GREEN HYDROGEN
Path to Decarbonization

Ajay Shankar | Meenu Saini | Chitranjali Tiwari

THE ENERGY AND RESOURCES INSTITUTE
Creating Innovative Solutions for a Sustainable Future

POLICY BRIEF

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FROM THE DESK OF DIRECTOR GENERAL

For the past five decades, TERI has been at the forefront of India's development journey, providing transformative solutions through rigorous research, innovative technologies, and impactful advocacy. We have been instrumental in evolving understanding of the complex interplay between ecology and climate change and in driving sustainable development initiatives.

As India strides towards its vision of becoming a developed nation by 2047 while also committing to net-zero emissions by 2070, TERI remains committed to contributing to the analysis of the means of achieving these goals. We have established a dedicated Task Force on India's journey to net zero and just transitions.

A critical component of this transition is addressing the challenges of the hard-to-abate sectors that contribute significantly to India's emissions. For these fossil fuel-dependent industries, the options are twofold: electrifying processes with green electricity or, where electrification is not feasible, replacing fossil fuels with hydrogen. Green hydrogen, often referred to as the "energy carrier of the future," offers numerous advantages. It can be produced from carbon free renewable and nuclear energy. By adopting green hydrogen as a clean energy solution, India has the potential not only to reduce its carbon footprint but also to create new economic opportunities, generate employment, and strengthen energy security.

India's commitment to a clean energy transition is widely acknowledged, with the National Green Hydrogen Mission serving as a cornerstone of this endeavor. Recognizing hydrogen's transformative potential, many states are championing green hydrogen initiatives to support decarbonization across critical sectors.

This paper, "Green Hydrogen- Path to decarbonization", lays out policy measures to enable greater integration of green hydrogen into industry. There are specific recommendations for achieving success in hard to abate sectors at least costs. The policies it outlines target needs within specific sectors, ensuring India's pathway to net zero is both achievable and cost-effective.

To achieve this vision, it is essential to prioritize policies that support green hydrogen development across key sectors. This paper emphasizes that by acting decisively now, we can facilitate the transition of Indian industry towards carbon free green manufacturing.

TERI is committed to working closely with policymakers, industry leaders, and researchers to make this vision a reality. Let us join hands to build a sustainable, prosperous future for India—one powered by green hydrogen to take the hard to abate sectors to net zero.

Dr Vibha Dhawan
Director General, TERI

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ABBREVIATIONS

AE	Alkaline Electrolysis
AEM	Anion Exchange Membrane
BESS	Battery Energy Storage System
BF-BOF	Blast Furnace-Basic Oxygen Furnace
CAPEX	Capital Expenditure
CBAM	Carbon Boarder Adjustment Mechanism
CCUS	Carbon Capture and Storage
CO	Carbon Monoxide
CSP	Concentrated Solar Power,
DAP	Di-Ammonium Phosphate
DFI	Development Finance Institution
DR	Direct Reduction
DRI-EAF	Direct Reduced Iron-Electric Arc Furnace
EAF	Electric Arc Furnace
EIF	Electric Induction Furnace
EU	European Union
EV	Electric Vehicle
FCEV	Fuel-Cell Electric Vehicle
GST	Goods and Services Tax
IISc	Indian Institute of Science
IIT	Indian Institutes of Technology
IPCC	Intergovernmental Panel on Climate Change
MNRE	Ministry of New and Renewable Energy
MOE	Molten Oxide Electrolysis
NPCIL	Nuclear Power Corporation of India Limited
PEM	Proton Exchange Membrane
PLI	Production Linked Incentives
PSP	Pumped Storage Project
RCF	Rashtriya Chemicals and Fertilizers
SAFs	Sustainable Aviation Fuels
SECI	Solar Energy Corporate of India
SIGHT	Strategic Interventions for Green Hydrogen Transition
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cells
TRL	Technology Readiness Level

1.0 INTRODUCTION

The prognosis on climate change in the Intergovernmental Panel on Climate Change (IPCC) reports are getting bleaker. Global temperatures are already 1.1°C above pre-industrial levels. To avoid catastrophic consequences, limiting warming to 1.5°C is essential. This requires achieving net-zero CO_2 emissions by mid-century with decisive action in this decade. Many believe that limiting global warming to 1.5° C may no longer be an attainable goal and that keeping temperature increase to less than 2° C is also becoming difficult by the day. The lack of urgency in taking immediate action in the advanced industrial economies is disappointing and a cause of increasing concern.

At COP 26 in Glasgow in November 2021, Prime Minister Modi announced a substantial increase in India's climate ambition. The most important of these were:

- The immediate short-term goal of creating 500 GW of fossil fuel free capacity by 2030.
- Becoming net zero by 2070: the first commitment to a target year to become net zero.

These took our aspirations to a much higher level.

We, in TERI, have been analysing these in Discussion Papers. In our first paper titled "Roadmap to India's 2030 Decarbonization Target"[1] released on 27th July 2022, we looked at the challenges in achieving the ambitious 2030 targets and discussed feasible pathways for achieving these targets After in depth examination we came to the conclusion that though this would be very challenging, it was doable. Our fossil fuel free capacity has gone up from 41% in 2022 to 45% now. It is 201 GW. Solar capacity has gone up from 54 MW in March 2022 to 90 GW by September 2024.

Thereafter, we have looked at the 2070 net zero goal in our paper titled "India's Journey to Net Zero-A Conceptual Framework for Analysis "[2] released on 20th May 2024. We have pointed out that the sooner the emissions in a sector peak the lower would be the costs of reducing emissions to net zero. Hence new lumpy capital investment decisions need to factor in the ultimate costs of reaching net zero. The contours of the journey to net zero for electricity are becoming clear. Through electrification, carbon free road and rail transport can now be envisaged.

However, there are 'hard to abate' sectors where globally the picture is still hazy. Green hydrogen is seen as a promising solution for these hard to abate sectors. India has been an early mover in embarking on its Hydrogen Mission.

The Prime Minister announced on Independence Day in 2021 India's intention of creating the Hydrogen Economy. A comprehensive Green Hydrogen Policy has been announced. The National Hydrogen Mission is now under implementation. It is ambitious and well-funded. This has the potential of taking India to the global frontier in developing technical capacities for eliminating carbon emissions from a range of processes in the hard to abate sectors. This paper examines the critical role of hydrogen in the journey to net zero. It suggests the way forward for creating competitive capacities for each downstream hard to abate sector. This is critical for creating the ability to be able to get to net zero at the least cost.

This paper examines Green Hydrogen as the means to achieving net zero in hard to abate sectors and not as an end in itself. It also recognises that the finances with the government are limited. Accordingly, the paper explores ways of getting desired outcomes at the least cost; the goal being the creation of globally competitive green carbon free production capacities in downstream hard to abate sectors. A competitive industry structure is desirable as this would facilitate movement down the cost curve. A strategy for achieving this is delineated. The implementation of sector specific pilot projects is suggested along with the ways of doing so.

