction pathway

While electrolyser and electricity costs will guide the long-term price trajectory of green hydrogen, there are soft cost elements that can help reduce green hydrogen production costs today to help spur market development. Specifically targeting duty waiver and reduction of the GST and T&D charges, the levelized cost of hydrogen (LCOH) can be reduced to around $3.2/kg in the best case, making it closer to becoming competitive with grey hydrogen (Exhibit 10).

Reduction of T&D charges is not a novel suggestion and should be pursued. The Ministry of Power already waives inter-state transmission system charges for electricity generated from wind and solar. Most recently, this waiver was extended to projects commissioned from 30 June 2025, including for pumped storage hydro and battery energy storage systems.[28] Extending this waiver to renewable-based hydrogen production can drastically improve the near-term economics of green hydrogen.

Beyond these soft costs, India should strive to reduce renewable power tariffs for hydrogen production. These could include revenue recycling of any carbon tax or coal cess, low-emissions PPAs, and avenues for firming electricity supply including discounted grid electricity to complement the VRE generation.

Exhibit 10 Soft cost led price-reduction pathway for current (2020) round-the-clock (RTC) renewable-based green hydrogen



Source: RMI Analysis

* Hydrogen price calculated for RTC renewable (@ ₹3.6/kWh) with average T&D charges

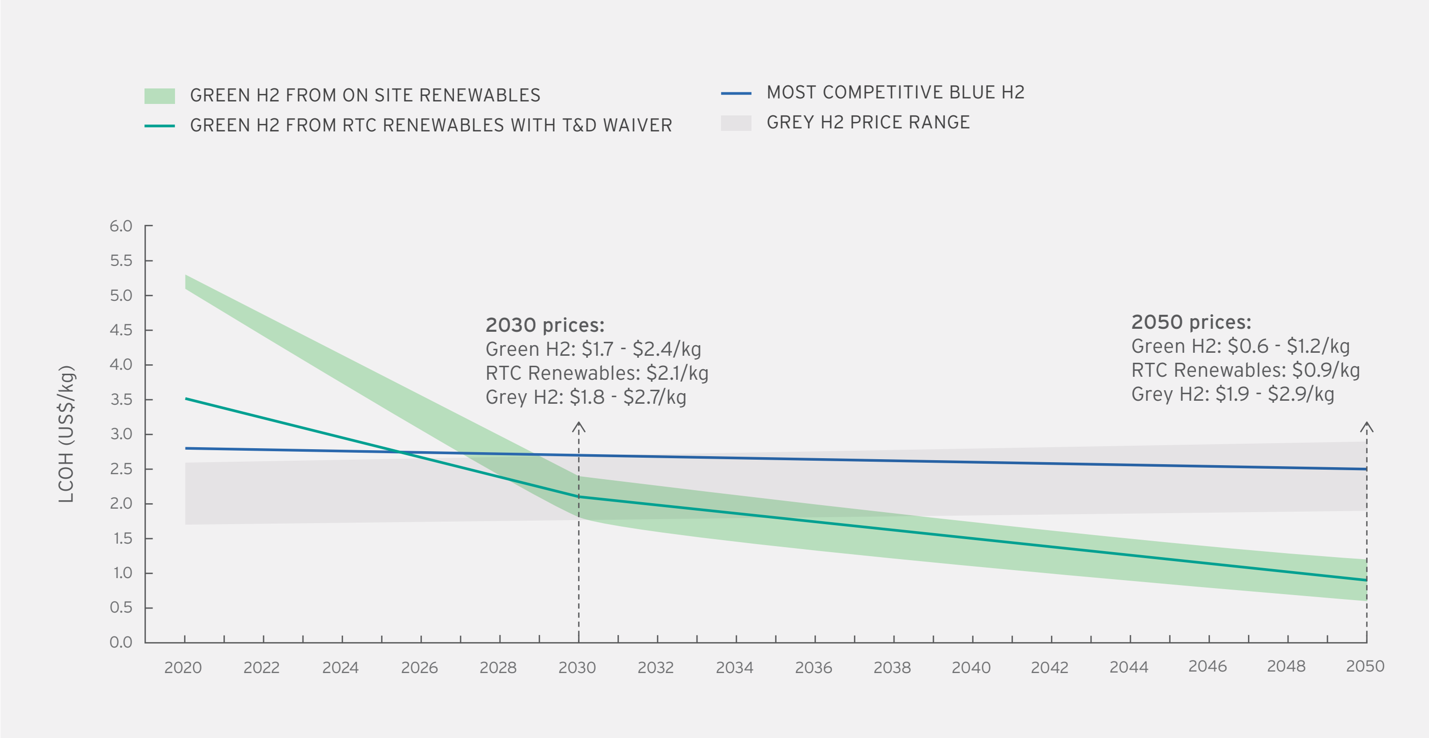
** The range is based on high and low end of electrolzyer capex price: $500 - 969/kW

Future Price Trajectory of Green Hydrogen

With an expected price decline for both electrolysers and renewables, our analysis indicates that in the best-case scenario, the cost of green hydrogen can fall to approximately $1.60/kg by 2030 and $0.70/kg by 2050 (Exhibit 11). Regardless of the scenario, the conclusion is clear. Green hydrogen can become competitive with grey hydrogen by 2030, if not earlier. Additional factors such as a potential carbon price on fossil fuels could also aid in the cost-competitiveness of green hydrogen.

Given the low LCOE of renewables, green hydrogen from standalone renewable systems or from RTC renewable arrangements will be more cost-effective than grid-connected electrolysis. Additionally, given that the grid is only gradually decarbonizing, the CO_2 intensity of hydrogen generated with grid electricity will also remain net positive even in the most VRE-rich case. While RTC renewables could be very cost-competitive today and in the near-term, there is a longer term potential for green hydrogen generation from standalone renewables, provided LCOE decline expectations materialise.

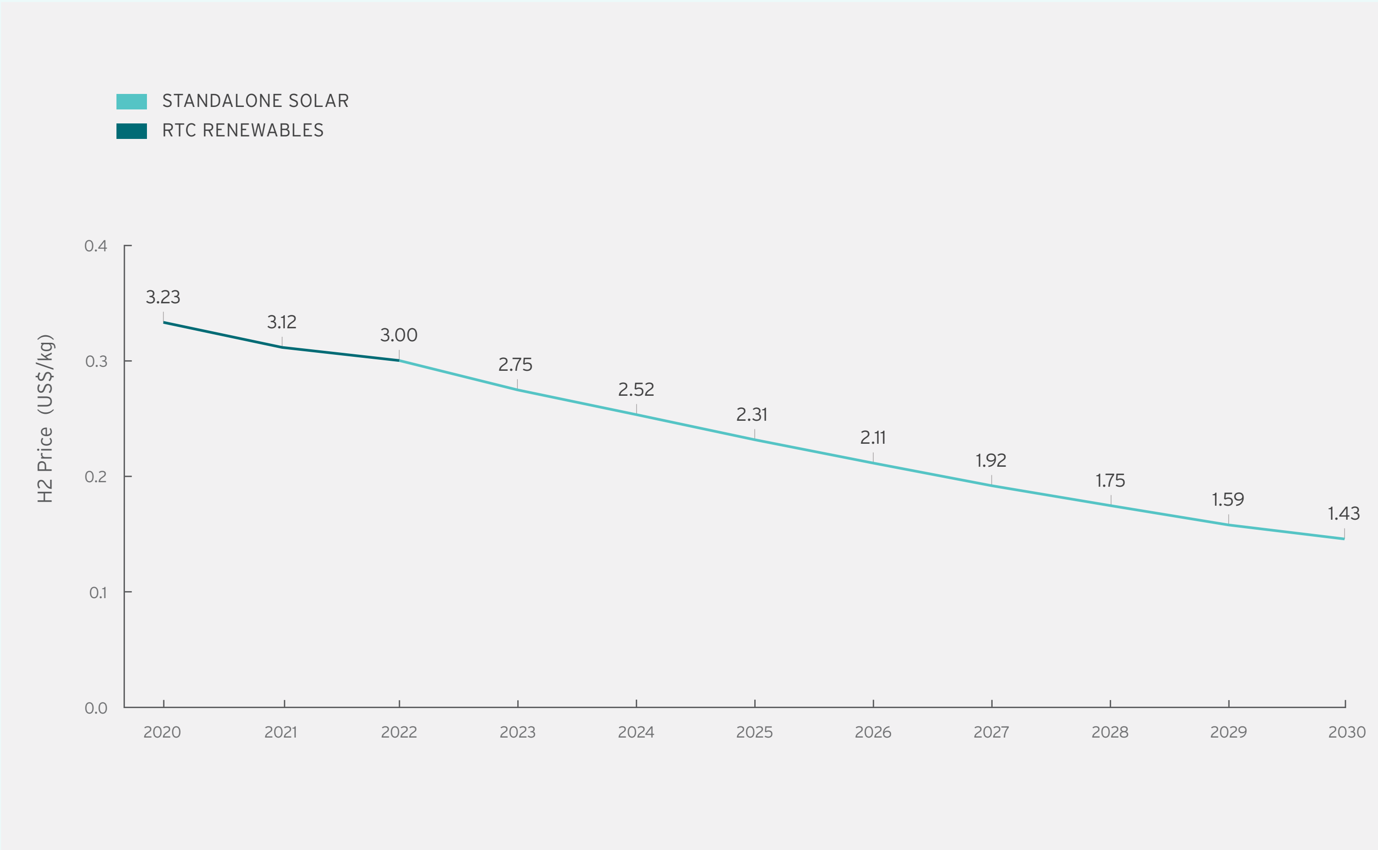
Exhibit 11 Projected price trajectory of solar-green hydrogen production based on decline in electrolyser and renewable costs



Source: IEA, BNEF, TERI, SECI, RMI Analysis

Box 2 Aspirational price targets can be conducive to green hydrogen market development

Exhibit 12 Most optimistic green hydrogen price trajectory



(Key assumptions behind this scenario: Electrolyzer Capex ($/kW): 500(2020) , 125 (2030); Full T&D waiver; GST waiver 18% to 5%); LCOE of solar (INR/kWh): 1.9 (2020), 1.5 (2030); LCOE of RTC renewables (INR/kWh): 3.6 (2020), 2.85 (2030))

As mentioned earlier, electrolyser price and the pace of its decline will be the most crucial determinant of long-term price trajectory of green hydrogen. An assessment of the most optimistic price decline scenario informed by a very aggressive electrolyser price decline assumption yields a hydrogen price of $1.4 / kg by 2030. While there is a degree of uncertainty to this outlook, it is fair to conclude that aggressive price decline targets coupled with relevant supply and demand side policy support could be effective tools for developing a viable and competitive green hydrogen market in the country.

Hydrogen Storage and Transportation Considerations

Storage will eventually become necessary given the variability of renewable sources and the possibility of large and consistent demand coming from industries. Storage costs could also potentially alter the cost economics of standalone renewables and RTC renewables-based hydrogen production, which can have higher capacity utilization. Availability of cheap natural storage like salt and rock caverns in India needs to be assessed further given the high cost of storage in pressurized steel tanks and the energy costs associated with chemical storage. Further consideration is around siting. Natural storage options will have limited flexibility while steel tanks could be sited close to consumption or production much more readily.

Transportation cost is another factor that can impact cost economics. Pipelines become cost-effective once hydrogen demand exceeds tens of tonnes per day.[29] As such, near-term development for large-scale industrial consumption could be located closer to production to minimize transportation and storage costs. Transportation through compressed hydrogen trucks looks to be the mainstay during the early phase of hydrogen development. Given that moving electrons is always more cost-effective than moving molecules, there will always be a case for siting production closer to consumption where possible.

Given that the evolution of transport and storage costs and deployment is a large unknown, government, in partnership with the private sector and other countries, must play a part in both infrastructure assessment and cost-reduction pathways. In the near term, an assessment is needed on the viability and upgradation costs of existing natural gas pipelines for hydrogen transportation, which could help minimize the transition cost to hydrogen.

Demand Prospect for Hydrogen in India

India currently consumes almost 6 million tonnes of grey hydrogen largely concentrated in industrial uses in refining and as feedstock to produce ammonia and methanol. Current hydrogen consumption is almost equally split between refining and ammonia production with a small share of consumption in methanol production. A small quantity of hydrogen, amounting to 0.3 million tonnes, is already being consumed for steel production. Beyond these sectors, our assessment indicates emerging potential demand in heavy-duty, long-haul freight transportation and to a limited extent in the power sector. Our assessment excludes niche applications such as in industrial forklifts and cell phone towers and city gas distribution. It also excludes demand potential from aviation, shipping, and potentially cooking, which are currently more speculative and technically in very early stages.

Hydrogen demand is assessed under a scenario where the pace and technology adoption are high, and policies are implemented to enable the green hydrogen transition. Scenario assumptions include a high uptake of green hydrogen in end-use sectors, increased penetration of fuel cell trucks, a rapid decrease in electrolyser and renewable costs, and options for financing this transition. Green hydrogen demand is estimated within the overall hydrogen demand by assessing the cost parity of green hydrogen-based end-use products against grey/brown hydrogen-based end-use products. CO_2 emissions and energy import savings are estimated and compared with a base case of grey hydrogen consumption in ammonia, refinery, methanol, and steel and oil consumption for heavy-duty trucking. A favourable policies (FPS) scenario is developed to assess the market potential through incentives, waivers, and mandates. The FPS analysis is intended to understand the market creation in the short term and hence is limited until 2030 only.

What drives sectoral demand for Hydrogen?

Demand drivers for hydrogen are highly sector specific. They depend on whether hydrogen is used as industrial feedstock with no other alternatives or whether it requires adopting new technology and displacing existing fuel or technology. Further, the pace of energy transition, new technology adoption, and the presence of requisite policy and financial support will also determine the demand outlooks for hydrogen. This section is a brief discussion of sector-specific demand drivers for hydrogen.

Refining

Hydrogen is essential to the petroleum refining industry and is primarily used for desulphurisation of products such as diesel and petrol. Hydrogen demand depends on two factors: 1) demand of petroleum products, which is bound to increase considerably if efficiency measures and low/zero-carbon alternatives are not adopted and 2) stringent policy actions on limiting the sulphur content from petroleum products—the more stringent the standards, the higher the requirement of hydrogen in desulphurisation.

Box 3 Case Study: Refining[30]

The REFHYNE Project in Germany, funded by the European Commission's Fuel Cells and Hydrogen Joint Undertaking and supported by Shell and ITM Power, aims to fully integrate green hydrogen into refinery processes at an existing refinery site. Construction began on a 10 MW electrolysis plant in 2019 at the Shell Rheinland refinery and is expected to begin producing hydrogen in 2021. This pathway, while a substitution for existing work in refineries today, also offers a pathway to green non-combustible products and an avenue for refineries to move away from oil derivative feedstocks. This stream of engagement offers potential for the valuation of emitted carbon and accordingly can link this to commodity markets. In the lxong run, this pathway leads to a carbon-neutral non-combustible refined products production stream.

Ammonia

Ammonia, a compound made of nitrogen and hydrogen, is extensively used in the chemical sector. Currently, the majority of the hydrogen feedstock for ammonia is mainly natural gas-based which can be replaced by the renewable-based electrolysis process to form green ammonia. Ammonia's applications can span across the following:

- Ammonia-derived fertilisers: Ammonia is majorly used in the manufacturing of nitrogen-based (urea) and other complex fertilisers such as diammonium phosphate (DAP). The demand for nitrogenous fertilisers is expected rise at the rate of 3 percent compound annual growth rate (CAGR) over the next decade, owing to rising population and increasing demand for food.[31]
- Ammonia as fertiliser: Although ammonia is majorly used as feedstock for other fertilisers, it can also be directly applied to soil, either in anhydrous form or as aqua-ammonia (ammonia dissolved in water). Anhydrous ammonia is readily available and can be easily applied to soil, however it requires careful consideration in terms of its transportation and storage.[32] Aqua-ammonia, on the other hand, is relatively safer than the anhydrous form and can be applied easily since it is not injected as deeply as the anhydrous form.[33]
- There is also the potential for the use of ammonia as a hydrogen carrier and fuel for shipping.

Box 4 Case Study: Green Ammonia[34]

Several developers around the world have announced projects to produce green ammonia. Norwegian agricultural company Yara has plans to convert an existing ammonia facility to use green hydrogen as a feedstock, with 20,000 tonnes of capacity converted by 2023 and expected completion by 2026. Siemens is establishing a Green Ammonia Demonstrator in the UK that aims to show a full carbon-free ammonia lifecycle from production to use as a fuel to produce electricity. The ammonia, in this case, essentially serves as an energy storage mechanism for excess renewable electricity. Renewable energy is used to power all the stages of ammonia synthesis, including the electrolysers to produce hydrogen, the air separation unit to produce nitrogen, and the Haber-Bosch process used to synthesize ammonia. Other industrial ammonia producers, including CF Industries in the United States and Iberdrola/Fertiberia in Spain, have announced plans to build electrolysers to synthesize green hydrogen as a feedstock for ammonia production. CF Industries, which has a target to reach net-zero carbon emissions by 2050, will build a 20,000 tonnes per year green ammonia plant in Louisiana. The Iberdrola/Fertiberia project will expand a 20 MW pilot plant to 800 MW of hydrogen production by 2027 with a $2.1 billion investment.

Methanol

Methanol is primarily used to produce various chemicals and solvents, and its use can be expanded as fuel for transport in the form of various blends, marine fuel, and cooking. Hydrogen is a main feedstock in the production of methanol and, in India, is currently produced primarily from natural gas. India currently produces only 13% of its methanol consumption with a policy goal to increase production through the Indian Methanol Economy program. Future demand will rest on emerging demand for speciality chemicals and solvents and the success of the Indian Methanol Economy program.

Box 5 Case Study: Green Methanol[35]

Most of the green methanol projects under development are led by Carbon Recycling International (CRI), which has projects under various stages of development in Europe and China. Its Emissions-to-Liquids (ETL) technology utilizes CO_2 captured from industrial or other sources and green hydrogen to produce low-emissions methanol, which can be used as a fuel or feedstock for other chemical products. The North-C-Methanol project, a collaboration between Proman, ENGIE, ArcelorMittal, and others, is a large-scale demonstration project located in Belgium and part of the North-CCU-Hub Roadmap.

Methanol-to-olefin plants are emerging, particularly in the APAC region, as effective pathways for the production of common use olefins found in plastics in particular. The utilization of captured carbon and green hydrogen to produce methanol creates a pathway to plastics production that could further reduce future need for fossil fuel extraction, while developing a more complete circular production pathway and creating a recognizable value market for carbon.

Steel

Hydrogen demand for the steel industry is a matter of technology competitiveness and fuel availability. Steel is mainly produced from three main processes:

- blast furnace – basic oxygen furnace (BF – BOF), which uses coking coal for reduction of iron ore;
- direct reduced iron – electric arc furnace/induction furnace (DRI – EAF/IF), which can achieve the reduction through use of either natural gas or coal on pelletized iron-ore; and
- EAF/IF with scrap steel, where scrap or recycled steel is directly heated via electricity to form steel.

The DRI process is where there is a potential role for hydrogen to replace fossil fuels, mainly natural gas.

Box 6 Case Study: Green Steel[36]

Arising out of Sweden's 2045 net-zero target, the HYBRIT project in Sweden, a collaboration between SSAB, LKAB, and Vattenfall, will replace coking coal with green hydrogen in the reduction process. Construction on the pilot plant (costing ~$150 million) began in 2018 and operations started in August 2020, with a goal to have demonstration completed by 2035. Arising out of this effort, LKAB has committed $47 billion to convert its operations. Multiple pilot plants to demonstrate other technologies are being built. ArcelorMittal has several projects underway across Europe that utilize green hydrogen in various ways in primary steelmaking to reduce emissions. In Bremen, Germany, a plant is planned that would inject green hydrogen into the blast furnace. The ArcelorMittal IGAR project in France is developing a hybrid blast furnace process using DRI gas injection and a plasma torch.