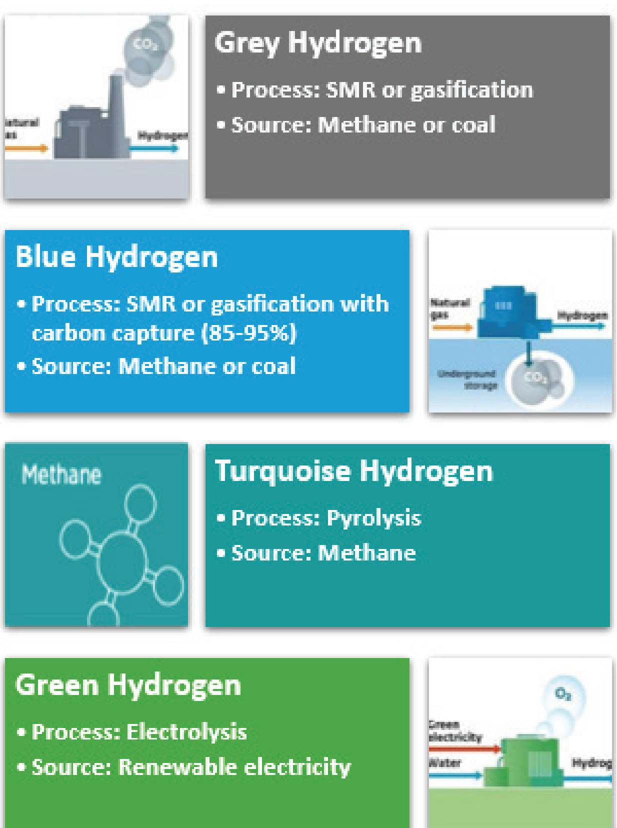
Success would position us as a major exporter of green zero carbon products. Global markets are already beginning to pivot in this direction, and we could try and get the early mover's advantage. It would also give us realistic assessments of the subsequent journeys to becoming net zero in each sector.

We hope that this paper would help in the policy discussion on getting to net zero in the hard to abate sectors at the least cost. Our costs could turn out to be the same, if not lower, than those of the advanced industrial economies. If we succeed, we may well find ourselves in a position of being able to achieve net zero earlier than 2070 and also be able to afford it.

2. Green Hydrogen

Green Hydrogen is being increasingly seen as a potential solution for decarbonization of the hard to abate sectors. The major hard to abate sectors are steel, fertilizer, cement, chemicals, heavy duty trucks, shipping and aviation. Hydrogen is produced by splitting the water molecule to get hydrogen through electrolysis. This hydrogen becomes green when carbon free electricity from renewables is used for production. Electricity generation from nuclear power plants does not entail carbon emissions and hence could also be used to produce hydrogen through electrolysis.

Biowaste and biomass can also be used to produce green hydrogen; biowaste being a renewable source of energy. India is one of the largest producers of bio waste. This has the potential of providing dispersed cost competitive production of substantial quantities of green hydrogen.



2.1. Hydrogen production processes

- **Hydrogen production through Water Electrolysis**:

Water electrolysis is the primary method for producing green hydrogen using renewable energy. Electricity is used to split water (H_2O) into its constituent elements, hydrogen (H_2) and oxygen (O_2). Electrolysis technologies, such as Alkaline Electrolysis (AE), Proton Exchange Membrane (PEM), Solid Oxide Electrolysis Cells (SOEC), and Anion Exchange Membrane (AEM), can be used to carry out this conversion. Each technology has its unique characteristics and is chosen based on factors like efficiency, scalability, cost, purity, operational flexibility, lifespan and application. These are presented in Table 01.

- **Hydrogen production through Biomass and Biowaste**

Biomass and biowaste can be converted into green hydrogen through biomass gasification or biogas reforming. At high-temperature biomass releases synthesis gas, or syngas, which includes hydrogen (H_2), carbon monoxide (CO), and other gases. The hydrogen present in syngas can be isolated and purified to produce green hydrogen. Biomass gasification proves particularly advantageous in regions abundant with organic materials, where the production of green hydrogen would also contribute to waste management. The current Technology Readiness Level (TRL) of biomass gasification for hydrogen production is at TRL 5-6 according to the IEA. However, there are also technologies at TRL level 8. The minimum feasible plant size for biohydrogen production is 250 kg per day, with a cost of production around USD 3 per kg of biohydrogen.[3] One such study, mentioned in Box 1, has been undertaken by IISC Bangalore.

- **Hydrogen Production Using Solar Thermal Energy**

Solar thermal processes harness concentrated solar radiation as the primary or exclusive source of high-temperature process heat. Direct solar water splitting denotes any method wherein solar energy is utilized directly to generate hydrogen from water, bypassing

Table 01: Electrolyser Technology comparison

Parameters	Alkaline	PEM	AEM	Solid Oxide
Electrolyte	Potassium hydroxide (KOH)	Perfluoroacidsulfonic (PFSA) membranes	Divinylbenzene (DVB) polymer support with KOH or $NaHCO_3$	Yttria-stabilized Zirconia (YSZ)
Operating temperature	70-90 °C	50-80 °C	40-60 °C	700-850 °C
Operating pressure	1-30 bar	< 70 bar	< 35 bar	1 bar
Current density (A/cm^2)	0.25-0.8	1 to 2	0.5-2	0.3-1
Electrical efficiency of system (kWh/kg H_2)	50–78	50–83	57–69	45–55
Purity	99.5%-99.9998%	99.9%-99.9999%	99.40%	N/A
Lifetime of stack (thousand hrs.)	<120	<100	>5	<23
Technology readiness level (TRL)	9	9	4–5	5–6
Maturity level	Commercialized	Commercialized	R&D transitioning to commercialization	R&D transitioning to commercialization
Advantages	Cost effectiveness, scalability, efficiency	High H2 quality, Compact, Quicker response	Aiming for lower cost by using non-noble materials	Better suited for continuous use, potential waste heat utilization
Disadvantages	Diaphragms in AE, while enabling gas intermixing, reduce operability at high pressures; thicker diaphragms counteract this, with increased resistance and decreased efficiency.	Requires expensive noble metals for durability	Lower conductivity and chemical and mechanical stability issues due to slower kinetics leads to shortened operational lifetimes	Stack degradation at high temperatures, durability, sealing problems

Source: TERI analysis (Based on IRENA, WRI, Reuter and TERI study)

the intermediate electrolysis stage.[4] One such method is known as photoelectrochemical water spitting. This method employs semiconducting electrodes within a photoelectrochemical cell to convert light energy into hydrogen's chemical energy. It utilizes semiconductor materials immersed in a water-based electrolyte, where sunlight activates the water-splitting process. The integrated photoelectrochemical reactor focuses incident light, enabling thermally optimized photo-driven water splitting or photo electrolysis. Water is pumped to the

Box 1: Indigenous technology: A 250 Kg/day Biohydrogen pilot plant IISC Bangalore

The process consists of two steps. In the first step, biomass is converted into syngas – a hydrogen-rich fuel gas mixture – in a novel reactor using oxygen and steam.

In the second step, pure hydrogen is generated from syngas using an indigenously developed low-pressure gas separation unit.

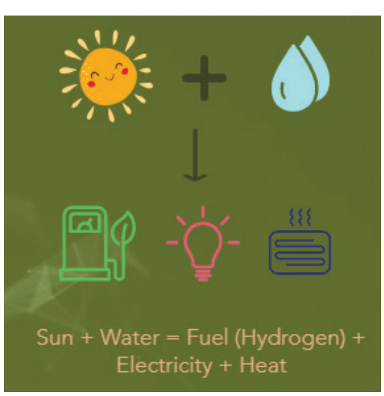
This process is a highly efficient method of generating green hydrogen – it produces 100 g of hydrogen from 1 kg of biomass.

The project was supported by the Ministry of New and Renewable Energy and the Department of Science and Technology of the Government of India. The team also acknowledges the support of the Indian Oil Corporation Limited in scaling up the technology to produce 0.25 tons of hydrogen per day for use in hydrogen-powered fuel cell buses.

reactor, and concentrated light interacts with a photo absorber layer and catalyst layer, facilitating a thermally optimized process. Arb - a technology by SoHHytec is one such example of photoelectrochemical process (Box 2) which is currently at demonstration stage.

Box 2: "Arb" – a novel hydrogen generation technology by SoHHytec

A Switzerland based start-up is using solar concentrators and patented integration photo-electrochemical device to produce hydrogen and oxygen from water. The company has established its first pilot plant at Lausanne, Switzerland. Technology is flexible and modular. It can produce hydrogen, oxygen, heat and electricity using solar energy and water. During nighttime it can also use grid electricity & water to produce hydrogen and oxygen. Thus, it has the capability to operate round the clock.



The technology is currently at TRL 8, and the company is expanding into the Indian market, targeting industries that are already utilizing hydrogen.

- **Hydrogen production through nuclear energy**

Electricity from nuclear reactors, which is carbon free, can be used to produce hydrogen through electrolysis. Though this is being called 'pink' hydrogen, we believe that it is green hydrogen as there are no carbon emissions in the production of electricity from nuclear power plants. The role of nuclear power in decarbonisation is being recognised in the international community belatedly. With new generation of nuclear power plant technologies, including the SMRs (Small Modular Reactors), the cost of nuclear power may decline, and it could be an alternative competitive source of carbon free electricity for use in electrolysis. An added advantage of nuclear power is that its generation is steady round the clock, unlike variable generation from renewables. Using nuclear power for hydrogen production for electrolysis instead of renewable energy may prove advantageous, as with round the clock supply, high-capacity utilisation of the hydrogen production plant would be feasible. Renewables with storage would also enable this.

The high temperature from a nuclear reactor could be used to directly split the water molecule to get hydrogen without first getting electricity and then using it for electrolysis. This is a promising idea. It needs work to develop the technology to be followed by the setting up of a pilot project.

2.2 Storage and transportation of green hydrogen

Green hydrogen is highly inflammable and strict safety standards of transportation and storage are essential. We should adopt international standards in this regard. Development of cheaper materials which comply with the prescribed safety standards , would lower the cost for downstream use.

2.3 The Cost of Green Hydrogen Production

Currently, the cost of hydrogen produced through electrolysis ranges from approximately \$3.6/kg to \$5.8/kg, depending on technological choices and associated expenses. The cost of hydrogen derived from biowaste stands at around \$3/kg.[3] However, with declining costs of electricity from renewables and electrolysers combined with increasing electrolyser efficiencies, the cost of green hydrogen is expected to come down. Furthermore, as electrolyser capital costs decrease, the concern over lower capacity utilization, driven by variable electricity generation from renewables diminishes. The relationship between the utilization rate and per unit of output cost weakens with reduced capital cost. Water electrolysis remains the dominant method for green hydrogen production. But biomass and biowaste are alternative renewable sources to produce green hydrogen at comparable, if not lower costs.

3. Green Hydrogen in Hard To Abate Sectors

It is relatively easy now to rapidly decrease the share of electricity being generated by using fossil fuels. Electricity from renewables combined with storage of renewable electricity can give reliable round the clock supply. Fortunately, this is now cheaper than electricity from a new thermal plant. So decarbonization of electricity combined with increasing electrification of road transport and industrial processes would take us towards net zero. But there are hard to abate sectors where eliminating carbon emissions remains a challenge.

Iron and Steel is the major emitting hard to abate sector with a share of 24% in the industry GHG emissions. Traditionally, coke is utilized as a reducing agent in steel production. Green hydrogen holds the potential to replace coke, leading to substantial reductions in carbon emissions from steel manufacturing.

In the Fertilizer industry, the production of ammonia, the key input for fertilizer production, relies heavily on natural gas. Green hydrogen can replace natural gas in this process and eliminate the carbon emissions from the use of natural gas.

In transportation, aviation and shipping are hard to abate sectors.

Surface transport, railways, two wheelers, three wheelers, cars, buses and light duty trucks can all be fully electric. These are also turning out to be increasingly cheaper for the consumer in India.

Only long-distance heavy-duty trucks may need to be run using green hydrogen to become carbon free as electric heavy-duty trucks are still a work in progress.

3.1 Iron and Steel Industry

Steel production significantly contributes to GHG emissions, accounting for approximately 8% globally. 1.91 tonnes of CO_2 are emitted per tonne of steel produced. The production of steel poses a formidable challenge due to its inherent dependence on fossil fuels, with over 80% of the fuel mix consisting of fossil fuels, particularly coal.

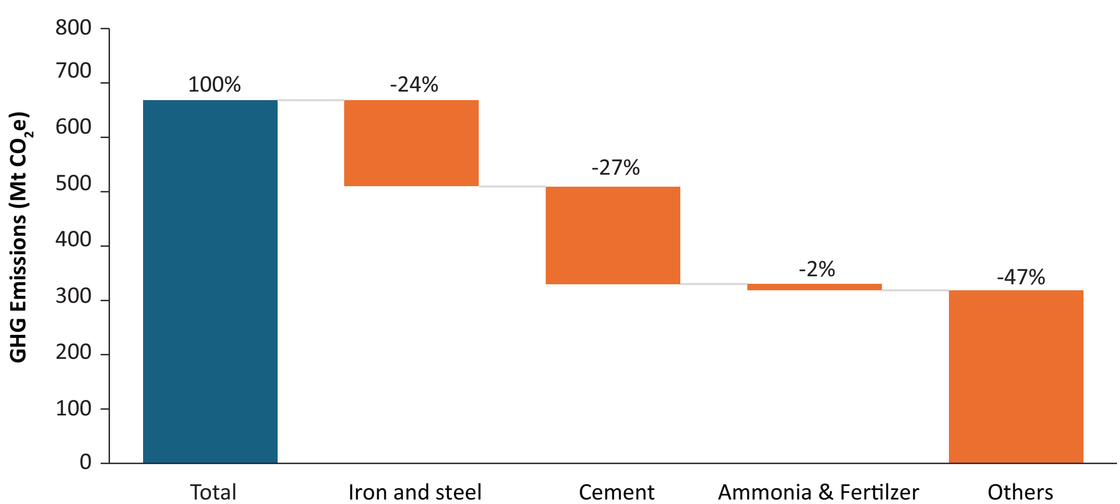


Figure 03: GHG emissions of industries

**Includes manufacturing and construction industries and IPPU emissions*

Others include industries -Aluminium, pulp and paper, engineering sector, non-ferrous metals, chemicals bricks, textile and leather

Source: MoEFCC. (2023). India: Third National Communication and Initial Adaptation Communication to the United Nations Framework Convention on Climate Change. New Delhi: Ministry of Environment, Forest and Climate Change, Government of India

These fossil fuels serve dual roles as reducing agents for iron ore and as fuels for high-temperature operations.