Long-Haul Freight and Heavy-Duty Vehicles (HDVs)

Like steel, hydrogen demand for long-haul freight will depend on movement towards low-carbon transportation and the competitiveness of technology options with respect to diesel and against each other. Two technology options exist to electrify HDVs: battery-electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). Both these technologies are complementary, and their uptake will depend on technology merits, refuelling time constraints, efficiency considerations, costs, and duty cycles.

Box 7 Beyond Freight—The Potential Role for Hydrogen in Aviation and Shipping[37]

Hydrogen's role as a fuel for the transport sector can extend beyond road transport to shipping and aviation. Shipping and aviation sectors use heavy fuel oil and jet fuel respectively. Moreover, there are very few alternatives to decarbonize these sectors, and they are less readily available and more expensive than conventional fuels. Hence, hydrogen or hydrogen-based compounds such as ammonia or methanol can play a big role in decarbonizing shipping and aviation.

On the shipping side, various efforts are underway to decarbonize international maritime shipping led by the International Maritime Organization (IMO). IMO has set a goal of reducing international shipping emissions to 50% of 2008 levels by 2050. A major chunk of these emissions reductions can come from ammonia as a shipping fuel. By 2050, 25% of the fuel demand in this sector can be met via ammonia. Ammonia has a competitive advantage when compared with hydrogen—its higher energy density makes it easier to store.

Another option is to power ships with fuel cells powered by hydrogen, but that route is more geared towards commuter ferries or short-distance transport and competes directly with battery-powered ships. In India, domestic coastal and inland waterway shipping contribute to just 6% of the total freight moved and is the least carbon-intensive mode in terms of CO_2 emitted per tonne-km of freight moved, even when powered with fossil fuels. However, with the Indian government's focus on promoting multi-modal and inter-modal transport, demand for shipping could rise in the future, meaning increased emissions from burning fuel oil. Hydrogen and ammonia can play a role, but there are still significant challenges to their uptake including high cost compared with conventional alternatives, storage infrastructure requirements at ports, and the need to change vehicle designs.

The aviation sector has the highest carbon emissions intensity of any other mode of transport. With rising income levels, the increase in tourism, and increasing demand for faster deliveries by consumers, emissions from the aviation sector will grow exponentially. By 2050, aviation will be the second-biggest emitter of freight transport-related CO_2 emissions in India, registering a 100-fold growth. Similar growth is projected for passenger aviation as well.

The technology options to decarbonize the aviation sector include 1) battery electric, 2) hydrogen-powered fuel cell, 3) hydrogen-powered turbine, 4) sustainable aviation fuels made from waste and agriculture residues, and 5) electrolytic hydrogen-based synthetic fuels. No one technology stands out as a single solution for decarbonizing the aviation sector; each technology has its own merits and challenges. For example, battery electric and hydrogen fuel cells can deliver the maximum decarbonization benefit per passenger-km or freight tonne-km, however their use will be restricted to short distance, smaller flights. The other three technologies can be deployed for long distance-larger aircrafts, however significant challenges exist due to lack of storage infrastructure. High costs also remain a barrier for all technologies.

Decreasing costs due to improved technologies and economies of scale, policy push introducing demand incentives, supply mandates and a carbon tax, and innovative financing and business models can enable decarbonization of aviation.

Power Sector

High demand growth and renewable penetration introduces the challenges and prospect of flexibility and VRE integration. Hydrogen proponents have also proposed the concept of power-H2-power as another form to provide storage and flexibility. But actual demand for hydrogen will be limited by its competitiveness against other technologies such as battery storage and demand response, in addition to the unique nature of the country's grid and emerging supply and demand structure.

Potential future application – Electrofuels for ground transportation

Electrofuels (e-fuels) are primarily hydrogen-based fuels that are produced via hydrogen derived from the water electrolysis process. The primary examples are methanol and ethanol which can be blended with or completely replace existing fossil fuels (with required design changes) for powering vehicles. E-fuels can act as a complementary technology to biofuels due to their existing limitations around feedstock and applicability in certain end use cases. In the near term, e-fuels can be utilised as blended fuels with either petrol or diesel, and there is a long-term potential of using them in M100/E100 engines (100 percent methanol or ethanol content). E-fuels have the following advantages:

- E-fuels can be produced at a lower cost in the near future due to lower prices of renewable electricity and declining electrolyser costs, hence outcompeting other production processes.
- Reduction in well-to-wheel emissions — emissions are reduced at the point of generation of the fuel, owing to the use of green hydrogen. Even tailpipe emissions are reduced on account of reduced consumption of petrol or diesel.

Box 8 Does hydrogen make sense as cooking fuel?

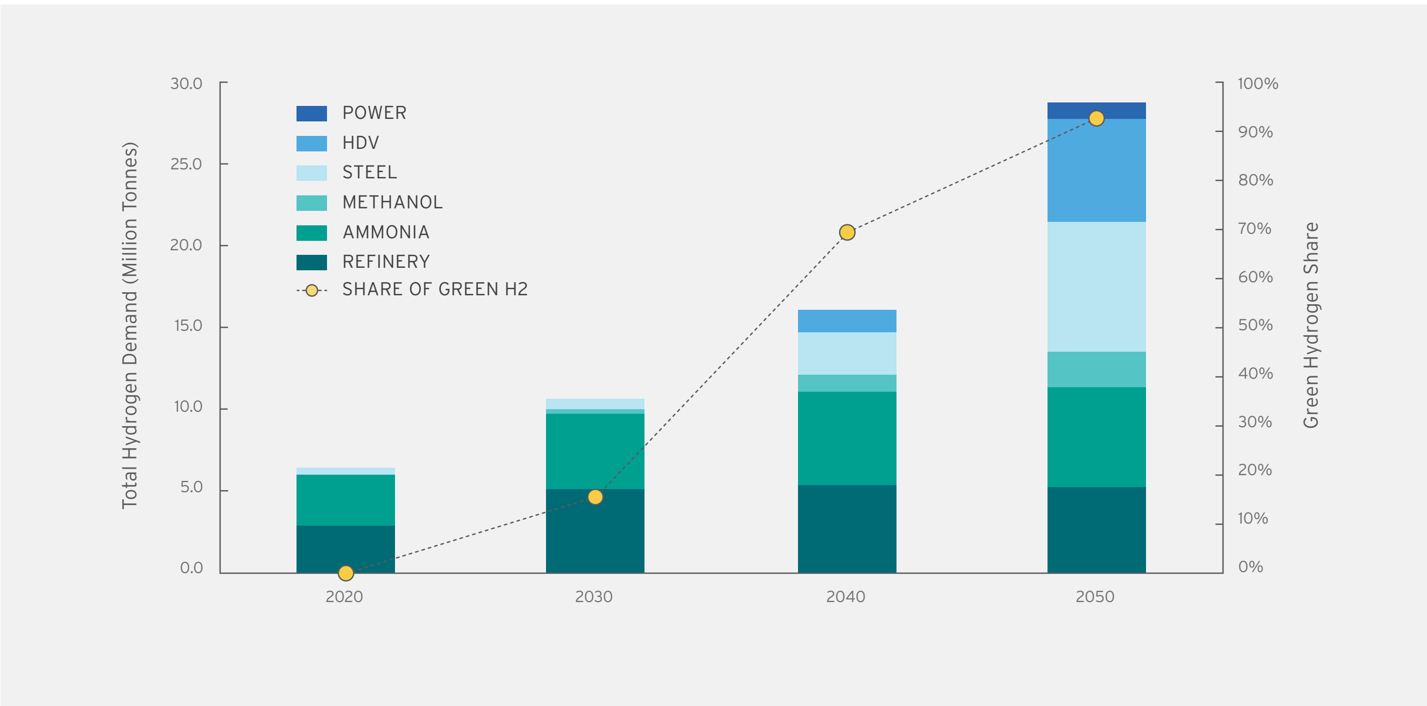
Hydrogen's potential as fuel for clean cooking has been discussed and experimented with. But given the distributed nature of cooking demand, electrification is a better pathway for bettering access to decarbonized cooking. Hydrogen could play a role through blending into existing city gas distribution (CGD) network in urban areas. But even there given hydrogen's characteristics, there is also a limit to blending in existing pipeline infrastructure. Due to the low density and higher diffusivity of hydrogen, existing gas pipelines should be coated / made of different material to withstand higher compression ratios. Furthermore, rigorous testing is required to understand the long-term impact of hydrogen, on materials and equipment with leakage, flame stability, back firing, ignition and must be investigated to ensure system safety, efficiency and environmental performance. Additionally, hydrogen specific furnaces and stoves do not exist outside of prototypes.

Hydrogen Demand Outlook

As per our assessment, hydrogen demand can potentially grow more than fourfold between 2020 and 2050, amounting to around 29 million tonnes by 2050 (Exhibit 13).

While steel and heavy-duty trucking will be the long-term driver for demand, in the near term, demand will likely be driven by the more mature markets in industrial feedstock—ammonia and refining. Increasing consumption from these two sectors can result in a demand of almost 11 million tonnes per year by 2030 from the current demand of around 6 million tonnes. Details of sectoral analysis are presented in Appendix B.

Exhibit 13 Hydrogen demand outlook and potential green hydrogen share at cost parity (without policy intervention)



Source: MoS, MoC&F, MoPNG, IEA, TERI, BCG, World Bank, RMI Analysis

The Potential for Green Hydrogen

Cost-competitive green hydrogen opens the possibility for market development, especially in industries that are already consumers of grey hydrogen. The share of green hydrogen will depend on the cost of production compared with alternative hydrogen sources, the share of hydrogen cost in the end cost of the product, as well any exogenous demand creation efforts that may be imposed in the near term. Purely based on cost-competitiveness, green hydrogen is expected to dominate the hydrogen market in the long run. Even in the 2030 timeframe, green hydrogen can play a significant role for both existing brownfield consumption and new greenfield investments. Almost 94% of hydrogen demand in 2050 can be met by green hydrogen, up from 16% in 2030. The cumulative value of the green hydrogen market in India could be $8 billion by 2030 and $340 billion by 2050.

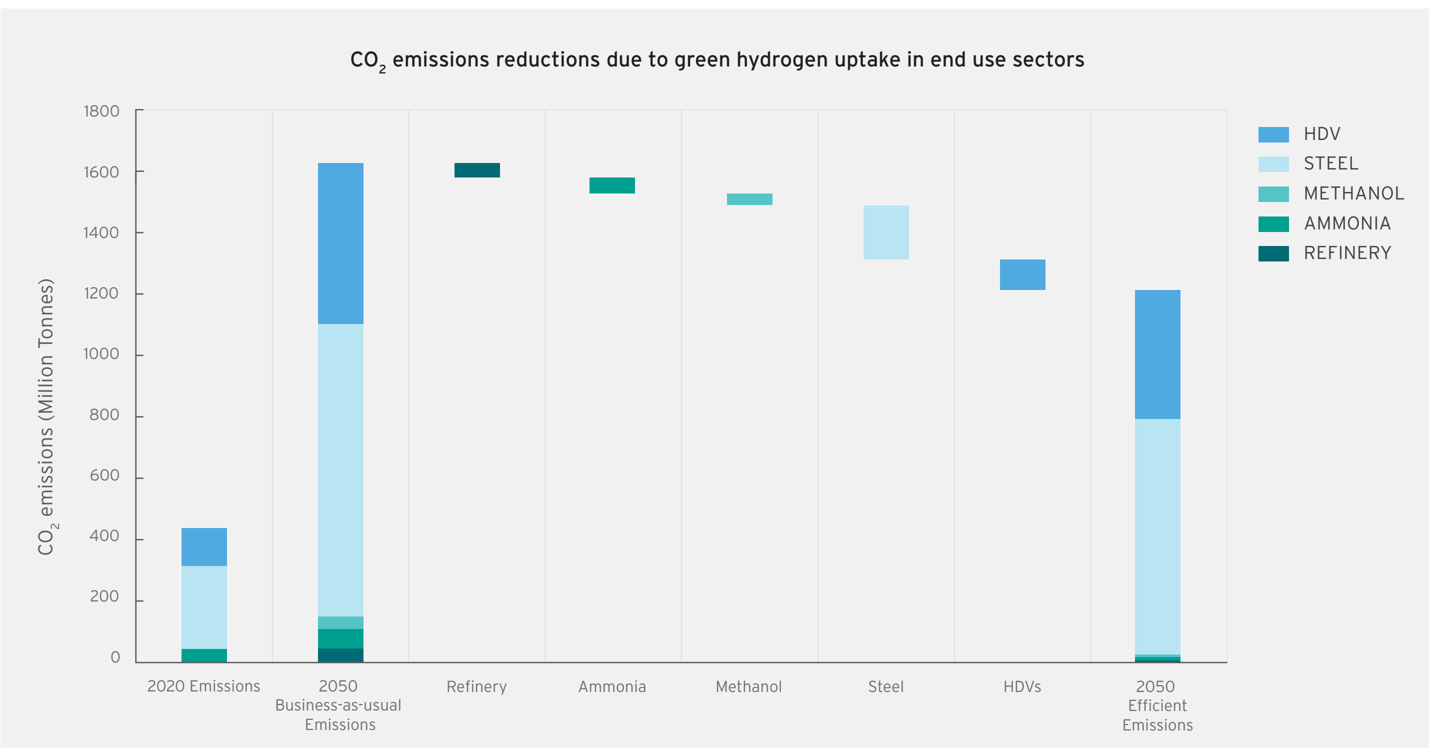
Refining and ammonia are the two sectors ripe for near-term utilization of green hydrogen given the already large share of hydrogen they are consuming and are expected to consume in the near term. But new hydrogen application areas like steel and heavy-duty vehicles become much more prominent drivers for the green hydrogen market in the long run, making them ideal for small- and large-scale pilot development.

CO_2 and Energy Import Savings

This transition has significant impact on the greenhouse gas emissions of the hard-to-abate sectors. Cumulatively, between 2020 and 2050, India can abate 3.6 giga tonnes of CO_2 emissions compared with a limited hydrogen adoption case. While industrial feedstock is an easier market, the majority of long-term decarbonization potential lies in steel followed by heavy-duty trucking, since their scale of demand is much higher.

When looked at from an energy security perspective, domestically produced green hydrogen can translate to a net energy import savings of $246–$358 billion cumulatively between 2020 and 2050 ($3–$5 billion between 2020 and 2030 alone). This is on account of a reduction in both natural gas imports as grey hydrogen is replaced with green hydrogen and oil imports as long-haul freight transitions to hydrogen fuel cells trucks.

Exhibit 14 CO_2 emissions reductions in 2050 due to green hydrogen uptake

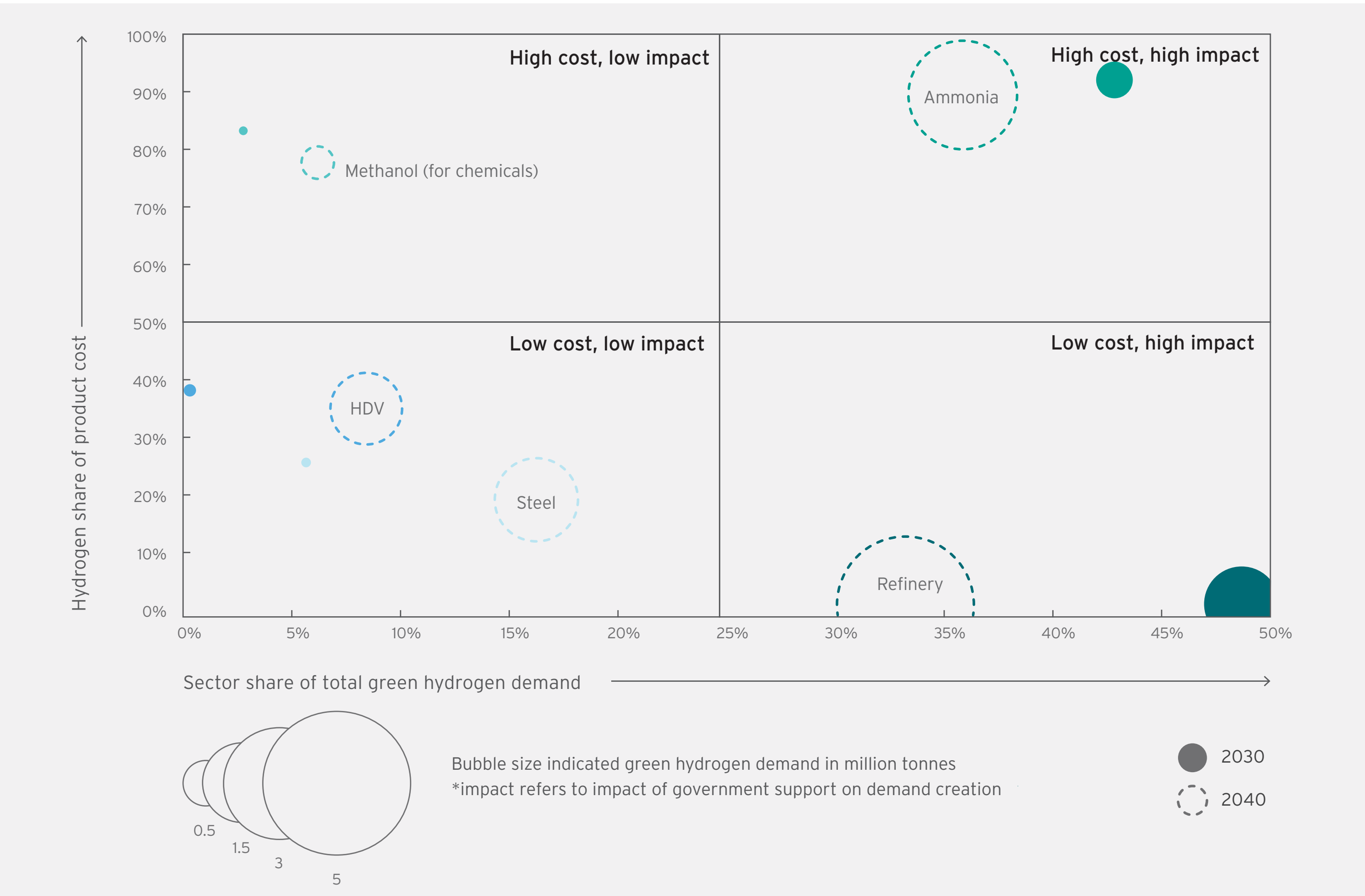


Source: RMI Analysis

Near-Term Market Development

Encouraging market development for green hydrogen will require further analyses than can inform decision-making. Exhibit 15 lays out the relationship between the impact of hydrogen on the price of the final products of the end-use sectors and their green hydrogen market potential by 2030 and 2040. End-use sectors should be assessed to identify those ready for scaled consumption and those ripe for small- and large-scale pilot development.

Exhibit 15 Assessing opportunity for green hydrogen market creation by 2030



Source: RMI Analysis

Targeted Viability Gap Funding (VGF)

A targeted *viability gap funding* (VGF) mechanism that can help address industry-specific cost differentials/ green premiums for some of the possible early markets should be considered. As Exhibit 15 shows, refining and ammonia could be ideal sectors for a targeted VGF approach in the initial phase of green hydrogen development. This is due to the current size of hydrogen consumption and the potential to replace grey with green hydrogen.

The impact of hydrogen on the price of refinery products is much less than that of ammonia where hydrogen as a feedstock constitutes almost 80%–90% of the cost of end products like urea. From a government expenditure perspective, the refinery sector is relatively more ideal for VGF given that hydrogen contribution to end product cost is only around 2%–4%.

But ammonia provides credible opportunity as well given the large share of subsidy the government already provides for urea imports. India currently imports almost 25%–30% of its annual urea consumption.[38] Directing part of the existing subsidy outlay towards VGF for green ammonia production could also make sense from an import substitution and supply security perspective while making the VGF expenditure for ammonia closer to being revenue neutral.

VGF can be directed through multiple economic instruments such as depreciation benefits, tax benefits, production-based incentives, and capital subsidies, as Germany is currently promoting for electrolytic hydrogen production. Another measure to incentivize industry is carbon contracts for difference mechanisms or green subsidies that cover the differential costs between conventional and green hydrogen-based technologies, improving the affordability of asset conversion. Lastly, a production-linked incentive for end products like green steel and green ammonia could be instituted.

The level of VGF should also be differentiated based on whether these are targeted towards existing brownfield assets or newer greenfield assets. Replacing grey hydrogen in older plants is bound to demand higher VGF due to depreciated assets, while newer plants will demand lower VGF. For newer applications such as steel, long-haul freight, and a city gas network, assessment must be conducted to inform VGF potential in the medium term against existing fuels that green hydrogen will be replacing.

Hydrogen Mandates

A mandate-driven approach can also aid in market creation. One way is to blend hydrogen with natural gas by injecting it into existing natural gas pipeline networks. This mode of blended hydrogen has recently been featured in the national hydrogen strategies of the Netherlands and Australia, in addition to a host of small-scale pilot projects.[39] Blending can ensure demand certainty for early investors in green hydrogen production and could be crucial for early learnings and scaling efforts. Also, at low blend volume, this strategy could be very cost-effective for market creation.

Blending mandates can be put into effect for two major sectors — industries that currently use hydrogen as a feedstock and city gas distribution (CGD). Hydrogen can be blended with natural gas for industries such as ammonia, refining and methanol, as many of these industries tend to along natural gas pipelines. Additionally, hydrogen can also be blended with existing city gas network of piped natural gas and compressed natural gas.

Well designed blending mandates can complement sector-specific VGF to create a high degree of demand certainty for scaled deployment of green hydrogen. Mandates can be driven by requiring all new greenfield investment to use green hydrogen or by increasing the blending of green hydrogen in existing brownfield units. Exhibit 16 proposes such a potential mandate.

Exhibit 16 Potential mandates for existing applications

Sector	Target Type	Mandate	Cut-off Date for the sector to go 100% Green
Refinery	Corporate level targets	50% by 2030	2035
Fertilizers	Import substitutions	100% by 2030	2040

Source: NITI Aayog

For new applications, an aspirational target-based approach that can inform future mandates should be applied. Appropriate mandates could be designed in time to build markets in those application areas.

Industrial Cluster Identification and Development

VGF and mandates should also be suppplemented with geographical assessments to identify potential clusters around existing factories, transmission infrastructure, and renewable hubs. Industrial clusters have been a common strategy across many of the hydrogen roadmaps being developed, for example in the European Union (see Box 9).

Box 9 Hydrogen Cluster Development in Europe[40]

The European Union has historically focused on the establishment of clusters as focal points for industrial policy. Since 2008, the European Cluster Observatory has mapped around 3,000 industrial clusters—regional concentrations of specialised companies and institutions that cooperate closely. The EU sees clusters as playing a crucial role in building collaboration, supporting innovation, setting up transnational partnerships, and advancing the carbon-neutrality agenda. The European Cluster Collaboration Platform is an online hub for clusters to develop partnerships, share knowledge with each other, and participate in funding calls.

Europe's largest hydrogen cluster currently is the NortH2 cluster in northern Netherlands. It was launched by a consortium comprised of Groningen Seaports, Shell Nederland, Gasunie, Equinor, and RWE. It aims to produce hydrogen in Eemshaven, Netherlands, using electricity generated by a mega-scale offshore wind farm. The plan provides for a large electrolyser and a smart transport network using Gasunie's existing natural gas infrastructure. It is expected to transport 1 million metric tonnes of green hydrogen to industries in northern Netherlands and north-west Europe annually by 2040.

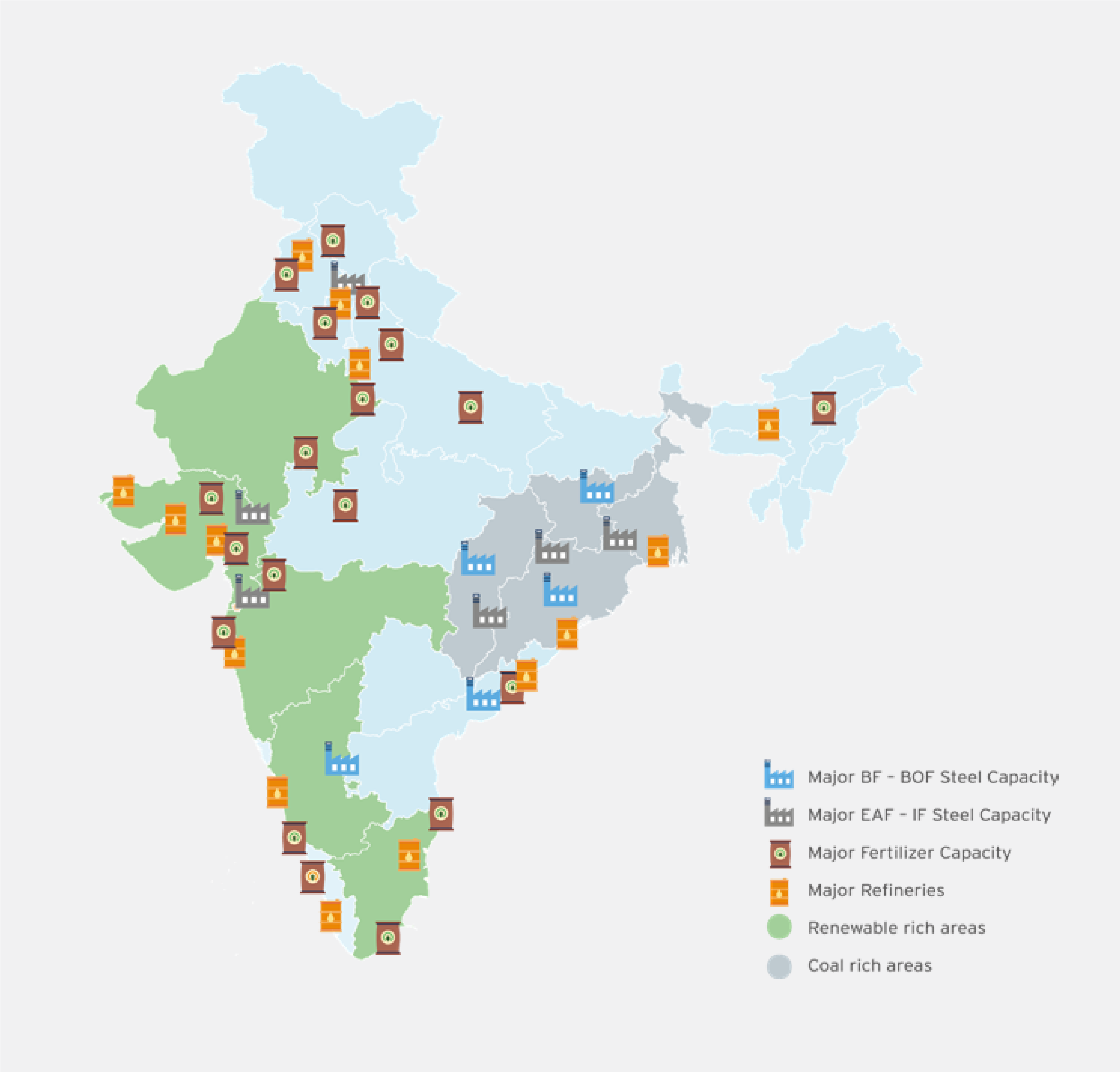
Industrial clusters can help coordinate and concentrate support to advance green hydrogen adoption. Providing incentives and support to priority regions while creating green hydrogen procurement quotas for industries located in these clusters can solve demand and supply, as well as alleviate finance constraints to accelerate deployment. Several strategies (in Korea, Denmark, EU, France, among others) have similarly focused on supporting full value chains in high-potential regions.

Clusters will be essential in the near-term to guarantee offtake certainty for early green hydrogen pilot projects while reducing infrastructure costs. But in the future, scaled industrial clusters could also become a vector for demand aggregation, diversification of the local industrial base using hydrogen, and lowering of production costs due to emerging economies of scale.

As a new pipeline network emerges, or existing gas pipelines become retrofitted and ready for hydrogen transportation, these early clusters can also emerge as green hydrogen industrial networks.

Cluster identification should be guided by concentration of existing and expected end-use facilities and cost of hydrogen production given local dynamics around land and other resources. CEEW's analysis presents a possible early industry cluster in India focusing on fertilizer and petrochemical in the western coasts and iron and steel in the eastern belt.[41] A key conclusion is that several of the most economically significant clusters, from the perspective of hydrogen deployment, are located close to some of India's best renewable resources (see Exhibit 17).

Exhibit 17 Location of key industrial facilities



Source: PPAC, NITI Aayog, CEEW

However, even clusters located away from India's renewable-rich regions, for example, iron and steel clusters in Odisha, still have access to large amounts of a high-quality solar resource.[42] Given that shipping electrons is always easier than shipping molecules, emerging RTC renewables should also be looked at for hydrogen production even where renewable resources may not be locally available.

Pilot and start-up scaling efforts through dedicated hydrogen corridors

Given the nascency of the sector, pilots will be critical. India can support prototype-stage projects to create domestic supply chains and bring a local context into innovation:

- In the short-term, demonstration projects can be set-up either by government public sector undertakings or by private entities with government encouragement. The aim should be to address how to produce and scale green hydrogen (see Box 10 for ongoing pilots projects in India).
- Early pilots could be concentrated around existing clusters of feedstock and petrochemical industries highlighted above, followed by the steel sector. A similar approach could be applied to transportation by identifying and targeting major freight corridors in the country in the medium to long term. Technology demonstration pilots for FCEVs could also be conducted on government offices or university campuses.
- Government could enable upscaling of lessons from the pilots and demonstration projects by having a centralized platform for collating and disseminating results, as well as for hosting industry discussions and dialogues.

Other Demand Creation Efforts

As sector use of green hydrogen matures from pilots, the government should identify policy instruments to encourage demand aggregation, including assessment of any public procurement pathways. This can be crucial in enabling scaled deployment. Further, introducing voluntary purchase mechanisms and green certifications for products such as green steel, green ammonia, and green methanol can raise awareness among the end consumers and enable a consumer-driven market pull for green hydrogen in the long run.

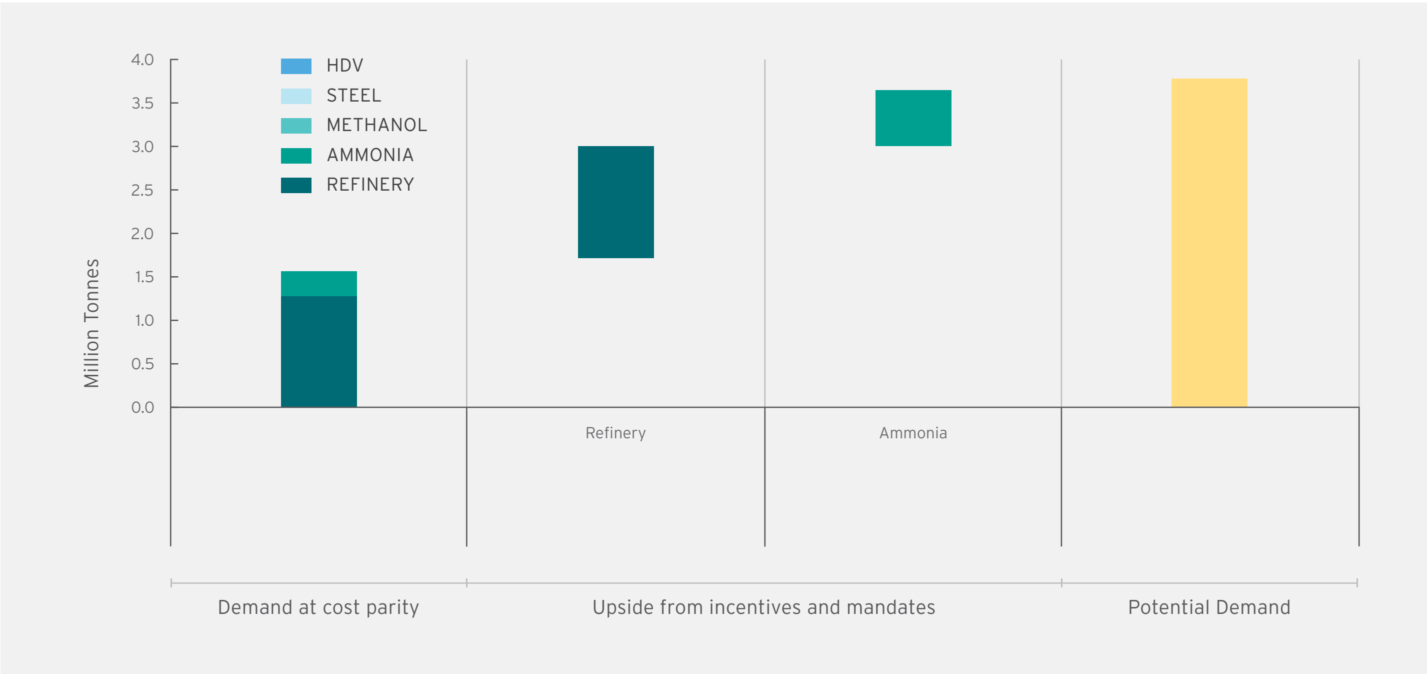
Upside to Green Hydrogen Demand

All these market creation instruments along with favourable policies around near-term cost reduction can result in a substantial increase in green hydrogen demand by 2030.

Box 10 Ongoing Demonstration Pilots in India[43]

The government is already taking steps to introduce green hydrogen-based pilots in the country. The government-led public sector undertaking (PSU), Indian Oil, is at the forefront of the green hydrogen revolution. It is planning to setup India's first green hydrogen unit for the Mathura refinery, which will be used to process crude oil. Moreover, it plans to utilize low-cost wind power from Rajasthan (wheeling it to Mathura in Uttar Pradesh) to power this green hydrogen plant. The organization has also been conducting a pilot using hythane (H-CNG), a blend of compressed natural gas (CNG) and hydrogen. The pilot involved retrofitting 50 CNG buses to test the feasibility of the H-CNG-powered vehicles and their impact on emissions and fuel economy. Another government-run PSU, NTPC, has recently set up a tender to establish a first-of-its-kind hydrogen refuelling station to be powered entirely by renewables in Leh through a stand-alone 1.25 MW solar system.

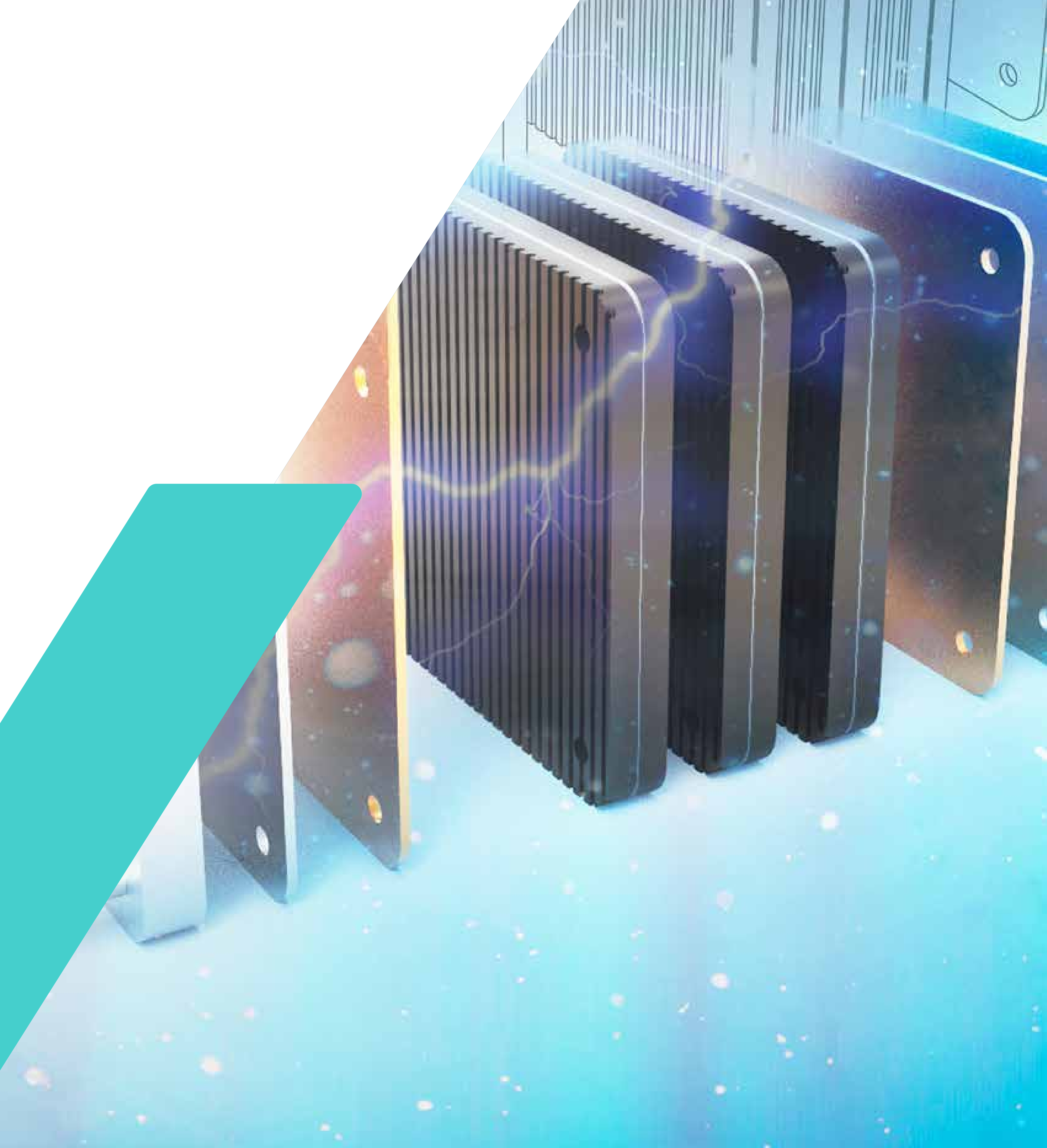
Exhibit 18 The potential increase of the green hydrogen market under the FPS scenario in 2030



Source: NITI Aayog, RMI Analysis

Under the FPS scenario, green hydrogen demand can be expected to almost double to 3.7 million tonnes from 1.7 million tonnes in refence scenario (Exhibit 18). This additional demand will be critical in enabling the green hydrogen economy to mature in the long term creating opportunities for both energy transition as well as industrial growth.