India's steel industry has considerable diversity, employing various technologies such as Blast Furnace-Basic Oxygen Furnace (BF-BOF), coal-based Direct Reduction (DR), gas-based DR, Electric Induction Furnace (EIF), and Electric Arc Furnace (EAF). The secondary steel industry, mainly reliant on coal-based Direct Reduced Iron-Electric Arc Furnace (DRI-EAF), is prominent.

Globally, DRI-EAF operations utilize natural gas or syn gas to create a blend of carbon monoxide and hydrogen, serving as a precursor to grey or blue hydrogen, for reducing iron ore to iron in primary production. In India, 9 units operate with natural gas or syn gas, while the rest rely on coal based DRI.

Various innovations for decarbonizing the sector have emerged, including Hydrogen DRI, the injection of hydrogen in the BF-BOF route, Carbon Capture and Storage (CCUS), and breakthrough technologies such as Molten Oxide Electrolysis (MOE) and Electrowinning.

Two leading decarbonization pathways have emerged for primary steel: clean hydrogen-based DRI-EAF is the most developed (TRL 6-8), and CCUS is rapidly developing (TRL 5-8). For secondary steel decarbonization, EAF-based production using 100% renewable electricity is a mature and available technology.

H_2 DRI appears to be the promising option. However, there are technical complexities which need to be addressed. It is seen that green hydrogen-based steel is likely to be 50-70% more expensive than conventionally produced steel. This is expected to reduce to 20-29% by 2030-31.[5]

3.2 Fertilizers

Ammonia serves as a primary component for the majority of fertilizers. The primary use of ammonia is for nitrogen-based fertilizer, which accounts for the utilisation of 70% of ammonia production.[6] Hydrogen is produced by steam reforming process of feedstock (NG, LNG, or naphtha). This hydrogen is combined with nitrogen to produce ammonia. Urea is formed by exothermic reaction between ammonia and CO_2. Two key considerations for green fertilizer manufacturing are Replacing Fossil Fuel-Derived Hydrogen and Addressing CO_2 Concerns.

The well established Haber-Bosch process, converting hydrogen into ammonia can undergo a sustainable transformation with the adoption of green hydrogen. Green hydrogen produced through renewable-powered electrolysis can seamlessly replace hydrogen derived from fossil fuels in this process. The result is the production of carbon-free ammonia with the only byproduct being oxygen from the electrolysis of water, eliminating carbon emissions. One concern in the transition to carbon free ammonia/ green ammonia is the additional CO_2 source required for urea production. The traditional natural gas-based production method emits about 1.8 tons of CO_2 for every ton of ammonia produced, while green hydrogen would bring it to near zero, as the process only has water vapour as part of its emissions.[7] Setting up urea plants near CO_2 producing sources like cement plants could be one of the options moving forward.

Many organizations, such as Rashtriya Chemicals and Fertilizers (RCF) in collaboration with GAIL (India) Limited, and ACME Solar Holdings, are actively working towards reducing the carbon footprint of the fertilizer industry through green ammonia production projects.

3.3 Shipping

Green methanol, green ammonia, and green hydrogen are considered sustainable green fuel options in the shipping industry. Green ammonia is produced using green hydrogen and nitrogen through the Haber-Bosch process. Green methanol is created by combining green hydrogen with captured carbon dioxide. The choice between fuel cells and internal combustion engines depends on vessel type and operational requirements. Two broad categories of shipping, short-distance and long-distance, demand different technological solutions. Short-distance shipping takes place on routes between nearby ports, The relatively shorter distances allow the use of cleaner energy: electric propulsion and biogas. Long-distance shipping needs fuels with higher energy density. Hydrogen powered engines for shipping are also under development. Green ammonia and green

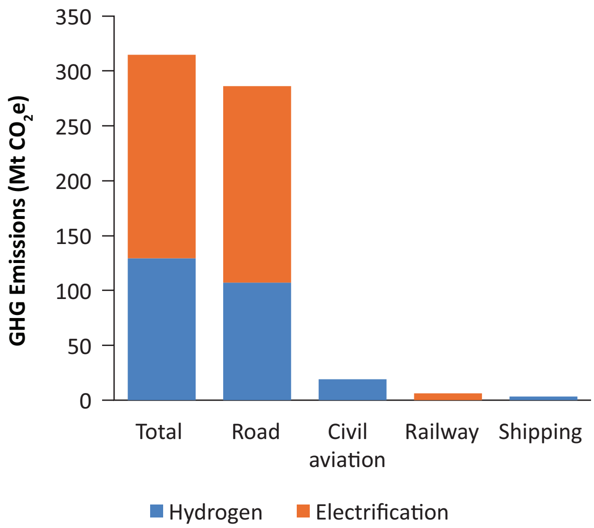


Figure 04: Decarbonization potential across transport sector

Source: TNC- IAC-MOEFCC (2023), Transitioning India's Road Transport Sector, IEA

methanol are options as they can provide the required energy for long routes.

3.4 Civil Aviation

The aviation sector has been looking to switch to Sustainable Aviation Fuels (SAFs). These are fuels, derived from biofuels, waste feedstock, or synthetic sources. They have been promoted and are being used by blending with normal aviation fuel to reduce carbon emissions from aircraft.

However, in order to become Net Zero, the industry is now seeing the need for hydrogen-powered aircraft. Hydrogen however has a specific energy-per-unit mass that is three times higher than traditional jet fuel. This would call for a fresh approach for configuring an aircraft using hydrogen.

Hydrogen can be combusted through modified gas-turbine engines or converted into electrical power that complements the gas turbine via fuel cells. The combination of both creates a highly efficient hybrid-electric propulsion chain powered entirely by hydrogen. In addition to this Hydrogen can be used to create e-fuels, which are generated exclusively through renewable energy.

One major challenge for a hydrogen-powered aircraft is the storage of hydrogen on board. Currently, liquid hydrogen storage is among the most promising options. Storing hydrogen as compressed gas presents challenges related to weight and volume requirements in aircraft design.