Manufacturing Opportunities



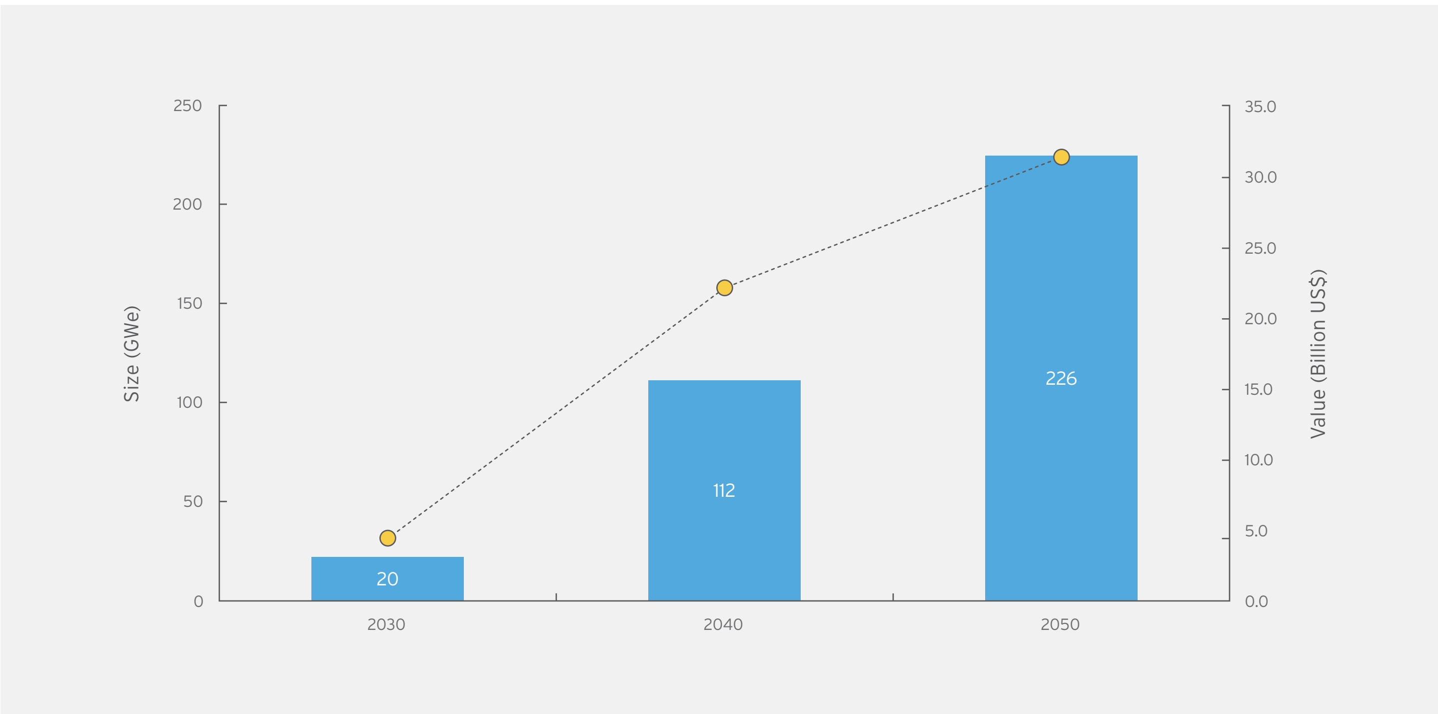
Manufacturing Opportunities

Beyond supply and demand, India's robust economy and manufacturing and industrialization ambitions present other opportunities to partake in the emerging global hydrogen economy. A robust market for green hydrogen translates to a growing demand for production and consumption technologies such as electrolysers and fuel cells and an opportunity for scaled manufacturing.

India's Electrolyser Demand

In our reference case, India's own internal market for electrolysers could be around $31 billion by 2050 representing a demand of 226 GW (Exhibit 19). By 2030, India can expect a demand of 20 GW.

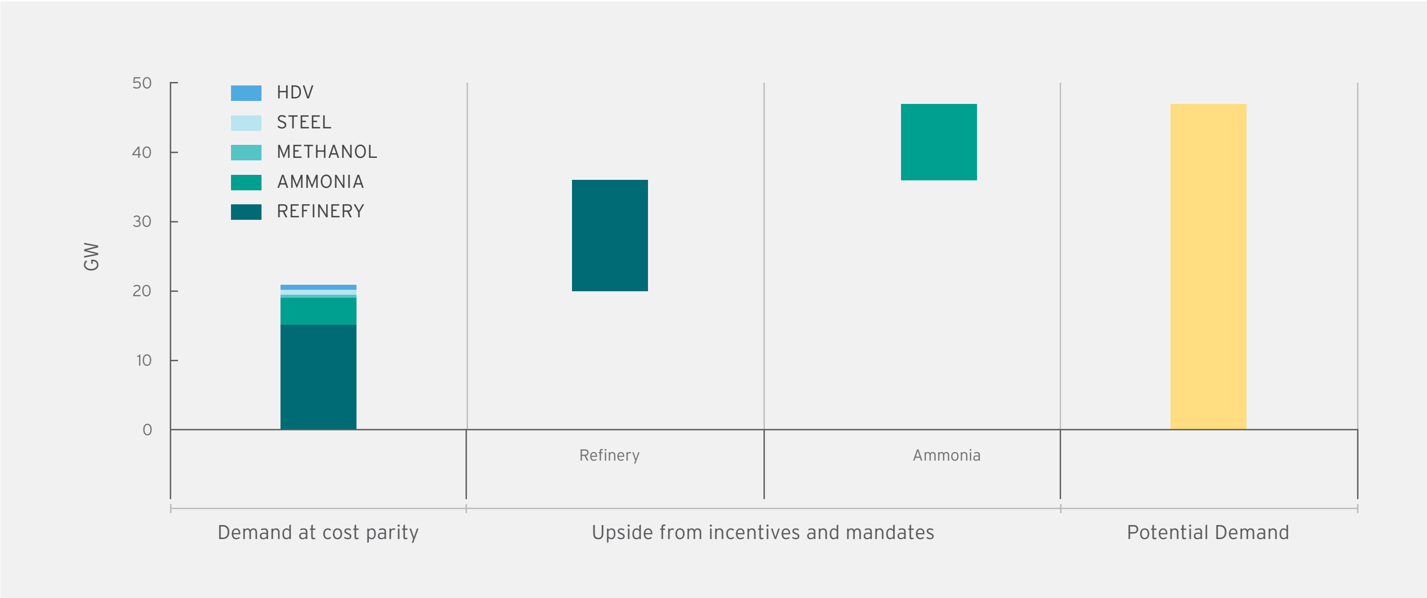
Exhibit 19 Potential electrolyser market in India



Source: RMI Analysis

There is significant near-term increase in the FPS scenario and demand of up to 44 GW can be expected by 2030 (Exhibit 20), provided VGFs, mandates, pilots, and cost reduction incentives can accelerate market development. Early government efforts can help domestic manufacturers capture a significant share of the pie while potentially emerging as a global manufacturer.

Exhibit 20 The potential increase in the electrolyser market under the FPS scenario for 2030



Source: NITI Aayog, RMI analysis

Technology Review and Implications for India

The market for electrolysers is dominated by alkaline and polymer electrolyte membrane (PEM) technologies with advanced electrolyser technologies like solid oxide and anion exchange membrane nearing commercial deployment as well.

The fundamental components of the electrolyser consist of the stack and a large array of *balance of plant (BoP)* components. The actual splitting of water into hydrogen and oxygen occurs at the stack level and is supported by the various systems that fall collectively under the BoP. Fundamental differences between PEM and alkaline electrolysers are at the stack level (Box 11). BoP components are common across both types of electrolysers.

Box 11 The Difference between PEM and Alkaline Electrolysers

The structure for both PEM and Alkaline electrolysers is similar but there are a few differences.

A PEM electrolyser relies on reversing the fuel cell process and requires no electrolytes.

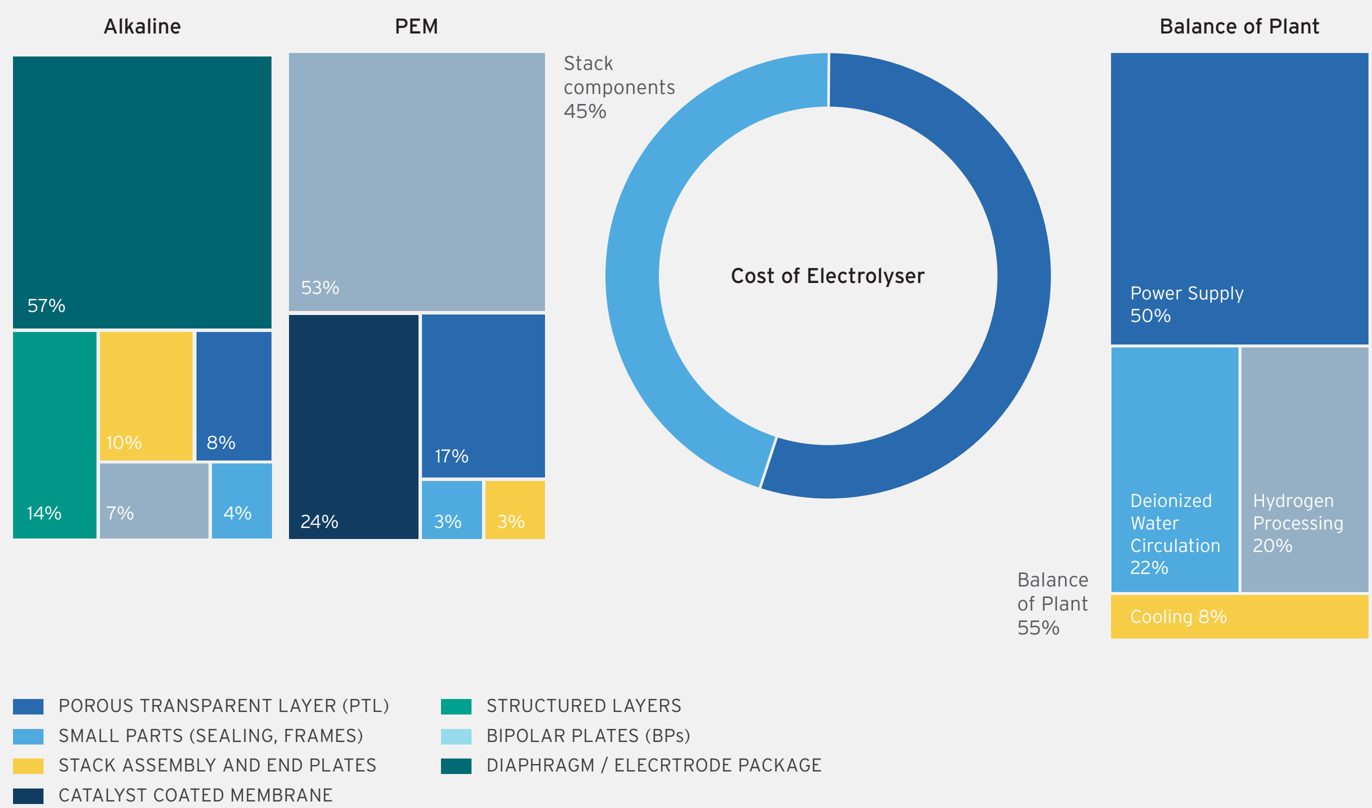
An alkaline electrolyser, on the other hand, is a much more mature technology (it has been in commercial application since the 1950s) but requires an electrolyte liquid.

PEM stack components rely on rare earth metals. The cathode and anode layers of a PEM stack are created by depositing metals like iridium or platinum on either side of the membrane. These are the scarcest and most emissions-intensive metals available. The bipolar plates of the PEM stack are built using gold- or platinum-coated titanium while the PTL can be built with titanium or carbon cloth. Alkaline electrolysers rely mostly on nickel whose supply is more diversified than rare earth metals.

Compared with alkaline electrolysis, PEM electrolysis has the advantage of quickly reacting to the fluctuations typical of renewable power generation. But PEM electrolysers tend to be costlier. As electrolyser deployment moves towards the gigawatt-scale market, the lower cost of alkaline electrolysers is advantageous when it comes to scale deployment.

Although the stack contributes close to 50% of the total cost of both PEM and alkaline electrolysers, the balance of plant (BOP) remains the predominant cost contributor for both electrolysers (Exhibit 21). The stack, power supply, and water circulation system make up more than 80% of the cost. Power supply alone accounts for 20%–30% of the total system cost of electrolysers today. If seawater is utilized to produce green hydrogen, the cost of desalination further increases the water purification costs. This subsystem is the second-largest cost component within the balance of plant.

Exhibit 21 Cost breakdown of electrolyser (Adapted from IRENA[44])



When it comes to the stack, the cost differs based on the technology. The material intensity of PEM, especially with its heavy reliance on rare-earth metals and precious metals like gold and platinum, means that material costs constitute a much larger share than manufacturing and assembly costs. The easy availability of nickel coupled with a simpler design makes alkaline electrolysers 50%–60% cheaper than PEM electrolysers. Hence the stack cost of the alkaline electrolyte is not dominated by the material costs but the manufacturing costs amounting to 40% to the total stack cost.

The Domestic Manufacturing Opportunity in India

Stack Manufacturing

When it comes to stack manufacturing, India's initial positioning is limited by import dependence for metals like platinum, iridium, and even nickel. Even for new technologies like solid oxide electrolysers, critical materials are in short supply globally and almost 95% comes exclusively from China. This import dependency reduces near-term competitiveness, challenging private sector interest in developing stack manufacturing capabilities within the country.

Additionally, there is the question of skilled labour for stack manufacturing. While it warrants further research, early conversations with electrolyser manufacturers indicate that skilled labour may not be a problem, and the country's scientific and engineering professionals are able to meet foreseeable demand.[45] Regardless, further assessment is required on whether the current level of technical education and research is providing an adequate labour force as well as institutional knowledge for the country to partake in the hydrogen economy in general and electrolysers in particular.

But in the longer term, the country can still leverage its expected growth in domestic green hydrogen demand to encourage private sector interest. To begin manufacturing electrolysers in-country, the government could develop the following strategies:

- Identify and invest in research, development, and commercialisation of low-cost electrolyser technologies that require minimum rare earth metals.
- Secure a robust supply chain of metals and mineral and identify electrolyser recycling strategies. These strategies could be developed in parallel with the domestic advanced chemical battery ecosystem, which may need similar materials.
- Spur local demand for green hydrogen through mandates and incentives. This will help create demand certainty for manufacturers to build up stack manufacturing capabilities.

Balance of Plant

Given that power supply, water circulation, and hydrogen processing units account for 50% of the electrolyser costs and with potential for further cost reduction, India still can grow its position in the global electrolyser market by emulating the progress it is making in the electronics space. India's electronics manufacturing has grown from $29 billion to $70 billion in a span of five years (2014–2019). This has resulted in India's electronics exports growing 39% year-on-year to $8.8 billion in 2019 coupled with a 5% contraction in electronics import.[46]

This growth has been spurred by multiple Government schemes that incentivized local manufacturing of electronics including the Phased Manufacturing Program, the Modified Special Incentive Package Scheme, electronics manufacturing clusters, and the National Policy on Electronics 2019. Those schemes, along with the recently announced Production Linked Incentive scheme for solar PV, automobiles, and batteries are potential models that can encourage electrolyser manufacturing in the near term.[47]

While the country can leverage its experience in power electronics manufacturing, efforts are required to identify and establish standardized BoP components for the global electrolyser market. This calls for room for collaboration with global manufacturers to establish standards for BoP components. Further, the supply ecosystem in the country must be improved to increase overall domestic value capture.

Encouraging Electrolyser Manufacturing

India's electrolyser manufacturing ecosystem is at a nascent stage today (see Box 12). Much is left to be seen in how the government further encourages both research and development efforts to indigenize technologies, while encouraging development of start-ups and OEMs engaged in electrolyser manufacturing. Building the electrolyser ecosystem requires the government to introduce direct and indirect incentives to attract domestic and international players to create electrolyser manufacturing capacity in the country.

Box 12 Existing Electrolyser Manufacturing and Research Efforts in India[48]

As per the Ministry of New and Renewable Energy, India is already home to half a dozen alkaline electrolyser manufacturers today. However, the ministry acknowledges the need for improving electrolyser technology to make them more efficient and economical. A few PSUs in India possess the manufacturing capability for producing BoP components, but the domestic production of electrochemical stacks remains muted. The current electrolyser demand in India for the chlor-alkali industry is met by international manufacturers. Indigenous solutions providers have also partnered with international electrolyser manufacturers to meet the domestic demand for hydrogen.

Beyond commercial hydrogen production activities, there is significant research being done across various institutions in the country. A few notable research projects are mentioned below:

- Bhabha Atomic Research Centre (BARC) has developed an alkali water electrolysis technology for commercialization that can produce 10 Nm3/hr of hydrogen.
- CSIR-CECRI, Karaikudi is designing electrodes and electrolytes for hydrogen generation using seawater with reduced titania as a catalyst.
- The University of Lucknow is exploring the use of transition metal mixed oxides for alkaline water electrolysis along with preparing electrodes using suitable techniques.
- A consortium of institutes including IIT Kanpur, IIT Madras, Dayalbagh Educational Institute, IIT Jodhpur, CECRI Karaikudi, and BARC are aiming to develop a scalable design for a solar hydrogen generation system using multiple technologies.
- ONGC Energy Centre alongside IIT Delhi are utilizing Sulphur-iodine thermochemical hydrogen cycle to generate low-cost clean hydrogen fuel for industrial consumption.

A target-backed government incentive can greatly accelerate manufacturing. The European Union has set a target of 6 GW of electrolyser capacity by 2025 and 40 GW by 2030.[49] The ambitious targets are backed by a functioning carbon trading mechanism and stricter emission norms. Given the significant increase predicted for electrolyser manufacturing in the next decade, Indian manufacturing of electrolysers that support the Indian green hydrogen industry could signal the advent of a sunrise opportunity.

Initiatives like the United Nations Framework Convention on Climate Change's Green Hydrogen Catapult coalition aim to drive down the cost of green hydrogen to less than $2/kg by scaling up manufacturing of electrolysers from the current estimated capacity of 2 GW to 25 GW by 2026.[50] This growth is expected to materialize rapidly with the commercial viability of hydrogen expanding beyond the transport sector to the industry and building sectors in the coming decade. This growth is attracting global manufacturers like Orsted, ACWA Power, Envision, Yara, Iberdrola, and Snam, which have already committed ambitious manufacturing targets for electrolysers.

Encouragement towards electrolyser manufacturing can ensure supply-chain security for the Indian hydrogen economy and set up India to take advantage of this emerging industry. Production and demand side encouragements for green hydrogen as well as direct incentives for manufacturing will be necessary. Further, non fiscal measures like improving the process for regulatory clearances coupled with preferential treatment in public tenders can also enable the environment for domestic manufacturing of electrolysers.

Research and Development Program

Beyond encouragement for manufacturing a commercial results-oriented research and development program should be instituted focusing on electrolysers, fuel cells (see Box 13 for a review of fuel cells), and associated components looking at efficiency improvement, cost reduction, stack life extension, and development of a technology less dependent on metal and material imports. This program can be a collaborative effort by key industry players and renowned academic institutions.

India should invest $1 billion in R&D by 2030 to catalyse the development of commercial green hydrogen technologies across the value chain. Instead of blanket funding of research Institutions, the government can implement a focused and commercial results-oriented R&D program with well defined targets and rewards/incentives for commercial technology development.

NITI Aayog recommends a mission mode R&D drive in collaboration with the industries in the following area:

- Early-stage R&D to enable technologies that reduces the cost of hydrogen delivery and dispensing.
- Manufacturing techniques to reduce the cost of automotive fuel cell stacks at high volume.
- R&D that reduces the costs of manufacturing electrolyser components, using advanced techniques such as additive manufacturing.
- Compression of hydrogen to 875 bar using electrochemical cells and metal hydride materials.
- Improve efficiency and reduce the capital cost of hydrogen liquefaction, using a vortex tube concept.
- Establish the potential for magnetocaloric technologies to liquefy hydrogen at twice the energy efficiency of conventional liquefaction plants.
- Secure critical mineral supply either through indigenous development or global collaborations for the supply chain of Nickel, Zirconium, Lanthanum, Yttrium, Platinum, Iridium and other key raw materials used in electrolysers.

A model R&D program is given below as an example of such a target-based technology development program.

Exhibit 22 Proposed technology innovation and scaling funding

Type	Initiative	Participants	Public Investment	Private Investment	International Agencies
Early stage R&D	Grand Challenge	Industry-Academia Joint Teams	$400 Million	$50 Million	2035
Prototype and Validation	Industrial Test Beds	National Labs or Private Entities	$100 Million	$5 Million	$25 Million
Commerical Scale Up	Hydrogen Venture Capital	VC Funds	$500 Million	$300 Million	$200 Million

Source: NITI Aayog

Box 13 A Review of Fuel Cells[51]

Fuel cells are in a sense the opposite of electrolysers. Instead of splitting water into hydrogen and oxygen using electricity, it houses an electrochemical reactor that uses energy source natural gas or hydrogen as a main source to produce electricity. They consist of an electrolyte and two electrodes. Hydrogen molecules react with the anode to form positive hydrogen ions and electrons. The ions travel through the electrolyte to react with air (oxygen) at the cathode, while the electrons pass through a connected circuit generating electricity. Finally, hydrogen ions and electrons combine with oxygen at the cathode to produce water.

Fuel cell technologies are similarly differentiated based on the stack technology. PEM is the most used fuel cell and is suited for transport applications due to its lower operating temperature requirements and quick start. The other technology options are more suited for distributed power generation, except for alkaline fuel cells, which are mainly used in military applications.

Cost Implication

Manufacturing costs dominate the total cost of PEM fuel cells, whereas the share of materials cost is much lower. An increased scale in production can bring the manufacturing costs down dramatically—a 45% reduction in fuel cell system costs is plausible with scaling from 10,000 systems to 200,000 systems. India's scale in terms of manufacturing capability and demand and low-cost labour can help reach economies of scale much faster. Investment in larger equipment, advancement in manufacturing operations, better utilization of machinery, and aggregated procurement are the biggest factors to reduce manufacturing costs related to fuel cells.

India's Domestic Manufacturing Opportunity

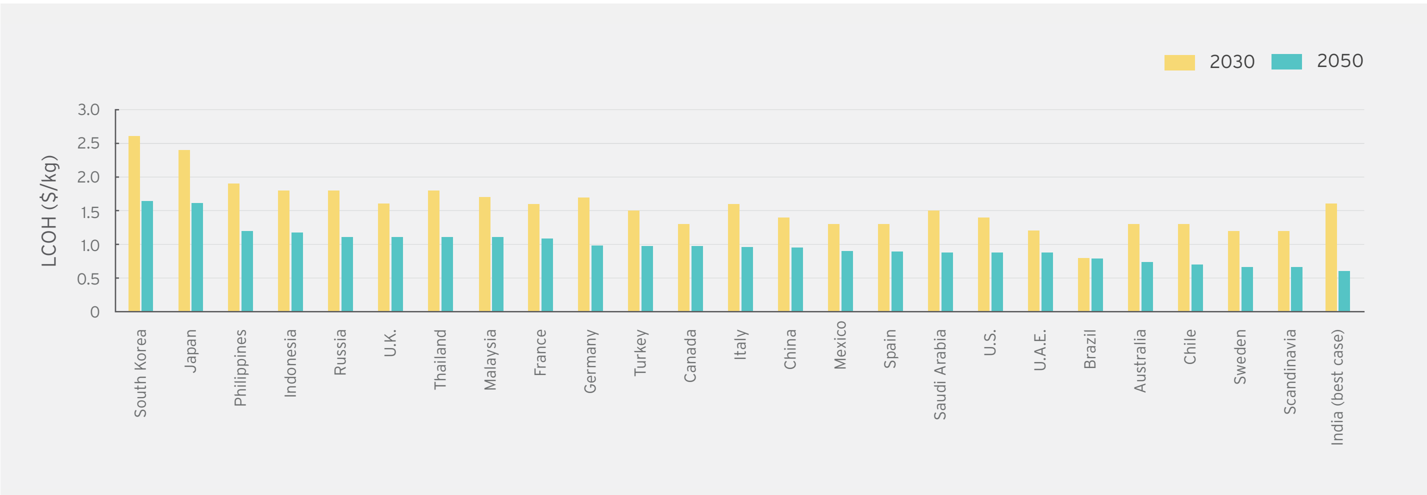
RMI's analysis indicates that fuel cell demand through heavy-duty trucking alone presents a $4 billion market opportunity by 2050 in India, amounting to 10%–18% of global fuel cell demand by 2050. Similar to electrolysers, this could create opportunities for domestic manufacturing in India. Market size and manufacturing opportunities for fuel cells can be even greater if stationary fuel cell systems also play a role in the future.

Export Opportunities

Export Opportunities

India's domestic demand expectation will mean that it will not be a pure export-driven hydrogen producer like the Middle East or Australia. But driven by the low cost of renewables in the country, India can still emerge as a one of the most competitive sources for green hydrogen in the world (Exhibit 23). This will impact not just the prospects for hydrogen exports but also the competitiveness of low-carbon products with embedded hydrogen such as green steel and green ammonia.

Exhibit 23 Comparison of levelized cost of green hydrogen in selected countries



Source: BNEF,[52] RMI Analysis

Hydrogen Export Opportunities

Disparity in sources and consumption of green hydrogen is bound to create markets for green hydrogen as a tradeable energy commodity in the long term, albeit with challenges. We are already seeing early momentum as traditional energy importers like Japan and South Korea, willing to pay premium prices, are increasingly pursuing the possibility of importing hydrogen through ocean shipping (e.g., with Australia, see Box 14) either through LH_2, LOCHs, and NH_3. European countries are also welcoming the prospects for both intra-regional and international hydrogen trade. Traditional energy exporting regions like Australia and the Middle East are increasingly positioning themselves for hydrogen exports.

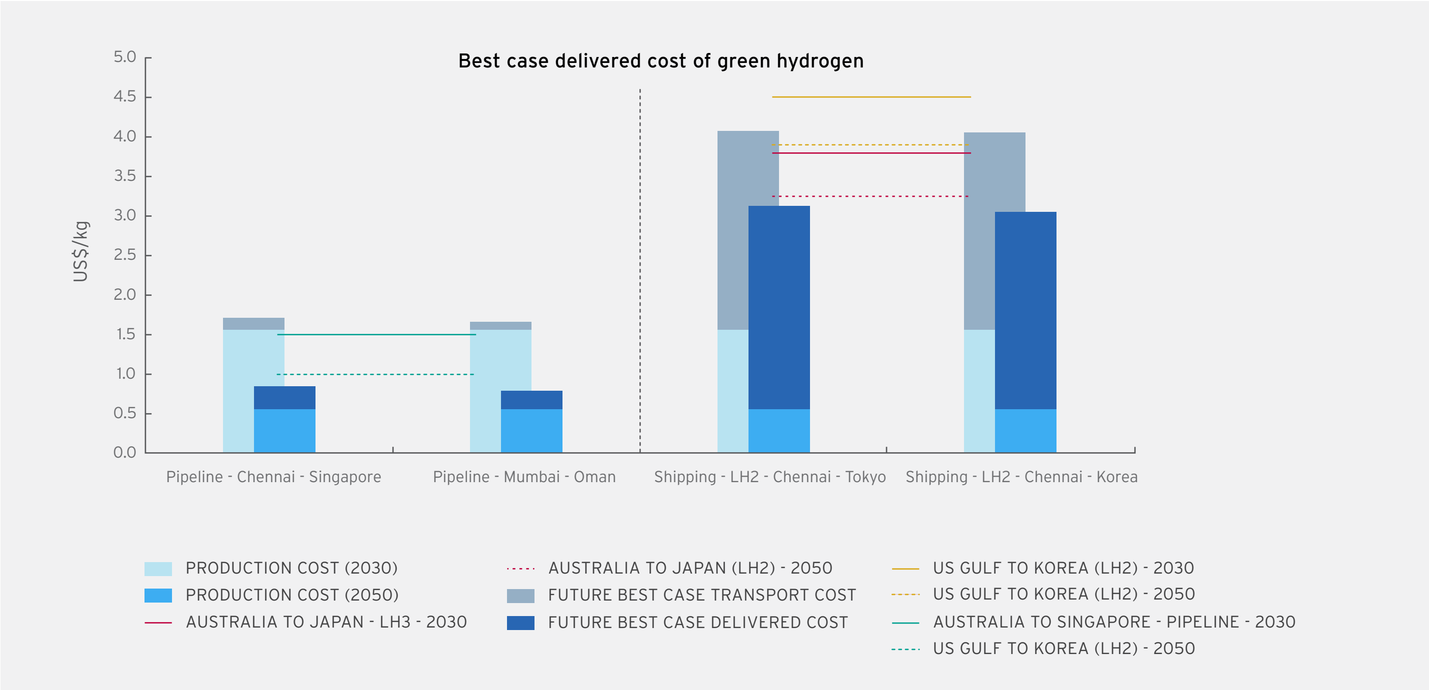
Box 14 The Japan-Australia Hydrogen Energy Supply Chain (HESC) Project[53]

Japan and Australia are currently working on a **Hydrogen Energy Supply Chain (HESC) Project,** the world's first endeavor to ship hydrogen over the ocean. It aims to safely produce and transport clean liquid hydrogen from Australia's Latrobe Valley in Victoria to Kobe in Japan. HESC hopes to demonstrate the viability of an end-to-end hydrogen supply chain. The HESC Project is being developed in two phases, beginning with a pilot, and moving on to commercialization. In the commercialization phase, coal from the Latrobe Valley will produce blue hydrogen due to the addition of CCS. Australia aims to kickstart a hydrogen export industry with this project. The pilot phase is to be completed in 2021 with commercial operation targeted for the 2030s depending on the results of the pilot.

Competitiveness of Indian Green Hydrogen Exports

Green hydrogen from India in 2050 could be remarkably competitive with hydrogen from countries like Australia and the United States, which are already in conversation for ocean shipping of hydrogen. Even by 2030, Indian green hydrogen could be competitive at the margin for select geographies.

Exhibit 24 Potential delivered cost of Indian green hydrogen



Source: BNEF,[54] TERI, RMI Analysis

The prospect for pipeline trade to major ports and energy trading hubs in the region like Singapore exists if end-use sectors such as shipping and the airline industry (in addition to refining) increase their use of hydrogen.

Challenges to Hydrogen Export

However, this brief analysis doesn't highlight the various techno-commercial challenges to international hydrogen trade and India's preparedness for it.

While marine hydrogen trade is theoretically promising, many challenges persist. Unlike petroleum or natural gas where resources are constrained by geography, green hydrogen could be produced onshore, provided resources (land, renewable electricity, etc.) are adequately available. Export-dependent countries, willing to pay a price premium, can also theoretically utilize imported liquified natural gas (LNG) to produce hydrogen onshore through steam methane reformation (SMR).

With LOHCs and hydrides like ammonia, the additional energy cost of conversion makes cost considerations necessary.

Pipelines, on the other hand, remain underdeveloped, even nationally. As of 2016, there were only approximately 2,800 miles of dedicated hydrogen pipeline installed globally, with 1,600 miles of those in the United States.[55] This contrasts with over 130,000 miles of onshore oil pipelines and 300,000 miles of onshore natural gas pipelines in the United States alone. Hydrogen blending is being proposed and utilized in national natural networks but has not been used in international trade yet. Due to their high capital cost and long lifetime, hydrogen pipelines are typically reserved for high volume flows. Lastly, the issue of hydrogen embrittlement of steel can result in safety concerns and potential cost considerations.

This challenge of infrastructure preparedness is both global and local. India's lack of experience as a hydrocarbon exporter means there is a comparatively steeper learning curve before it can effectively compete with regions like Australia and the Middle East, which are also equally blessed with the prospect of low-cost green hydrogen. In the near-term this will involve assessment of infrastructure readiness for hydrogen exports. Brownfield assets including pipelines and LNG import terminals can theoretically be repurposed for exports but given all the challenges related to hydrogen transportation and storage, a thorough assessment is warranted.

Near-term infrastructure development should also be cognizant of such long-term prospects.
In the longer term, becoming an energy exporter will require the country to invest in improving the business environment, including aspects such as transparent access to land, labour, and capital; a legal mechanism to honour contracts; and a stable political environment.

Near-term infrastructure development should also be cognizant of such long-term prospects. In the longer term, becoming an energy exporter will require the country to invest in improving the business environment, including aspects such as transparent access to land, labour, and capital; a legal mechanism to honour contracts; and a stable political environment.

Green Hydrogen-Embedded Low-Carbon Products

Exporting hydrogen itself may have techno-commercial challenges. But markets for products that rely on low-carbon hydrogen as inputs (such as green steel and green ammonia) can also be competitive opportunities to leverage the green hydrogen potential of India. Although it is early to ascertain how these markets might evolve, this section helps illustrate the potential of India's low-carbon ammonia and steel in global markets.

Green Ammonia

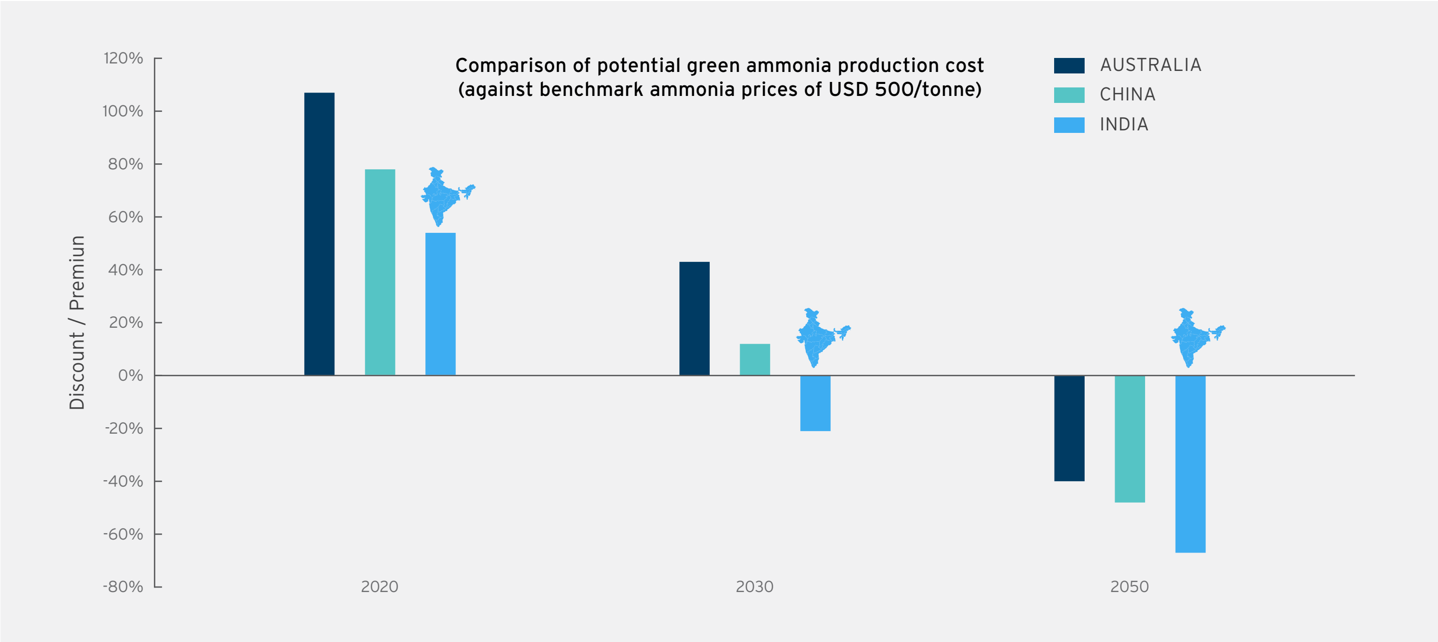
Given the existing demand of hydrogen for ammonia production, ammonia offers a more immediate path to market than many other use cases. Beyond traditional use cases like fertilizer and industrial feedstock, ammonia is now being looked at for power generation, marine fuel, and most importantly, as potentially the most competitive energy carrier for the sea borne hydrogen trade.[56] Unlike other "green" commodities, the supply chain and logistics for ammonia is highly developed and includes wide networks of ports, storage facilities, and established shipping routes.[57] And given its centrality in many sectors there are additional avenues for moving up the value chain, boding well for the future of a global trade in green ammonia.

A decarbonization agenda is shaping global demand. Japan is expanding the use of ammonia as co-firing fuel for its coal plants and targets annual consumption of 3 million tonnes by 2030 and 30 million tonnes by 2050.[58] Several companies are developing innovative engines and turbines that can use ammonia as a feedstock.[59] Ammonia projects for marine fuel are also emerging.

India's Potential

Given the cost sensitivity of ammonia to the price of hydrogen, as discussed in Chapter 2, evolution of the global green ammonia market will also rest heavily on the prices at which green hydrogen can be delivered. In our analysis, India's early renewable LCOE advantage leads to low-cost hydrogen and offers advantages in related electrified processes. Today, ammonia produced by this pathway would come at potentially a significant premium over ammonia produced by conventional pathways.

Exhibit 25 Cost comparison of green ammonia



Source: RMI Analysis

However, through innovation and continued cost decline, the pathway of production could become significantly cheaper. This cost advantage could also potentially improve India's competitiveness for green hydrogen trade, given ammonia's role as an energy carrier. Since infrastructure for ammonia production already exists for the fertilizer industry, there are significant synergies India should explore for expansion to cater to an emerging global demand for green ammonia.

Creating a Global Market for Green Ammonia

Building a global market for green ammonia will require significant expansion of end use from more cost-sensitive fertilizer and industry to energy applications, which potentially could absorb slightly higher cost in the right geographies. Identifying and encouraging applications that can pay a higher green premium need to be supported.

Decarbonization goals have and will continue to dictate the longer-term direction of green ammonia. Therefore, early leadership from prominent nations and clear alignment in global policy direction is needed to provide the right signal for the private sector to invest in market building.

To sustain and grow the market, significant innovation and lowering of capital and energy cost will be required. This could involve instituting research and development and incentive mechanisms at a multilateral level. Mechanism like carbon prices can also provide much needed levelling of the economic gap for many of the end uses.

Green Steel

There is a tacit recognition of steel being an increasingly important and viable pathway for hydrogen use. DRI technology is already in use through natural gas, and the first commercial pilots for hydrogen DRI are already running. Major steel producers have announced their foray into green steel, with seven out of the ten biggest steel producing countries initiating green steel projects.[60] Most of the investments are concentrated in Europe with Sweden leading the way.[61] Swedish green steel start-up H2GS AB recently raised $105 million targeting an annual production of 5 million tonnes by 2030.[62] India's own Tata Steel has announced plans for green steel in its UK plants.[63]

Decarbonization seems to be the biggest driver for this shift and most projects are in countries with aggressive CO_2 reduction targets. But the steel mills of progressive companies that currently invest in and commit to low-carbon production only represent 8% of global steel production. A 100-fold step-change in the pace of transition is needed for the steel industry to adhere to a 1.5°C pathway.[64] Given project lead-time and the long lives of steel mills, there is a need for immediacy in initiating this transition.

India's Potential

This recognition bodes well for the future of the global green steel market. The only question is when it will start making economic sense for scaling this transition. Hydrogen-based steel is expected to be cost-competitive between 2030 and 2040 in Europe.[65] But this scenario can be accelerated if an adequate carbon price is introduced or if the price of hydrogen drops substantially.

Exhibit 26 Cost comparison of green steel

Source: RMI Analysis

Steel is a traditionally tight margin market. Thus prices reflect a very tight capacity to absorb variable costs. In our assessment, the same advantage of low hydrogen cost that allows India a potential advantage in manufacturing ammonia creates a pathway for steel. This is further strengthened when considering the significant volume of electric arc furnaces in use in India today (around 56% of current fleet)[66] that could be used in DRI crude production. Additionally, while not modelled, the potential to utilize slack capacity in these EAFs would further reduce the cost points.