Airbus's ZEROe[8] project aims to achieve hydrogen aircraft commercialization. The company has set an ambitious goal of launching the world's first hydrogen-powered commercial aircraft by 2035. The key milestones revolve around establishing the means of propulsion, either via hybrid hydrogen-electric fuel cells or direct hydrogen combustion.

3.5 Cement

Around 60% of cement-related emissions are process emissions. These could potentially be addressed only through CCUS technologies. Electrifying kilns and use of bio-based fuels present a viable solution for tackling the remaining emissions. However, electrification is at a relatively low TRL. Hydrogen as of now has not been the focus of discussion globally for the cement industry.

4. Green Hydrogen Policies and Initiatives

4.1 India's Green Hydrogen Mission

India has set itself the goal of attaining energy independence by 2047 and reaching Net Zero by 2070, Green Hydrogen has emerged as an essential pillar for this transition. The Union Cabinet approved the National Green Hydrogen Mission in January 2022. The National Green Hydrogen Policy[9] was notified on 15th August 2021. A very comprehensive strategy has been outlined in the Policy. It envisages the production of at least five million tons per annum of green hydrogen by 2030, with potential to reach ten million tons per annum with growth of export markets. The need for a whole of government approach has been recognised. Accordingly, an Empowered Group has been put in place to coordinate.

The government has already committed ₹19,744 crores for:

a. ₹17,490 crore for the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme

b. ₹ 1,466 crore for pilot projects

c. ₹ 400 crore for R&D

d. ₹ 388 crore towards other Mission components

Recent developments in India's green hydrogen initiatives include awarding of the SIGHT Scheme (Mode-1-Tranche-I) on 9th January 2024 to 10 companies, with a total capacity of 412,000 tons per annum (TPA) of green hydrogen. Additionally, on 16th January 2024, guidelines for SIGHT Mode 2A (an aggregation model for green ammonia) and Mode 2B (an aggregation model for green hydrogen) were notified. To further boost green hydrogen production, the Component II: Incentive Scheme for Green Hydrogen Production (under Mode 1) - Tranche-II was announced by the Ministry of New and Renewable Energy (MNRE) on 3rd July 2024, with a planned capacity of 450,000 TPA of green hydrogen. SECI issued tender for hydrogen hubs on August 2024 for development of two green hydrogen hubs of individual capacity of atleast 1,00,000 MTPA of Green Hydrogen with central financial assistance of up to Rs. 100 crore each for supporting core infrastructure of hubs. These steps signify India's commitment to accelerating its green hydrogen transition.

The Hydrogen Mission aims to establish two plants for the production of green hydrogen-based urea and green hydrogen-based DAP (Di-Ammonium Phosphate) through a competitive bidding process. By 2034-35, the goal is to substitute all ammonia-based fertilizer imports with domestically produced green ammonia-based fertilizers. The bidding process for the production of 5.39 lakh MT per annum of green ammonia for supply to fertilizer companies was initiated on June 8, 2024.

A few examples on the present status of adoption of Green Hydrogen in the country are given below:[10]

i. GAIL Limited has started India's maiden project of blending Hydrogen in City Gas Distribution grid. Two per cent by volume of hydrogen is being blended in CNG network and 5 vol% of hydrogen is being blended into PNG network at City Gas Station of Avantika Gas Limited (AGL), Indore in the state of Madhya Pradesh.

ii. NTPC Limited has initiated blending of Green Hydrogen up to 8% (vol/vol) in PNG Network at NTPC Kawas Township, Surat, Gujarat from January 2023.

iii. Besides these, other PSUs have taken up various projects such as:

   a. Hydrogen based Fuel-Cell Electric Vehicle (FCEV) Buses in Leh by NTPC

   b. Hydrogen based Fuel-Cell Electric Vehicle (FCEV) Buses in Greater Noida by NTPC

   c. Oil India Limited has developed a 60-kW capacity hydrogen fuel cell bus, which is a hybrid of an electric drive and a fuel cell.

   d. Demonstration pilot plants for production of Green Hydrogen through water electrolysis using solar power, biomass oxy steam gasification and CBG reforming for refuelling 15 no. of Hydrogen Fuel Cell buses by Indian Oil

In addition, several entities have announced plans to set up production facilities for Green Hydrogen/ Green Ammonia in India.

4.2 State level policies and initiatives

The Green Hydrogen Mission has spurred state-level policy actions across India, with several states launching or planning their hydrogen initiatives to become leaders in hydrogen technology and its derivatives. Below mentioned are a few state policies that have been released thus far, showcasing the widespread commitment to advancing the hydrogen agenda.

1. **Maharashtra Green Hydrogen Policy**
   - Production Target of 500 KPTA by 2030
   - An outlay of over Rs 8,000 crores
   - Policy benefit:
     - » Exemption from cross subsidiary surcharge and electricity duty
     - » 50% exemption from intra-state transmission charges and wheeling charges
     - » Priority of land allotments
     - » 1% interest subsidy on hydrogen transport project
     - » Subsidy of Rs 50 per kg for blending green hydrogen into gas and capital subsidies for the establishment of 20 hydrogen refuelling stations and 500 hydrogen fuel cell-based passenger vehicles
2. **Uttar Pradesh Green Hydrogen Policy**
   - The policy spans five years
   - Emphasizes on cost reduction targets, blending goals (20% green hydrogen by 2028, 100% by 2035), and a capital expenditure subsidy of 60% in 2024 for electrolysers with a minimum capacity of 50 MW.
   - The policy focuses on key industries like chemical, fertilizer, and refinery
   - Offers monetary incentives (₹3,500 per tonne of green urea, 30% one-time grant support for technology purchases up to ₹50 million), and supports ecosystem creation and skill development

3. Rajasthan Green Hydrogen Policy

- Ambitious target: 2000 KTPA energy production by 2030.
- Incentives for Projects:
  - » 50% rebate on transmission charges and Exemption from surcharges for 10 years
  - » Priority in land allocation.
  - » 30% subsidy for green hydrogen research centres.
- Waiver of Charges:
  - » 100% waiver on wheeling and transmission charges.
  - » Reimbursement/waiver of banking charges for 7-10 years.
- Investor Incentive: Exemption in transmission and distribution charges.

4. Andhra Pradesh Green Hydrogen and Green Ammonia Policy

- Target- 0.5 MTPA Green Hydrogen production capacity or 2 MTPA Green Ammonia production
- Incentives for Green Hydrogen Projects:
  - » Reimbursement of net SGST revenue from sale
  - » 100% exemption of Electricity Duty for the power consumed
  - » 25% of Intra-state transmission charges shall be reimbursed for a period of five (5) years
  - » allocation of Government land for development on priority basis at lease rate of INR 31,000 per acre per year
  - » 100% exemption from payment of land use conversion charges and from payment of stamp duty

5. West Bengal Green Hydrogen Policy

- Facilitate identification of green hydrogen centres by GIS mapping
- Establish State Centre of Excellence for R&D and techno-economical study
- 100% waiver on land use conversion tax, land registration and stamp duty and electricity duty

Apart from the announced state green hydrogen policies mentioned above, some states have hydrogen policies at the draft stage, such as Assam, Bihar, Punjab, Haryana, and Gujarat. Meanwhile, other states like Odisha, Madhya Pradesh, and Himachal Pradesh have incorporated green hydrogen into their renewable energy (RE) policies.