Creating a Global Market for Green Steel

Given the importance of steel to industrialisation, and the economics of multiple sectors, building a global green steel market will require coordinated policies, pooling of investment and research and development resources, harmonisation of product and process standards, and significant transition financing. RMI lists the following set of interventions that could encourage this transition:

Exhibit 27 Interventions towards a global green steel market

Market Information

- A differentiated low-carbon steel product to enable the supply-demand dynamic to create price premium for a higher-performing supplier
- Asset portfolio differentiation to reduce risk exposure to medium-to-long-term market development toward a low-carbon future
- New vehicles to scale intellectual property (IP) beyond single entitie

Policy Intervention

- Industry self-regulation and decarbonization commitments of critical scale
- Carbon taxes or equivalent mechanisms to reduce the cost advantage of high-carbon manufacturing
- Import tariffs based on carbon content to protect the local market from carbon leakage (i.e., competition from high-carbon import)
- Carbon performance requirements in government and/or private procurement

Finance Intervention

- Government or voluntary support to lock in value premium for low-carbon steel production to reduce uncertainty for investors in emerging technology
- Late stage R&D support for commercialization of technologies currently in pilot stage
- Investor pressure on steel companies to disclose and improve their carbon performance
- Securitization programs or other financial tools to manage the potential write-down value of high-carbon production assets

Source: RMI[67]

Key Takeaway

This preliminary analysis effort is not sufficient to provide granular justification of specific cost points, but the trend indicates the potential areas of advantage that India could begin to leverage today. The continued drive towards low-cost renewables further supports the expected declines in electrolyser capital expenditures and improvements in efficiency that will drive to significantly more competitive pricing for export hydrogen and commodities. Although India would appear to have some advantage, these will be significantly competitive markets internationally as similar cost declines materialize in other countries. Flexibility and nimbleness will be required to realizable this advantage in the long term.

Ultimately, this export competitiveness circles back to market creation to enable scaled deployment of green hydrogen so that price decline expectations can be met. In the medium term, export projects can potentially serve as a market creation mechanism for green hydrogen production. Green ammonia can be an ideal product since India should already be targeting ammonia for fertilizer production. In due course, India can also pre-empt the green steel market through export-oriented pilot projects and manufacturing schemes. Government-to government cooperation must be leveraged to develop collective frameworks and labelling and standards around green hydrogen and embedded products.

Box 15 Financing the Hydrogen Transition[68]

Enabling India's hydrogen transition will require an increased access to and flow of finance on part of several stakeholders. Different stakeholders have different roles across technology stages due to differing risk appetites and investment horizons. Considering these roles help define the most effective ways for each stakeholder to finance green hydrogen. Mobilising finance will be particularly important to ready the market for achieving large-scale deployment.

Public Finance

Government expenditure and publicly owned bodies are crucial to every stage of technology innovation due to longer-term investment outlooks and greater tolerance for uncertainty. Governments can provide grants and loans to start-ups and projects, support entrepreneurs through incubators and investor networks, and put in place regulations that manage first-mover risks. They are crucial source for concessional finance to bridge markets and support scale-up. Government can also use public procurement and purchase incentives to create demand in niche markets and "crowd in" private investment.

Globally, governments are moving towards supporting commercialisation and demonstration of entire value chains, often through public-private partnerships. Nations are increasingly using regions, cities, or industrial clusters as focal points of financing. In addition to direct support and programs, public financial institutions are being engaged to support the transition.

Multilateral Finance

Multilateral development banks (MDBs) and climate finance institutions can help catalyse technological adoption across stages in partnership with public and private actors. MDBs can provide venture capital and investor networks to entrepreneurs and projects, and support governments in developing enabling policies/regulations. They can also explore support to demonstrations and pilots with industry actors. MBDs are also crucial for concessional finance and can capitalise guarantees and risk-sharing facilities to support scale up. They can also provide directed lending to local financial institutions. Although interest in hydrogen has been growing, substantial funds have not yet been mobilized.

Private Finance and Industry

Private investment and business input is essential to developing a robust market, spreading market awareness, and creating space for evidence-based policymaking. Corporate venture capital can incubate applications of green hydrogen and provide opportunities for scale-up. Industries can finance in-house pilots and first movers, possibly via public-private partnerships. Further, the larger financial industry can adjust investment criteria and build capacity for maturity, engaging in risk-sharing and blended finance models. They can also develop project finance models for green hydrogen. Private equity is slowly being mobilised, signified by the launch of HydrogenOne Capital— the world's first hydrogen-dedicated investment fund, worth $315 million. Project finance, although a viable financial mechanism for funding hydrogen projects, is still at early stages of exploration.

Policy and regulatory risks are seen to constrain private investment in hydrogen projects, especially in nascent markets such as India. Hydrogen has limited commercial viability at this stage due to higher upfront costs, longer payback periods, and unproven returns. But this creates an opportunity for a national program to prime India through the design of de-risking schemes such as guarantees, first-loss tranches, and concessional insurance while simultaneously building the capacity of public and private financial institutions.

Steps to make India a global hub of green hydrogen

Steps to make India a global hub of green hydrogen

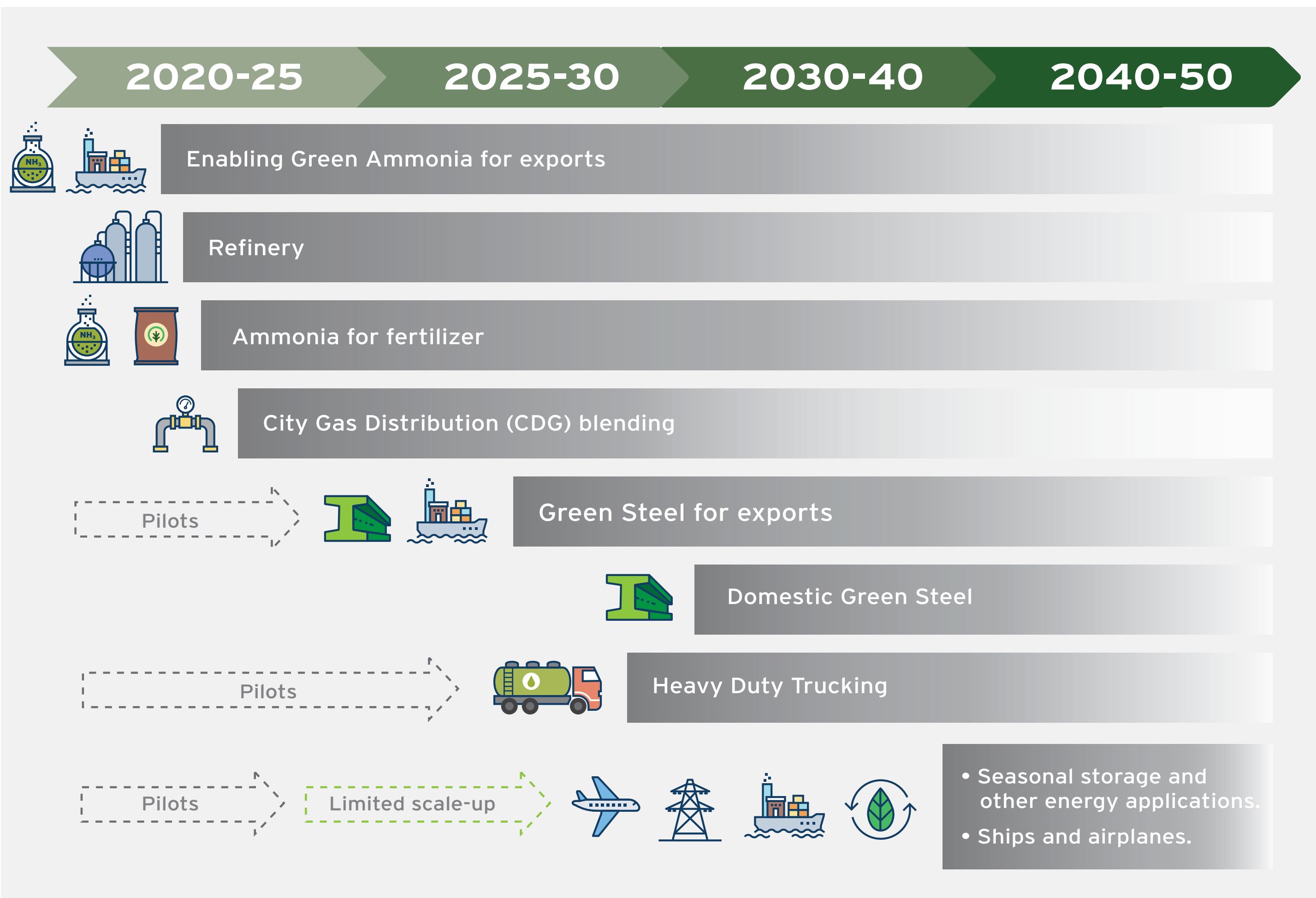
The analyses and discussions presented in this report are only meant to highlight the opportunities that green hydrogen presents for India for decarbonization, manufacturing, and exports. Real action is required for the country to truly benefit from these opportunities.

This chapter distills the insights into ten actionable recommendations that can lead to a National Action Plan on Green Hydrogen to guide and enhance the National Hydrogen Mission.[69]

1. A detailed roadmap focused on all aspects of 'Green Hydrogen'

The recent announcement of the National Hydrogen Mission signals the right intent but it needs to be complemented with further policy direction in the form of a national roadmap/strategy. The emphasis of this roadmap should be to elaborate on the government's vision for green hydrogen in multiple sectors with timelines and investment aspirations given the long-term cost advantage and multiple benefits that we have established in this report. This will improve investors' confidence and will converge the entire value chain and the various government agencies towards a singular vision.

Exhibit 28 Potential direction of a National Green Hydrogen Roadmap



Source: NITI Aayog

2. Establish an aspirational cost-reduction target and initiate supply-side intervention for achieving cost reduction of green hydrogen

Enabling this roadmap with require both demand and supply side interventions. In tandem with cost reduction targets in the roadmap, the government should also focus on enabling a **cost reduction pathway** for green hydrogen to be produced in the country. The current Green Hydrogen policy lays out adequate measures focusing on inter-state transmission (ISTS) charges waiver and open access for green hydrogen and green ammonia production. It can be further improved by:

- Reduction or exemption of tax and duties like the GST and custom duties;
- Dollar-based tariffs for green hydrogen like the standard practice in the oil and gas sector; and Other measures such as revenue recycling of any carbon tax, low emission PPAs, and avenues for firming electricity supply including discounted grid electricity to complement VRE generation.

To further motivate the private sector, the government should establish an aspirational price decline target. Such a target is proposed below:

Exhibit 29 Proposed aspirational hydrogen price targets

Year	2025	2030	2050
Green H2 Price	\$1.50/kg	\$1/kg	< \$1/kg

Source: NITI Aayog

3. Initiate mandates and incentives towards a visionary target of 160 GW of green hydrogen production capacity including 100 GW of exports

In the demand sector, the government should set a visionary target complemented by strict mandates and adequate VGFs on more immediately addressable end-use demand.

End-use sectors should be further assessed to identify those sectors ready for scaled consumption and those ripe for small- and large-scale pilot development. They should also be supplemented with geographical assessments to identify potential clusters around existing factories, transmission infrastructure, and renewable hubs. Such cluster identification can also include the prospect of exports.

A plan should also be set to propose **clear mandates** around hydrogen blending in existing and potentially future consumption sectors. This will provide demand certainty for early green hydrogen projects and encourage early market development. Potential mandates being proposed by NITI Aayog are shown in Exhibit 30.

Exhibit 30 Potential mandates for existing applications

Sector	Target Type	Mandate	Cut-off Date for the Sector to go 100% Green
Refinery	Corporate level targets	50% by 2030	2035
Fertilizers	Import substitutions	100% by 2030	2040

Source: NITI Aayog

For new applications, where the viability of using green hydrogen is still nascent, necessary incentives should be designed. One example is a PLI scheme for green steel targeting export markets. NITI Aayog is proposing the several visionary targets for new applications (Exhibit 31).

Exhibit 31 Aspirational targets for new applications

Sector	Type	Targets
Steel	Old plants	Fleet level carbon intensity by 2035 should be less than 2 tonnes of CO_2 per tonne of steel
	New capacity	At least 20 million tonnes of green hydrogen- based green steel to be made in India primarily for exports
City Gas Distribution (CDG)	Pilot and subsequent scale-up	10% blending by 2025 and 20% by 2030
Green Ammonia	Exports	25 million tonnes of exports to countries such as Japan, Korea, and the European Union
Heavy-Duty Vehicles (HDVs)	Pilots on specific routes	1,000 trucks, 50 boats, and 10 aircrafts to be piloted by 2030. Three hydrogen corridors to be developed across the country based on state grand challenge.
Power	Allow participation in RTC tenders	Where economics makes sense, allow hydrogen to compete with other storage technologies in Round the Clock tenders by SECI.

Source: NITI Aayog

Box 16 Assessing Viability Gap Funding for Exports

India has the potential to become a major exporter of green hydrogen-based products, given a strong base of manufacturing excellence and ample availability of cheap renewable sources. However, the current high cost of green hydrogen compared with grey hydrogen will act as a major roadblock for India to transition to a global force in green hydrogen production and consumption. One policy instrument that can enable cost parity of green hydrogen with grey is VGF, where a developer setting up a green hydrogen plant would be provided marginal funding so that the green hydrogen price would become equivalent to grey hydrogen prices.

Since exports provide a strong potential for scaling green hydrogen uptake and fall within the priorities of Government of India, an analysis has been developed to assess the amount of VGF required to match India's green hydrogen export aspirations. This assessment is an illustration and similar methodology can be followed to assess VGF for other end uses.

Three scenarios for green hydrogen prices are assumed (representing the lower, middle and higher end of green hydrogen prices previously shown in Exhibit 11 of this report). In each scenario, the price of green hydrogen in a given year is compared against a target grey hydrogen price in that year. Then, the required electrolyser price to reduce the green hydrogen price to the target price is assessed. The difference in the upfront electrolyser prices multiplied with the electrolyser capacity in that year gives the yearly VGF required. This process is repeated for each consecutive year. The electrolyser capacity for this analysis is based on the target of 95GW by 2030. Moreover, the starting year for VGF is 2024, with ending year differing in each scenario.

Exhibit 32 VGF and electrolyser capacity for exports

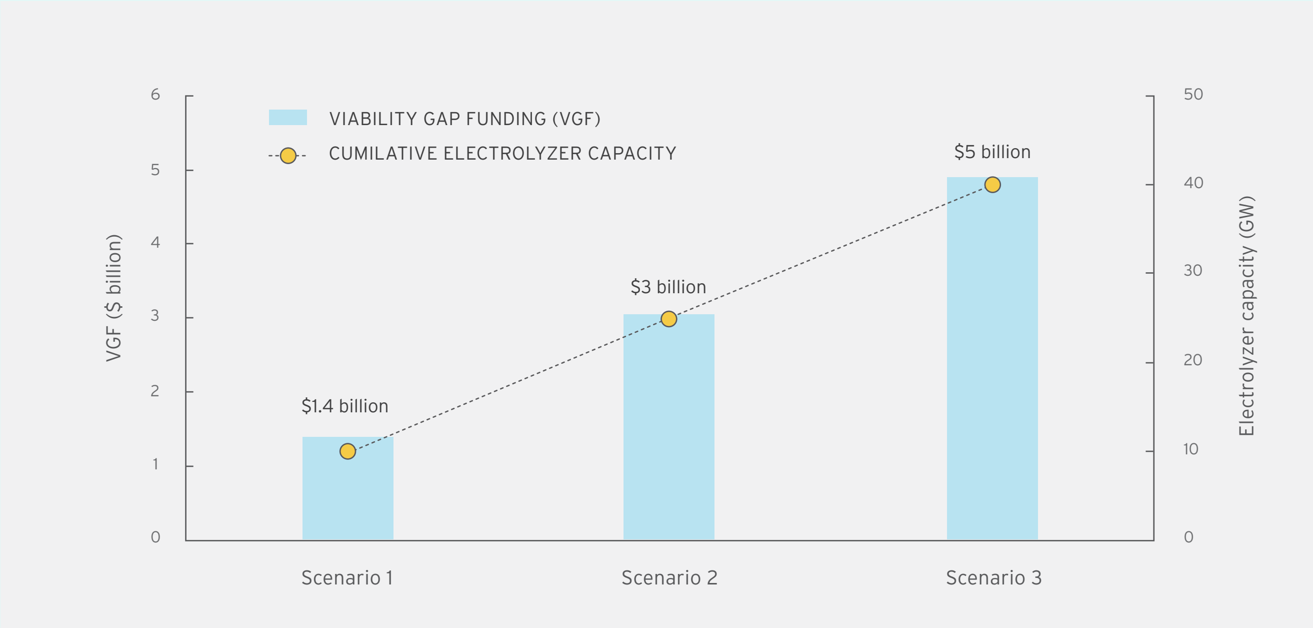


Exhibit 32 shows the VGF required for exports along with associated electrolyser capacity in the three scenarios. Overall, a range of $1.4 billion - $5 billion will be required in VGF for India to match its aspirational electrolyser targets for exports. It's also interesting to look at why and how VGF is different for each scenario. In scenario 1, where price declines for green hydrogen are happening at the fastest rate, the VGF will only be required from 2024 to 2026. This is mainly because from 2027, green hydrogen prices will be less than the target grey hydrogen price, negating the need for VGF. Moreover, the electrolyser scale till 2026 is around 10 GW of cumulative capacity. In scenario 2, the VGF requirement runs for four years, from 2024 to 2027. In this scenario, the cumulative VGF requirement is $ 3 billion, which is twice the requirement in scenario 1. This is because of two reasons – 1) the VGF is for four years instead of three years, because the price parity is reached from 2028, instead of 2027 as in the first scenario and 2) cumulative GW capacity is also higher because of added capacity in the year 2027. Similarly, VGF is the highest in scenario three because price parity of green hydrogen happens in 2029, thereby necessitating the requirement of $5 billion across five years (2024 – 2028).

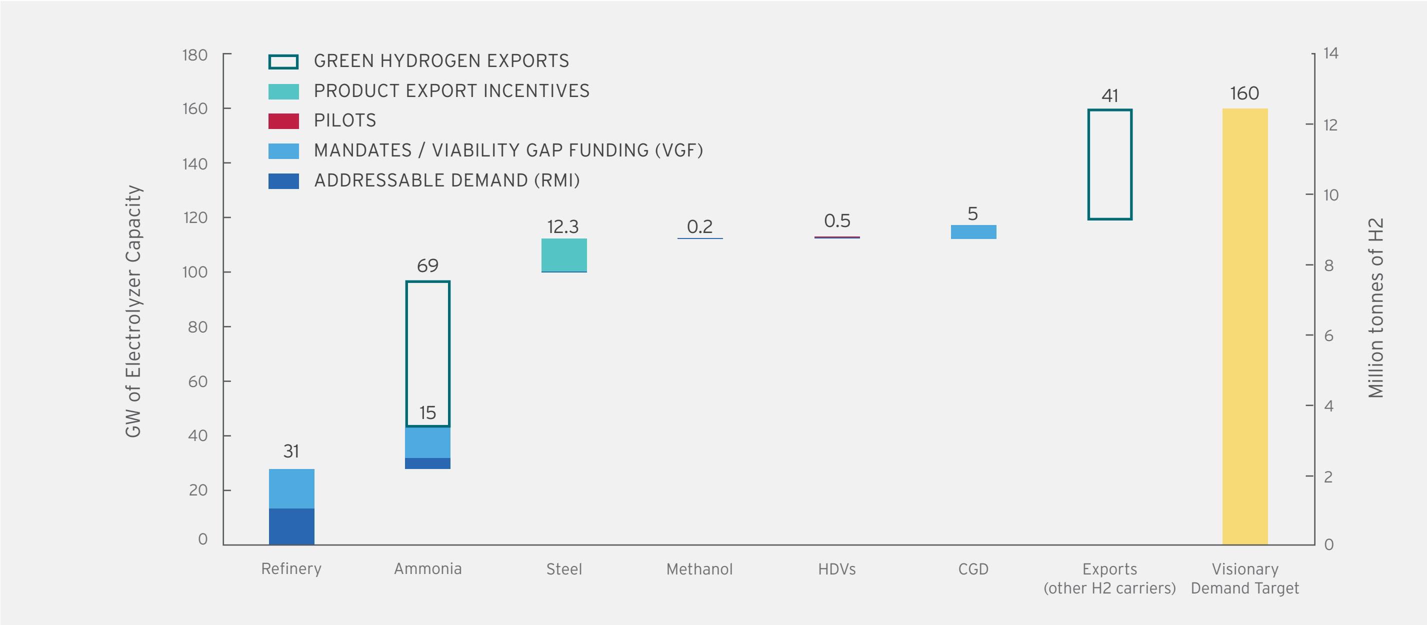
Source: RMI Analysis

Exhibit 33 Resulting cumulative electrolysis capacity targets

	Market	Targets for cumulative electrolysis capacity by 2030
Green Hydrogen Demand Targets	Addressable demand (RMI)	20 GW
	Initiatives-based Demand	45 GW
	Exports aspiration	95 GW
	Total	160 GW electrolysis

Source: NITI Aayog

Exhibit 34 Visionary 2030 electrolysis target for green hydrogen production



Source: NITI Aayog

4. Set-up visionary electrolyser manufacturing capacity target of 25 GW for 2030 coupled with supportive manufacturing and R&D investments

Given how important electrolyser cost is to the cost-reduction pathway for green hydrogen and the significant manufacturing opportunity it represents, the roadmap should identify a timeline and scale of maunfacturing support for electrolyser. India should envisage a production capacity accounting not only for Indian demand, but also for burgeoning global demand. Radically improving the speed of regulatory clearances coupled with preferential treatment in public tenders will help catalyse local manufacturing.

The report predicts a significant increase in electrolyser manufacturing in India in the next decade. India should look at a minimum target of 25 GW by 2030. The manufacturing of electrolysers to support the Indian green hydrogen industry could signal the advent of a multibillion-dollar sunrise opportunity with significant export potential. In addition to electrolysers, manufacturing of necessary value chain components such as pipes, cylinder storage, compressors, heat exchangers, nozzles, hoses etc should be encouraged using adequate local value creation initiatives.

India should invest $1 billion in R&D by 2030 to catalyse the development of commercial green hydrogen technologies across the value chain. Industry and academia should be ecouraged to particiapte together as teams in well capaitalised grand challenges with specific aspirational targets. R&D in alternative clean hydrogen production processes like bio-hydrogen technologies should also be encouraged.

5. Initiate green hydrogen standards and a labelling programme

While the definition of Green Hydrogen has been established in the policy, it is important to undertake immediate actions on standard development and harmonisation:

- Though standards are already available for grey hydrogen, they are designed for limited industrial use. It is important to construct new hydrogen standards keeping in mind the widespread use of hydrogen across sectors.
- Standards for new products such as electrolysers, fuel cells, and other new products are required.
- A digital (AI/ML equipped) labelling and tracing mechanism certification of origin should also be initiated for ascertaining the green credentials of all supply route of hydrogen including electrolytic, fossil fuel based and bio based hydrogen.
- Government-to-government mechanisms must be utilized towards initiating global regulations and standard harmonization.

- Public entities such as BIS (Bureau of Indian Standards) and PESO (The Petroleum and Explosives Safety Organization) are expected to take a leading role in this process.

6. Promotion of exports of green hydrogen-embedded products and green hydrogen through an international alliance

Exports of green hydrogen-embedded products in the near term and of green hydrogen itself in the medium to long term could also serve as important levers for market creation and participation in the emerging global green hydrogen market. The government must explore forming government-to-government partnerships with target geographies such as Japan, Korea, Germany etc and integration of hydrogen into existing energy and industrial partnerships globally. This should include developing collective frameworks and labelling and standards around green hydrogen and hydrogen-embedded products like green steel and green ammonia. The government should also explore near-term incentives around green ammonia and green steel production through public incentives to bridge the initial viability gap.

Exhibit 35 Policy driven demand targets of major import focused countries

Region	2030	2050
Japan	3 MMTPA	20 MMTPA
South Korea	3.9 MMTPA	27 MMTPA
Germany	2.7 - 3.3 MMTPA	

7. Investment facilitation

The government has a large role in providing financial certainty to early adopters of energy transition technologies. In the near term a credit worthy offtaker like SECI can be nominated to aggregate demand in the initial period. In the long run, a smooth and market-oriented green hydrogen industry should be developed. Efforts should be made to ensure availability of long tenor and low-interest finance for viable green hydrogen projects. Developing a functioning carbon market can also accelerate decarbonization of hard-to-abate sectors, thereby making green hydrogen projects financially more viable in the process. This will help create a more predictable cash-flow for early adopters without loss to the Indian exchequer, while making them more competitive with existing carbon-intensive processes.

It is estimated that more than $250 billion (INR 18 lakh crore) investment is required just to meet the 160 GW electrolysers target (for financing the electrolysers and associated renewable capacity).[70] It is critical for India to take a leading role in accessing low-cost climate finance through either multilateral institutions or by capitalising on bilateral agreements with developed nations to access part of the $100 billion/year commitments made during COP16.

8. Encourage state-level action and policy making related to Green Hydrogen

To ensure a widespread adoption of new technologies, national and state-level policy decision-making need to go hand in hand. It is evident from policy efforts on electric vehicle (EV) adoption in India, where various states have launched their own policies to complement national-level policies, that dedicated action is important at the state-level. Similarly, all states should be encouraged to launch their own state-level green hydrogen policies. Since each state is unique, the policies can be targeted based on their needs and strengths, where some states could focus on low-cost green hydrogen production either through electrolytic or bio-based routes, while others could focus on demand clusters, etc.

9. Encourage capacity building and skill development

Building a robust hydrogen economy is going to be new to India. This will necessitate appropriate and rapid skills development across the ecosystem including government, industry, and academia. While technology knowhow is essential, focus must go beyond to include business models, policies, and geopolitics. A scalable skills programme will have to be designed, developed, and deployed rapidly.

10. Construct an inter-ministerial governance structure

Considering the multi-sectoral impact of the hydrogen economy, governance of the transition efforts will be critical. An interdisciplinary Project Management Unit (PMU) with globally trained experts must be created which can dedicate fulltime resources to effectively implement the mission. The PMU must be nimble enough to adapt to global trends in this fast-evolving sector. At the policy level, an inter-ministerial mechanism should be instituted to coordinate across the various line ministries' and departmental efforts required to achieve the target of the mission. Each co-chair of the inter-ministerial mechanism would have a specific target to achieve.

Conclusion

Conclusion

Hydrogen can play a critical role in India's energy transition by enhancing its industrial competitiveness in an increasingly decarbonizing world, boosting economic development, reducing CO_2 emissions, and improving public health and quality of life. Major countries around the world are placing big bets and investing in hydrogen-based technologies, and India can play a leadership role at the global level in moving forward the hydrogen economy.

The biggest value proposition of hydrogen is in decarbonizing the hard-to-abate sectors. Historically, these sectors have been difficult to address because of a lack of technically and economically feasible technologies. Hydrogen can address many of these challenges and play a complementary role to other efficiency measures to effectively decarbonize these sectors.

Decreasing costs and an increase in renewable electricity, along with high-scale manufacturing and technology improvements in electrolysers will bring the cost of green hydrogen down in the near future, making it cost-competitive with existing technologies and fuel options. With increased pressure on industries such as steel, refining, and ammonia to reduce their carbon footprint and de-risk their investment, hydrogen's importance and scale are bound to increase.

Apart from fulfilling national goals around reducing emissions and enhancing domestic manufacturing, hydrogen paves a way for India to become a global powerhouse of zero-carbon embedded export products. Products such as green steel and green ammonia present an early mover opportunity for India, given India's capability and resources to produce them at a cheaper rate than peer nations such as China and Australia.

Significant challenges need to be addressed to enable this hydrogen transition. Costs of production are currently higher, making all green hydrogen-based products more expensive than fossil fuel-based alternatives. Transporting and storing hydrogen are costly, and significant build-out of infrastructure is required to bring down the costs of delivered hydrogen. Regulations and standards are still not clear, and financing remains a big challenge.

Key actions are required by policymakers, industry players, and financial institutions to enable a hydrogen economy in India. Significant R&D funding geared towards hydrogen production and applications can help in technology improvements and reduce costs. A public-private partnership using these resources to conduct high quality research, develop pilot projects, test feasibility, and finally scale deployment can be a first key step towards widespread adoption of hydrogen.

Policy push is needed both on the demand and supply side. Demand incentives to ease the barriers of high cost can enable initial market creation and can be phased out as the market matures. Simultaneously, there must be a push on the supply side, combined with infrastructure, to provide green hydrogen at scale. This can be achieved with a combination of production-linked incentives for electrolysers and fuel cells, and requirements for the industry and private players to deploy these technologies.

While initial deployment can happen in certain end uses that use hydrogen as a feedstock such as ammonia, methanol, or refining, it's important to expand the applications into other sectors to achieve bigger scales. Standards and regulations around hydrogen production and use should be revisited, and implementation of new regulations and standards should be prioritized to enable a quick transition to a hydrogen economy.

Financing hydrogen production and applications is also a key component of this transition. Risk mitigation measures for industry players is crucial. This can be done by providing concessional funding, educating and building capacity for industry and public and private institutions to enhance multi-stakeholder collaboration, and shared learning on technology readiness and demonstration projects. These measures along with special funding for domestic pilot projects can increase industry and lender's confidence and help ease this transition.

India has a unique opportunity to become a global leader in the hydrogen energy ecosystem. With proper policy support, industry action, market generation and acceptance, and increased investor interest, India can position itself as a low-cost, zero-carbon manufacturing hub, at the same time fulfilling its goal of economic development, job creation, and improved public health.

Appendices

Appendix A: Global Examples of Hydrogen Strategies and Roadmap

European Union[71]

European Union			
Current Hydrogen Demand	Not Available	**Focussed Hydrogen Colour/ Source**	Low Carbon - Blue / Green
Policy Target Demand	6GW capacity by 2024; 40 GW by 2030 10 MMTPA green H2 by 2030		
Capital Allocated (US$)	609 billion	**Export/ Import Focus**	NA
Demand Focus (Industry)	1. Chemical feedstock 2. Refining	**Strategy Features** 1. Market development timeline 2. Direct investments 3. Other economic and financial mechanisms 4. Legislative and regulatory measures	
Demand Focus (Transport)	1. Medium and heavy duty 2. Buses 3. Rail		
Demand Focus (Others)	NA		

Germany[72]

Germany			
Current Hydrogen Demand	1.65 MMTPA	**Focussed Hydrogen Colour/ Source**	Carbon free - Blue / Green
Policy Target Demand	2.7 - 3.3 MMTPA by 2030		
Capital Allocated (US$)	15-25 billion	**Export/ Import Focus**	Import
Demand Focus (Industry)	1. Iron and Steel 2.Chemical feedstock 3. Refining	**Strategy Features** 1. Market development timeline 2. Direct investments 3. Other economic and financial mechanisms 4. Legislative and regulatory measures 5. Standardisation strategy and priorities 6. Research and development initiatives 7. International strategy	
Demand Focus (Transport)	1. Medium and heavy duty 2. Buses 3. Rail		
Demand Focus (Others)	NA		

Japan[73]

Japan			
Current Hydrogen Demand	2 MMTPA	**Focussed Hydrogen Colour/ Source**	Blue
Policy Target Demand	3 MMTPA by 2030 and 20 MMTPA by 2050 (5-30 by 2050)		
Capital Allocated (US$)	664 million	**Export/ Import Focus**	Import
Demand Focus (Industry)	NA	**Strategy Features**	1. Hydrogen price target 2. Market development timeline 3. Direct investments 4. Standardisation strategy and priorities 5. Research and development initiatives 6. International strategy
Demand Focus (Transport)	1. Passenger Vehicle		
Demand Focus (Others)	1. Heating 2. Power Generation		

South Korea[74]

South Kores			
Current Hydrogen Demand	220 KTPA	**Focussed Hydrogen Colour/ Source**	Grey / Blue / Green
Policy Target Demand	3.9 MMTPA by 2030 and 27 MMTPA by 2050		
Capital Allocated (US$)	653 million (annual targeted support for hydrogen project)	**Export/ Import Focus**	Import
Demand Focus (Industry)	NA	**Strategy Features**	1. Hydrogen price target 2. Market development timeline 3. Direct investments 4. Other economic and financial mechanisms 5. Standardisation strategy and priorities 6. Research and development initiatives 7. International strategy
Demand Focus (Transport)	1. Passenger Vehicle 2. Medium and Heavy Duty 3. Buses		
Demand Focus (Others)	1. Power Generation		

United States[75]

United States			
Current Hydrogen Demand	10 MMTPA	**Focussed Hydrogen Colour/ Source**	Low Carbon - Blue / Green /Others
Policy Target Demand	Not available		
Capital Allocated (US$)	> 15 billion	**Export/ Import Focus**	NA
Demand Focus (Industry)	1. Refining 2. Others	**Strategy Features**	1. Hydrogen price target 2. Research and development initiatives 3. Other economic and financial mechanisms 4. Direct investments
Demand Focus (Transport)	1. Passenger Vehicle 2. Medium and Heavy Duty 3. Buses 4. Aviation		
Demand Focus (Others)	1. Heating 2. Power Generation		

Australia[76]

Australia			
Current Hydrogen Demand	650 KTPA	**Focussed Hydrogen Colour/ Source**	Clean - Blue / Green
Policy Target Demand	Not available		
Capital Allocated (US$)	487 million	**Export/ Import Focus**	Export
Demand Focus (Industry)	1. Chemical Feedstock	**Strategy Features** 1. Hydrogen price target 2. Market development timeline 3. Direct investments 4. Other economic and financial mechanisms 5. Legislative and regulatory measures 6. Standardisation strategy and priorities 7. Research and development initiatives 8. International strategy	
Demand Focus (Transport)	1. Medium and Heavy Duty 2. Buses		
Demand Focus (Others)	1. Heating		

Chile[77]

Australia			
Current Hydrogen Demand	58.5 KTPA	**Focussed Hydrogen Colour/ Source**	Green
Policy Target Demand	5 GW/a(2025) 25 GW/a(2025)		
Capital Allocated (US$)	50 million	**Export/ Import Focus**	Export
Demand Focus (Industry)	1. Chemical Feedstock 2. Refining	**Strategy Features** 1. Hydrogen price target 2. Market development timeline 3. Legislative and regulatory measures	
Demand Focus (Transport)	1. Medium and Heavy Duty 2. Buses		
Demand Focus (Others)	1. Heating		

Appendix B : Sectoral Demand Assessment

Refinery

Opportunity

India's refinery sector is the fourth largest in the world in terms of capacity, processing almost 250 million tonnes of crude oil yearly.[78] Currently the refinery sector accounts for almost 3 million tonnes of hydrogen demand, representing 46% of the total hydrogen demand in the country.[79] The majority of this hydrogen is generated from on-site SMR plants, which amount to 27 million tonnes of CO_2 emissions currently, which are expected to rise to 47 million tonnes by 2050.[80]

However, the refinery sector can witness a dramatic decrease in CO_2 emissions through a higher uptake of green hydrogen. Green hydrogen uptake in the refinery sector is estimated to start around 2024 at a 1% share, which can reach 24% by 2030 and 100% by 2050.[81] This will enable close to zero CO_2 emissions from hydrogen production by 2050 and cumulative CO_2 emissions savings of 820 million tonnes between now and 2050.[82]

Cost Implications

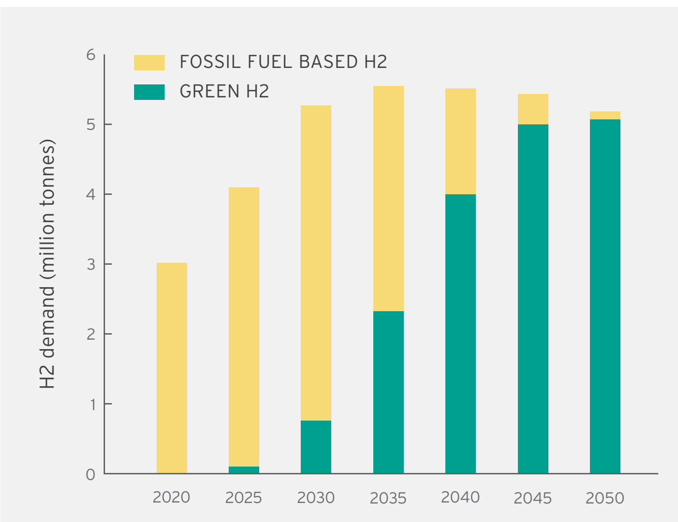
Currently, use of green hydrogen for desulphurization of different kinds of fuels is more expensive than using hydrogen produced from SMR. However, refining is unique in that the share of hydrogen cost per tonne of crude in refinery operating is much less (around 2%- 4%).[83] Hence, the cost premium associated with green hydrogen in the final refined product is not as significant as in some other sectors like ammonia or methanol, where the share of hydrogen cost as a percentage of total product cost can be up to 80%–90%.[84]

Refinery operating cost per tonne of crude where hydrogen is supplied by renewables is estimated to be on parity with hydrogen supplied through SMR by 2027.[85] However, with the premium in the years before parity is reached being so low (max 2% premium), this sector could be a potential early market for green hydrogen deployment and use.

Hydrogen Demand Outlook

Hydrogen demand from the refinery sector will increase until 2035. However, as petroleum demand starts to decrease beyond 2035 on the account of higher electrification of passenger and freight transport, hydrogen demand will also start to decrease. In addition to electrification, other efficiency improvements such as modal shift, logistics efficiency, non-motorized transport, and ride hailing can further reduce petroleum and associated hydrogen demand from refineries. Almost 100% of hydrogen demand from refineries in 2050 can be supplied via renewable electrolysis.

Exhibit 36 Hydrogen demand from refinery



Source: RMI analysis

Ammonia

Opportunity

With a growing need for fertilizer in the future, ammonia demand is set to double in the next three decades, increasing from 17 million tonnes in 2020 to 35 million tonnes by 2050.[86] This directly translates to CO_2 emissions of 40 million tonnes in 2020, increasing to 62 million tonnes by 2050.[87]

The path to decarbonization of ammonia production involves replacing fossil fuel-based hydrogen with the hydrogen produced from renewables. With a falling LCOE, the cost of green hydrogen will decline, making green ammonia competitive with conventional sources. However, existing urea plant locations and favourable renewable production in terms of lower costs are not aligned.[88] This means the location of green ammonia production in the future might shift to favourable renewable-energy-rich states that will have considerations around transport and storage. RTC renewable arrangement must be explored to mitigate some of these considerations.

In the efficient scenario with a higher uptake of green hydrogen, India can abate around 550 million tonnes of CO_2 emissions cumulatively between 2020 and 2050.[89] Switching to green hydrogen-based ammonia also alleviates India's energy security concerns by reducing natural gas imports.

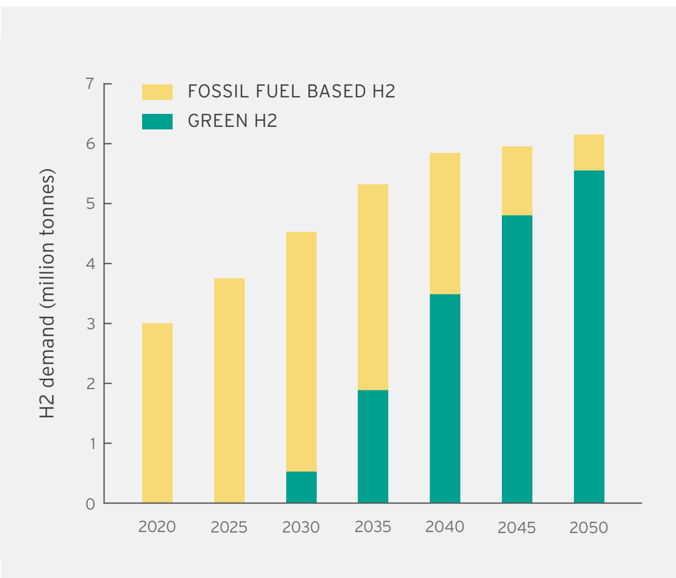
Cost Implications

Currently, green ammonia costs are higher than ammonia produced through the SMR process, even at the higher end of natural gas prices of $12/mmBtu. This is mainly due to high capital costs and lower utilization of electrolysers as well as higher electricity prices. With improvements in technology and economies of scale, electrolyser costs will decrease dramatically and renewable generation will get cheaper and more abundant. This will make green hydrogen-based ammonia fairly competitive by 2030 even at the lower end of a natural gas price of $8/mmBtu, where green ammonia will cost around $393/t$NH_3$ and grey ammonia will cost $415/t$NH_3$.[90] Transport and storage costs need to be considered if ammonia is to be used away from the point of production. Near-term projects that can use on-site green hydrogen for ammonia production should be prioritized in this decade, with a potential to move towards deployment post 2030.