6. Gujarat Hydrogen Policy

Under Government of Gujarat 'Policy 2023,' priority for leasing land for the development of green hydrogen production within the state. The lease period for solar, wind, and wind-solar hybrid projects dedicated to green hydrogen production is set at 40 years.[11] Gujarat is leading the way providing leading energy companies such as Reliance and Adani with land required for producing green hydrogen and generating solar power needed to produce it.

7. Punjab Hydrogen Policy

Punjab Hydrogen Policy targets a Green Hydrogen/ Ammonia producer with a production capacity of 100 Kilo tonnes per annum by the year 2030 and establish the Centre of Excellence (CoE) with different academic and research institutions and industries.[12]

8. Haryana Hydrogen Policy

Haryana Hydrogen Policy aims a production target of 250 kilo tonnes per annum (kTPA) Green Hydrogen by 2030, electrolyser manufacturing capacity of 2GW.[13]

9. Kerala Hydrogen Policy

Various initiatives have been undertaken, including the announcement of a Rs 200 crore scheme to set up green hydrogen hubs in Kochi and Thiruvananthapuram. "Kochi Green Hydrogen Valley" project aims to establish green hydrogen and ammonia plants, along with renewable energy infrastructure. ReNew Power has proposed an investment of Rs 26,400 crore for a green hydrogen project in Kerala aiming to establish a production capacity of 220 KTPA of green hydrogen.

10. Karnataka

In Karnataka, a project slated for execution between 2022 and 2027 aims to establish a 1.2 MTPA Green Hydrogen & Green Ammonia plant alongside a captive solar power unit.

11. Tamil Nadu

In Tamil Nadu, there is an initiative for a 5,000 MW solar PV plant, a 1.5 GW electrolyser, and a 1.1 million tonne ammonia synthesis loop.[14]

4.3 Private sector initiatives

Our largest firms have announced ambitious plans to make green hydrogen and bring costs down to 1 dollar per kg. This is a very positive development. It makes commercial sense for energy companies to strategically consider the post-fossil fuel age and begin their transformation now to ensure their survival and growth. Failing to adapt could lead to obsolescence in the future without fossil fuels. To illustrate, Blackberry and Nokia, ceased to exist due to their inability to see the coming change in the market.

5. Recommendations

The ideas on the way forward for the Hydrogen Mission in this paper have emerged from the recognition of the following:

- Green hydrogen is considerably more expensive than the fossil fuel it could replace to eliminate carbon emissions.
- Production of green hydrogen is not an end in itself but it is the means to an end. The end is downstream use from where carbon emissions would get eliminated.
- There is no demand in the market for green hydrogen for a downstream green product in India.
- Financial resources with the government for providing subsidies would remain a major constraint for the foreseeable future.
- To the extent explicit subsidies from the budget can be avoided or minimised, it would be better
- Implementing pilot downstream projects at the earliest in every segment would lead to the creation of demand for green hydrogen.
- Competitive procurement creates a competitive industry which drives innovation and cost reduction.

Given India's potential cost advantages in project execution, our costs could, in some cases, become the lowest in the world, as demonstrated in the solar power sector. Solar power serves as a major input cost for producing green hydrogen via the electrolyser route. India becoming one of the cheapest producers of green hydrogen is a feasible outcome. In addition, alternative hydrogen production methods from biomass, biowaste and nuclear power should also be developed in parallel.

Our aim should be to become the least cost producers of green hydrogen and then of downstream uses for carbon free production of goods and services. The driver for this outcome is focussed well-funded technology development and deployment by a competitive domestic industry structure. Repeatedly bids would drive firms to go down the cost curve. Hopefully we could even get to the global frontier in a leadership position. Technology development through public funds combined with the power of competition to get firms to innovate and reduce costs would be the key to success.

R&D and Technology Development

R&D funding may be given for work with a narrow focus after inviting proposals. These proposals could come from an institution or a firm or a consortium. In some cases where the problem appears daunting and the benefits from success appear large, two groups may be funded simultaneously to solve the same problem. This may appear expensive but success in reducing costs would far outweigh the higher expenditure of parallel efforts in technology development. Then, unsolicited proposals should also be entertained and funded. Domain experts should be inducted into the decision-making committee (s) for approving technology development projects. Eminent NRIs may be glad to serve on these Committees as they would be able to attend online These technology development projects should be well funded. It would be prudent to fund fewer projects but fund them fully to reach actual deployment stage rather than spread resources thinly. Also, there should be an initial acceptance that many such funded projects may not succeed, and this may be explicitly recorded in the approval of the program. Apprehensions of time and cost overruns or of lack of success should not inhibit decision makers. The aim should be to get better, more efficient and cheaper materials and processes. The fruits of technology developed from government research institutions like IISc and IITs should be made available as a public good free of cost to all.

SPV for Green Hydrogen Procurement

The reality is that as of now there is no market in the country for green hydrogen. This is the consequence of there being no market for goods and services that would use green hydrogen to replace carbon emitting fossil fuels and be more expensive. Conventional support mechanisms like SIGHT Programme or Production-Linked

Incentives (PLIs) may not deliver the desired outcomes in the absence of a market for green hydrogen and products made from it. It is necessary to understand an investor's perspective. He needs to see sufficient sustained demand in a price range where he can get adequate returns on his investment. On this basis, he has to raise equity and debt whose providers will do their own due diligence. Contractual long term purchase agreement at a price, L1 bid price, which generates reasonable returns gives full confidence to financial markets for both equity and debt. This has been seen in the Solar Mission where all the capacity has been created by the private sector and where financing has not been a constraint.

Procurement of green hydrogen from a prospective date for meeting downstream demand for different projects whose development is underway would create competitive production capacities for green hydrogen. Bidding for supply of hydrogen for each downstream project would facilitate movement down the cost curve and nurture a competitive industry structure. Competitive procurement of green hydrogen for different downstream pilot projects in the quantities and from the dates of the commissioning of these plants is being suggested to create the market for green hydrogen through individual long term procurement contracts. This could be done more efficiently by creating an SPV for such procurement. This SPV could be set up along the lines of SECI (Solar Energy Corporation of India) which through competitive procurement over the years enabled India to have the cheapest solar power. This can be repeated all the downstream green carbon free goods and services in the hard to abate sectors.

Hydrogen Production using electrolysers

The bulk of the procurement by the SPV should be for hydrogen production through electrolysers and for firm demand of downstream projects. Many firms are positioning themselves for green hydrogen production using electrolysers. In parallel, electrolyser production capacities are being developed.