Hydrogen Demand Outlook

Ammonia production contributes to 48% of the current hydrogen demand. By 2050, this demand is set to double, representing the third largest source (21%) of final hydrogen demand after steel and heavy-duty trucking. The majority of this demand will be used for ammonia production for the fertilizer industry. However, if ammonia as fuel for the shipping industry becomes viable, this demand will increase significantly. The share of the hydrogen demand met with renewables will start picking up around 2027 when green hydrogen-based ammonia reaches cost parity with natural gas-based ammonia, and will increase beyond that to represent an 88% share by 2050.

Exhibit 37 Hydrogen demand from ammonia for fertilizer



Source: RMI analysis

Methanol

Opportunity

With India's policy push towards using coal gasification for hydrogen production for methanol, the majority of hydrogen will be produced with coal by 2050 in a business-as-usual scenario. As a result, even though emissions from methanol currently represent a very small amount, they are bound to rise sharply, registering the highest growth among all the industrial sectors for the next three decades.

However, green hydrogen can play a key role in reducing emissions from this sector. With high uptake of green hydrogen-based methanol production, India can abate 150 million tonnes of CO_2 emissions cumulatively between 2020 and 2050.[91] The majority of these reductions will be achieved post 2040, with an increasing share of green hydrogen-based production.

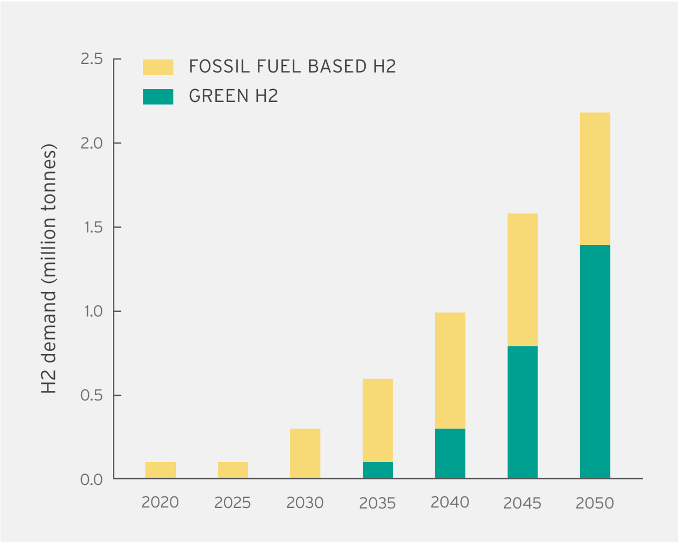
Cost Implications

India currently imports 80% of its methanol demand, mainly because it is much cheaper than producing methanol with imported natural gas.[92] However, coal-based methanol production can be much more cost-effective, given the cheap and abundant coal reserves in India. That is one of the main reasons why India is betting on coal-based methanol production—to drive the percentage share of domestically produced methanol that is cheaper. Currently, green hydrogen-based methanol costs are much higher than the natural gas or coal alternative. With falling costs of electrolysers and renewable electricity, by 2030, green hydrogen-based methanol will become cost-competitive with fossil fuel-based alternatives. Costs in 2030 for green hydrogen-based production could come down to $461/tonne of methanol,[93] compared with $470/tonne for the coal-based alternative.[94]

Hydrogen Demand Outlook

Hydrogen demand for methanol will increase at a 12% CAGR between 2020 and 2050. Currently natural gas is used for the majority that demand. However with the inability to compete with cheap imports and India's push towards coal-based methanol production, natural gas's share of hydrogen demand will decrease, while coal's share will increase. At the same time, green hydrogen's share will also start increasing once cost parity is achieved. By 2050, 60% of the hydrogen demand for methanol will be met via green hydrogen and the rest via fossil fuels.

Exhibit 38 Hydrogen demand from methanol



Source: RMI analysis

Iron and Steel

Opportunity

India is currently the second largest producer and consumer of steel, after China.[95] An abundance of iron ore reserves and low-cost labour position India as a very favourable market and production hub of steel. Steel is majorly used in building various types of infrastructure, vehicles, appliances, machinery, and equipment.
With India witnessing rapid growth in urbanization, infrastructure buildout, economic growth, and demand for cars and trucks in the coming decades, steel demand is expected to increase fivefold between 2020 and 2050 (93 Mt in 2020 to 528 Mt in 2050).[96]

India uses all three processes (BF-BOF—44%, DRI-EAF/IF—34%, and EAF/IF with scrap steel—22%[97]) to make steel. Currently, emissions from steel production account for a significant share—11% of total CO_2 emissions and 45% of industrial CO_2 emissions in India.[98] With increasing demand for steel and use of carbon-intensive processes and rising exports, emissions from the steel sector in India will rise from 269 million tonnes in 2020 to 951 million tonnes by 2050.[99]

It is imperative to reduce emissions from the steel sector in India, given the increasing demand and the associated increasing emissions. Hydrogen can play a key role. Instead of the coal or natural gas-based DRI process, hydrogen produced via renewables can be used as a reductant to convert iron ore pellets to pig iron. This process only leads to water as a by-product and creates no emissions. It's important that the EAF process is supplied with renewable electricity, which will lead to further emissions reductions.

Using green steel can help India abate 1.4 giga tonnes of cumulative CO_2 emissions between 2020 and 2050.[100] Green steel will account for 20% of total steel demand and can substitute 98% of natural gas-based DRI steel demand by 2050.[101] Steel has other potential pathways for emissions reductions complementary to the green hydrogen pathway, these are:[102] 1) improving the energy efficiency of existing furnaces and equipment, and 2) switching to a smelting reduction process combined with CCS, which eliminates the need for a blast furnace.

India can become a very strong market for domestic manufacturing and exports. Green steel exports will increase on account of more infrastructure buildout and the growth of automotive markets, allowing India to position itself as a global leader in green steel manufacturing.

Cost Implications

Currently, the conventional process of making steel and the one most predominant in India, BF-BOF and coal-based DRI process respectively, are much cheaper than the hydrogen-based alternative. This is mainly because of the low cost of fuel for the conventional options. Both BF-BOF and the coal based DRI process use coking coal and non-coking coal respectively, which is much cheaper than natural gas or green hydrogen.

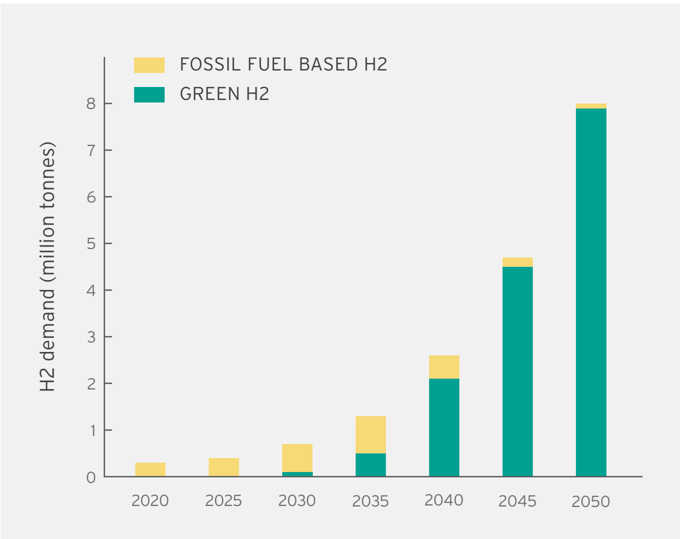
However, with the falling costs of renewables, hydrogen-based steel can reach cost parity with the natural gas-based DRI process by 2027, with costs of green steel around $460/tonne of steel.[103] By 2030, steel produced via the green hydrogen-based DRI process will be the most cost-competitive route, with costs around $411/tonne of steel, compared with $443/tonne for BF-BOF and $459/tonne for DRI-EAF.[104]

Hydrogen Demand Outlook

Steel production via natural gas-based DRI-EAF contributes to 0.3 million tonnes of hydrogen demand currently. That is bound to rise to 8 million tonnes by 2050.

Green hydrogen demand from steel production will start taking shape around 2030 and increase slowly until 2035 when pilot projects are deployed. The demand is expected to rise sharply beyond that when there is full-scale deployment. Steel will contribute to 27% of final hydrogen demand in 2050, the highest demand among all the potential sectors.

Exhibit 39 Hydrogen demand from steel in India



Source: RMI analysis

Long-Haul, Heavy-Duty Road Freight

Opportunity

Freight transport is critical to India's growing economy, providing citizens with goods, helping grow businesses, and improving quality of life. Road freight is an essential pillar of the overall freight transport sector, contributing to 71% of freight movement and 95% of freight-related CO_2 emissions.[105] Emissions from the road freight sector will increase fourfold between now and 2050 (188 Mt CO_2 in 2020 to 797 Mt CO_2 in 2050) in a business-as-usual scenario.[106] Moreover, the cost of logistics as a share of GDP is 14% in India, much higher than in the European Union or the United States.[107]

Although heavy-duty vehicles (HDVs) represent only 20% of total freight vehicles on the road, they are the biggest contributor towards India's road freight movement, hauling over 74% of road freight.[108] They are also the biggest emitter, producing 60% of road-freight CO_2 emissions, which is expected to increase to 66% by 2050.[109]

Electrification of HDVs can help reduce shipping and logistics costs, improve air quality, and reduce carbon emissions. Between 2020 and 2050, India can abate 2 giga tonnes of CO_2 emissions (0.7 giga tonnes from fuel cell electric trucks and 1.3 giga tonnes from battery electric trucks) and save $208 billion on oil import bills by transitioning to electric.

Two technology options exist to electrify HDVs—battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). Hydrogen-powered FCEVs offer key advantages and make a strong candidate to play a part in road freight HDV decarbonization, along with BEVs. In the near term, retrofitting existing diesel trucks with fuel cell applications could also be pursued.

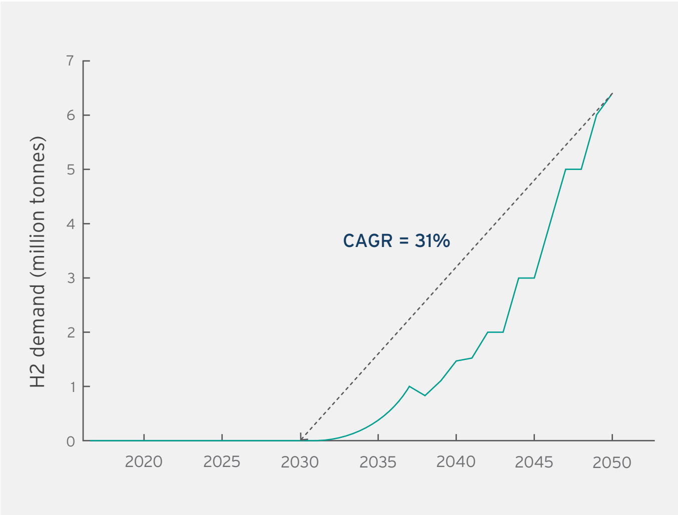
Cost Implications

Currently, both BEVs and FCEVs are more expensive than diesel trucks on a total-cost-of-ownership basis. The major drivers behind that are the higher capital cost of EVs, higher interest rates charged, and costs associated with battery packs and fuel cell stacks. However, declining battery and fuel cell prices due to production scale-up and technology improvements (between 2019 and 2030, battery and fuel cell prices are expected to fall by 64 percent and 61 percent respectively[110]), improved charging, and hydrogen refuelling station utilization, BEVs and FCEVs will be at cost parity with diesel trucks by 2027 and 2031 respectively.[111] A stronger policy push towards HDV electrification can bring the cost parity even sooner.

Hydrogen Demand Outlook

Currently, hydrogen demand for the transport sector is almost nonexistent, as no FCEVs exist on the market in India. However, in the efficient scenario, if HDV FCEVs sales penetration start to pick up around 2026, and reaches about 30% by 2050, the hydrogen and fuel cell system demand could increase, reaching 6.4 million tonnes and 16 GW, respectively, by 2050. In such a scenario, HDVs could amount to 22% of final hydrogen demand in India by 2050, and the cumulative market

Exhibit 40 Hydrogen demand from HDVs in the efficient scenario in India



Source: RMI analysis

size for fuel cells between 2020 and 2050 could be USD 40–54 billion (INR 3-4 lakh crore).[112] Such rapid growth signifies the opportunity for domestic manufacturing of FCEVs and fuel cell system components in India.

Power

Opportunity

The power sector in India is underdoing dramatic transition led by electrification, demand growth, and a large increase in renewable energy generation. High demand growth and renewable generation opens up the challenges and prospect of demand flexibility and VRE integration. Technical solutions like demand response, battery energy storage, and supply-side flexibility of thermal power plants are increasingly being touted as part of the suite of solutions.

Hydrogen advocates have proposed the concept of power-H2-power as another form to provide storage and flexibility to the grid, opening an end-use sector for hydrogen. Power-H2-power involves generating hydrogen in times of excess generation, storing it either physically or chemically (e.g., ammonia), and then at time of need, discharging it either through gas turbines (OCGT or CCGT) or fuel cells.

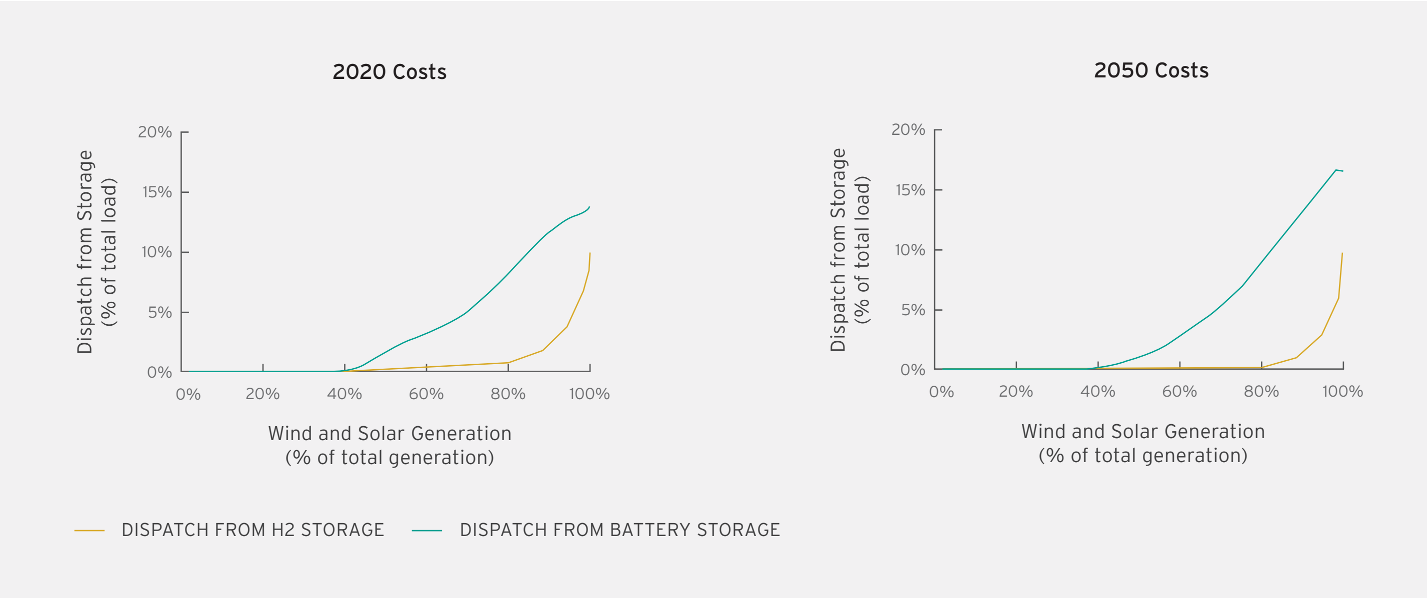
In contrast to technologies such as Li-ion batteries, the per unit costs of power-H2-power grow more slowly with a decreasing utilization factor. It is this relationship between per unit costs and utilization factor that makes power-H2-power among the most promising options for long-term storage (alongside other potential long-term chemical storage vectors, like ammonia).[113] Beyond providing flexibility, hydrogen is also seen as a potential fuel source for peaking power generation through existing gas turbines, and for power generation and back-up applications for distributed assets like cell-phone towers and replacement of diesel gensets.

Cost Implications and Demand Considerations

Hydrogen's usefulness for power, however, has its share of general costs. First, the conversion losses and round-trip efficiency of generation storage and consumption of hydrogen in a power-H2-power process is substantial enough to warrant a rethink of the usefulness for hydrogen especially when compared with other storage technologies. Round-trip conversion efficiency for current technologies may be in the order of 33%, increasing potentially to slightly less than 50% with technological improvements. Thus, converting electricity into hydrogen, or a similar chemical energy carrier like ammonia, is an inefficient process with substantial energy losses across the conversion chain.[114] Secondly, without cost reduction expectations being met, capital costs for both electrolysers and fuel cells remains substantially high.

In the Indian power sector, the opportunity of hydrogen is further limited. Considering only the use case for peaking power, it is only economical at margin when prices are where they are expected to be in 2050. By that time, there are a fair degree of technical and non-technical unknowns. Carbon pricing can theoretically alter the economics of hydrogen. However, even then, the challenge of supply, transport, and storage will possibly increase the cost of using hydrogen purely for meeting peaking power needs in India.
When it comes to the end use of hydrogen for power-H2-power applications, especially for seasonal storage, the unique load structure and renewable profile hinders the potential for hydrogen. Unlike countries in higher

Exhibit 41 Economics of battery energy storage and power-H2-power



Source: TERI[115]

latitudes with large winter heating loads, India's level of seasonal variation is limited, except in certain geographies in north India. The unknown here is how that might change with higher cooling penetration. But even then, India's most cost-effective renewable source is solar, which requires mostly intraday and non inter-seasonal balancing. Within this context, TERI's analysis shows that power-H2-power is only required at very high penetrations of VRE (above 80%). Battery storage is dispatched long before hydrogen gets a chance to be a part of the power balancing mix.

A key conclusion is that hydrogen and other seasonal storage options are only going to be necessary to squeeze out the last 10%–20% of dispatchable fossil generation during the transition to a very high VRE system. IEA's generation outlook estimates VRE to account for at most 69% by 2040 in its sustainable development scenario. Therefore, the prospect for power-H2-power in India is going to be visible only at the tail end of our scenario period and that too only marginal with limited impact.

Appendix C: Definitions

i. Hydrogen causes corrosion and brittleness when it comes into contact with some metals, requiring new coatings and other protective measures.

ii. Cryo-compressed hydrogen storage refers to the storage of hydrogen at cryogenic temperatures in a vessel that can be pressurized (nominally to 250-350 atm), in contrast to current cryogenic vessels that store liquid hydrogen at near-ambient pressures (Argonne National Laboratory, 2014).

iii. All monetary units in the report are listed in US dollars.

iv. The Hydrogen Council's Net-Zero analysis puts potential hydrogen demand 690 million tonnes by 2050, with total required investment to be around $7-8 trillion.

v. Alternate route of hydrogen production like bio-hydrogen are not addressed in the report. While limited in production potential, bio-hydrogen from agricultural waste could have locally synergistic advantage for distributed generation where resources and end consumers are readily available. Potential for bio-hydrogen should be further explored.

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