The competitive process should follow the approach of the National Solar Mission which in its initial phase successfully created a competitive industry structure. There were repeated rounds of bidding for quantities which were small and then went up. Many developers emerged in this new area and some of them are large firms now. Competition drove prices down.

Hydrogen production from Biomass/ Biowaste

The key preparatory step for this would be the organisation of the supply of the required quantity of biowaste to the identified site of the plant with its size being the smallest techno-economically feasible one. Separate bids for two pilot plants may be invited: one for establishing an oxy-steam gasification demonstration plant from solid biomass like wood, bamboo, coconut shell, and the other biochemical reactor plant to use urban sewage. Enough time may be provided for short listing potential bidders. Time would make it easier for Indian firms to tie up with potential technology developers in the world and be in a position to bid.

Hydrogen production from Nuclear Energy

Nuclear Power Corporation of India Limited (NPCIL) should initiate a small pilot project at the minimum technologically feasible size, either from an existing plant or one of the new plants under construction, to produce hydrogen by directly splitting the water molecule with the very high temperature heat that can be obtained from a nuclear reactor. In theory this is an attractive idea as energy is used to directly split the water molecule rather than first using energy to produce electricity and then use that electricity to electrolyse water and then get hydrogen. There should also be assured offtake of hydrogen for downstream applications to ensure demand for the hydrogen that would be used for sustained production and the project's viability.

SPVs for Downstream Green Hydrogen Based Projects

It would be desirable to create an SPV for each industrial segment for the development of the pilot plants. These SPVs may be promoted by the Ministries dealing with the industries chosen for developing pilot projects. Where the technology for such a plant is mature with at least one plant in successful operation, the best way to proceed would be to invite competitive bids for the setting up such a plant in India. The bid parameter should be the price of the green carbon emission free product. Purchase of the entire output of the plant through a long-term procurement contract should be assured. This would derisk the investment decision for putting up the plant. The supply of green hydrogen should be assured along with its price. Supply of competitively procured green hydrogen will lower the cost of downstream production. Further, it could also reduce the risks of potential bidders as they would only need to set up the plant, run it and not have to ensure the supply of green hydrogen for their plant.

The bid parameter should be the processing cost of conversion of the green hydrogen which would be provided along with other raw materials and inputs which the bidder would have to arrange. Price indexation would be provided as is the practice in all such long-term contracts. This bid design would de-risk investment with full offtake at a commercially viable price being assured for a long period. This should get very competitive bids and the lowest feasible price. It would be necessary to announce the intention of inviting bids so that potential bidders get enough time to prepare. After short listing of bidders, the bid and contract documents may be finalised transparently and in consultation with the short-listed bidders. This approach was tried in the UMPPs (Ultra Mega Power Projects) where the final bid price was far below the optimistic expectations. These bids may be the first of their kind in the world. Getting the bid process right would be crucial for success.

In so far as possible, all downstream projects may be developed through competitive bidding. Competition in an open market open to global players should get us the lowest feasible costs in each potential downstream use.

One pilot plant using green hydrogen having zero emissions in each downstream industrial segment should be developed. Work for developing such plants should be initiated simultaneously. The industrial plant should have the minimum technically feasible size. This would keep higher capital investment for a new green plant on the lower side. The more expensive output would have to be used. So, it makes sense to keep this additional expensive production that has to be absorbed to the minimum in the first instance. After price discovery it would be easier for government to see how much of a transition by way of new green capacities is affordable and sustainable. It can then determine inter se priorities on a more rational basis. It would also determine the pace at which bidding for new plants would be undertaken keeping in mind the reduction in carbon emissions, the additional cost of carbon free product and the ability of the system to absorb this extra cost.

Iron and Steel

As the technology is still in the drawing board stage, establishing a pilot plant is essential. Setting up a greenfield plant to produce carbon free steel would put India in a global leadership position. The risks of technology, time and cost in such a new project is too high for private capital. Such a plant can be set up if the government puts in all the money and takes all the risk. The government can derisk its investment by deciding to buy all the steel produced on a cost-plus basis. This steel would be more expensive than normal steel in the market. Government could use this steel in its own projects through public procurement. For these projects the additional cost of expensive steel would have a marginal impact which government can comfortably absorb. For a 20% mandate of procurement of green steel in total average for infrastructure sector, the project cost increases by only 0.37 - 1.1 %, depending on the premium. Even with 100% green steel uptake, the average total budget of the infrastructure projects increases by only 1.83% -5.50%.[15]

The project should be implemented by a dedicated SPV with all our steel firms being partners. They should be required to put in some equity in order to have a stake in success. The management and staffing should be joint in a genuine partnership mode. There would be joint learning in absorption of the technology, project execution, and smooth running of the plant. Once this plant begins to work smoothly, the actual higher cost of this steel would be known. Our steel producers would have the ability to build such carbon free steel plants on their own. Then they can decide whether the international market makes it worth their while to build such plants. The government would be in a better position to take a view on the pace at which it would like to get such plants built in India for the domestic market and the policy instruments it would consider appropriate.

Project execution by a consortium of steel firms, fostering collaboration and shared capacity development on this scale may be a first in India and would be a useful precedent. The aim should be to set up a minimum-size green steel plant, such as a 1Mt Hydrogen DRI plant. The SPV would need to establish technology transfer commercial arrangements with those who have come up with designs for such a carbon free steel plant.

Fertilizer

The setting up of a pilot project for producing green/ carbon free fertilizer may not need significantly higher capital expenditure (CAPEX) per ton of production capacity. The key change would be the production unit of ammonia which would produce green ammonia using green hydrogen instead of natural gas. The higher cost of the fertilizer would be primarily due to the higher cost of green ammonia. Additionally, new locations of cement and fertilizer plants should be strategically planned to ensure they are in proximity, facilitating a constant supply of CO_2 needed for urea production. Along the lines indicated above, bids may be invited for setting up a pilot plant of the minimum technically feasible size. The supply of green hydrogen may be assured, and bids may be invited for this supply from the date the urea plant would go into production. The bid parameter would be the cost of converting green hydrogen into green urea. Government could buy this fertilizer and give it to farmers at the price at which it is giving them normal fertilizer. For this green fertilizer, there would be a higher subsidy burden on the government which it should be able to afford. After price discovery, government could take a rational view on the pace at which new plants would be built through competitive bidding. The key trade-offs to be considered then would be movement down the cost curve by getting more plants built through competitive bidding, the higher subsidy burden, and the future cost of closing of carbon emitting plants to get to net zero.

Heavy duty trucks

Green Hydrogen is an option for moving heavy-duty trucks without carbon emissions. Batteries for heavy duty trucks are yet to become feasible. Initially picking up a few busy routes for implementing pilot projects would be the optimal way to proceed. The capital cost of a heavy truck would be higher than that of a normal truck. Hydrogen filling stations would need to be put up on the route with assured supply of green hydrogen. The per km cost of using green hydrogen as a fuel would be higher. Both the truck and the hydrogen would need to be subsidised. A critical mass by way of trucks and hydrogen filling stations have to come up simultaneously. This can be best done through a state specific SPV with the backing of the state government.

Announcements of subsidies for trucks and hydrogen filling stations may not generate the market response to achieve the critical minimum size of operations needed. One way of implementing the pilot project would be for the SPV to invite bids for a large number of trucks to have the volumes for getting a competitive price. These trucks may then be leased out at a subsidised rate which makes it appear attractive to truck operators. For the supply of hydrogen. competitive procurement of green hydrogen from biowaste may be tried out. This would have two advantages. First, a green hydrogen plant using biowaste would be smaller in size, with the economical supply of waste being a binding constraint. It would be easier to get such plants developed for transport rather than for an industrial application Further, there would be lower costs in transport of green hydrogen. For setting up and running of the filling stations the approach being used for petrol and gas filling stations should work. The SPV should see that there is enough volume of business for these stations.

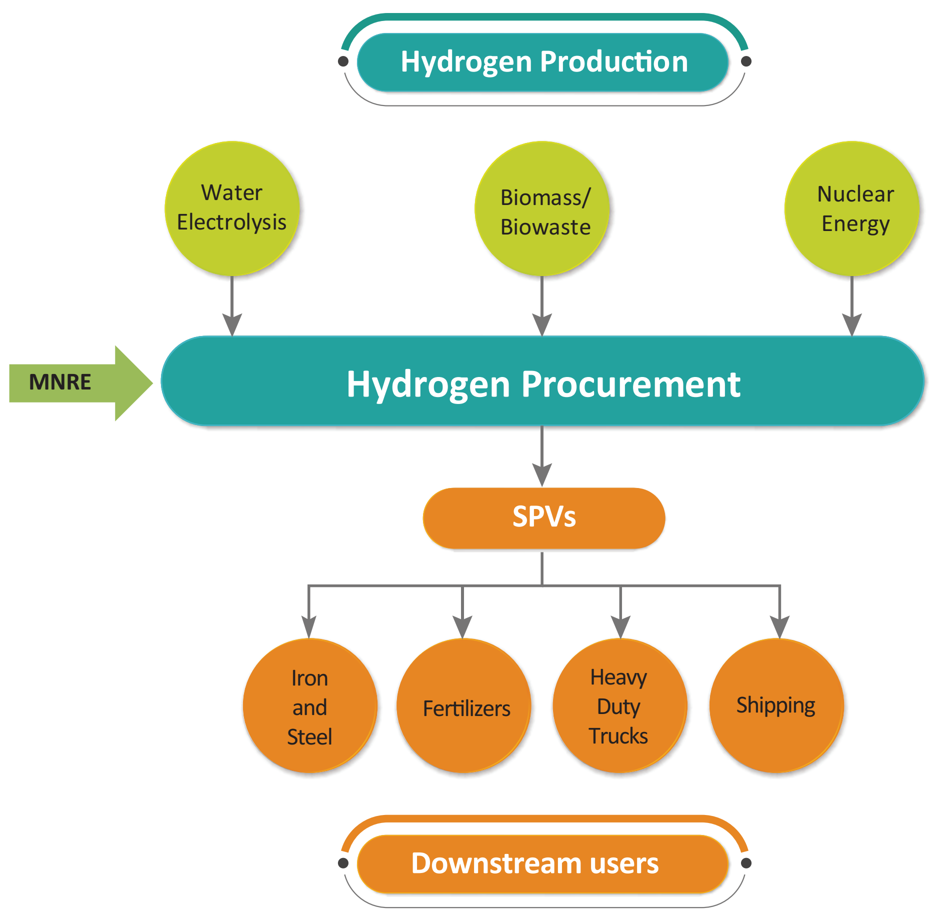
A holistic view of the number of trucks, freight kilometres, hydrogen filling stations and the volume of green hydrogen to be procured would be essential. Again, the sale price of green hydrogen would have to be subsidised by giving the truck operator an attractive per km cost vis a vis a normal diesel truck. The simplest way of giving these subsidies would be by lowering the GST rate for the truck as has been done for EVs and have a low GST rate for hydrogen. This would have the advantage of not needing budgetary provisions and disbursements for these pilot projects. After cost discovery and learning experience, decisions on the pace of scaling up can be taken. The trade off in the short run would be the tax revenues foregone on the one hand and Indian enterprises being able to have zero embedded carbon for this part of their logistics.

Shipping

Green ammonia can be used in shipping. Globally the use of green hydrogen directly or through green ammonia/ green methanol for shipping is being tried out. India could do the same on a modest scale to begin with. Price discovery by provision of green hydrogen and its deriviations at actual cost would be the way to go forward. Kerala could set a target date when all vessels being used for tourism would be carbon free. This would enhance the brand value of Kerala tourism. This can be done by the state facilitating the transition without any financial burden as the higher cost would be passed on to the tourists. Then some coastal green shipping pilot projects can be implemented in a similar manner.

Power generation

The use of green hydrogen and green ammonia may also be tried out for power generation to discover which is the cheaper and better option. When full decarbonization of electricity would be attempted one of these green fuels would be needed for meeting seasonal peaks in demand. PSP, CSP, and BESS, all offer only short-term, usually daily, storage for getting carbon free electricity round the clock.



As the first set of downstream pilot projects get completed and actual costs get discovered, the cost of a ton of carbon mitigation in a zero-emission process in different industries and processes would get known, A rational view on prioritisation and scaling up would then be possible. On scaling up the higher cost would have to be borne by the consumer and/or the government. Decisions would emerge from the assessments of the absorptive capacities of the consumer and the government. At one extreme the cost can be passed on fully to the consumer by regulating that all new capacity has to be carbon free and the cost advantage of older capacities can be neutralised by a carbon tax which fully neutralises this cost advantage. However, regulation mandating that new capacity should be carbon free would be feasible only when the market on the supply side has developed sufficiently and is in a position to meet all additional demand. It would also be prudent for such regulations to be notified to come into effect from a future date giving enough time for the market to be ready to conform to the new regulation without any disruption in supply. At the other end government can provide subsidy to fully offset the higher cost. The subsidy can be explicit from the budget or indirect through a lower GST rate or some combination of the two.

It may be prudent to use scarce resources for accelerating green downstream production to get a greater share of export markets rather than subsiding export of green hydrogen. An important new dimension is the EU (European Union)'s CBAM (Carbon Boarder Adjustment Mechanism) An export market for green products which have a higher cost is being created. India could potentially leapfrog and became a major producer and exporter of green carbon free manufactured goods. For this, government could create a DFI (Development Financial Institution) which provides long term credit at low real interest rates for the creation of new manufacturing capacities which meet the EU carbon standards. These new plants would be for exports while the existing plants could go on supplying to the domestic market. With this ring fencing, competitive capacities would emerge and movement down the cost curve would take place without any additional domestic costs being incurred. To the extent Indian firms become forward looking and government helps with soft financing, India could get the success in the export of manufactured goods that has been eluding it so far.

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