GOVERNMENT OF INDIA
MINISTRY OF NEW
AND RENEWABLE ENERGY

R&D ROADMAP FOR GREEN HYDROGEN ECOSYSTEM IN INDIA

(DRAFT)

ALL COMMENTS REGARDING THIS DRAFT ROADMAP MAY BE SEND TO ICGH2-MNRE@GOV.IN WITH THE SUBJECT LINE "COMMENTS ON DRAFT RND ROADMAP"

Preface

The National Green Hydrogen Mission has been approved by the Union Cabinet on 4th January 2023 with an outlay of ₹ 19,744 crore. The Mission aims at making India a global hub of Green Hydrogen production, utilization and export. A key component of the proposed Mission is to establish a conducive Research and Innovation ecosystem for Green Hydrogen in the country.

In the run up to the Mission's launch, it was decided that various stakeholders in the Government, Industry, and Academia should come up with a joint report outlining the current status of research and technology development in the country and provide recommendations for a national research and innovation roadmap to support the Green Hydrogen ecosystem. Accordingly, a drafting committee was constituted with experts and representatives from Office of Principal Scientific Advisor, Council of Scientific & Industrial Research, Ministry of Petroleum and Natural gas, NITI Aayog, Department of Science & Technology, Department of Atomic Energy, Defense Research and Development Organization, Indian Space Research Organization, Indian Oil Corporation Ltd., Indian Institute of Science, IIT Delhi, IIT Madras, IIT Bombay, IIT Kharagpur, IIT Kanpur, IIT Roorkee, IIT Guwahati, IIT Hyderabad, Central Electro Chemical Research Institute, National Chemical Laboratory, NTPC - NETRA , National Institute of Solar Energy, Confederation of Indian Industry, Indian Hydrogen Alliance, Federation of Indian Chambers of Commerce and Industry, Society of Indian Automobile Manufacturers, Council on Energy, Environment and Water, World Resources Institute, The Energy and Resources Institute. Joint Secretary, Ministry of New and Renewable Energy was the convenor of the committee.

Thematic sub-committees on hydrogen production, hydrogen storage, hydrogen transportation, and hydrogen applications assisted the committee and provided detailed insights on specific areas. The committee has prepared this draft roadmap through in-depth analysis of the current status of technology and ongoing research, benchmarking and gap. The roadmap recommends research and development actions for each part of the Green Hydrogen value chain. It is expected that this draft roadmap would serves as a guidance for developing a vibrant research and development ecosystem required to commercialize Green Hydrogen and contribute to India's ambitious climate and energy goals.

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Chapter 1: Green Hydrogen: Initiative for Research and Innovation in India

Technology development and innovation are crucial for achieving India's Green Hydrogen ambitions. A focussed approach would be required to solve critical cost and technology challenges to enhance Green Hydrogen production and use. The National Green Hydrogen Mission proposes a comprehensive R&D programme to drive innovation in various aspects of Green Hydrogen.

Hydrogen technologies across the value chain are currently under development. Mature technologies like electrolysers, fuel cells and carbon composite cylinders are not yet cost-competitive with alternatives;other upcoming technologies promising lower costs are yet to prove long-term performance. The aim is to design affordable, efficient, safe and reliable pathways. At the current levels of technology development, significant scope exists for improvement along each of these aspects. Accordingly, major economies and corporations are heavily invested in R&D.

India's R&D roadmap for green hydrogen technology aims to address these challenges and develop innovative solutions to overcome them. The roadmap focuses on developing new materials, technologies, and infrastructure to improve the efficiency, reliability, and cost-effectiveness of green hydrogen production, storage, and transportation. The R&D program will also prioritize safety and address technical barriers and challenges in developing a hydrogen economy.

Research and Development strategy under the Mission

The National Green Hydrogen Mission proposes the following strategies for R&D:

a) Support innovation to increase the viability and feasibility of Green Hydrogen production, storage, transportation, and utilization and enhance the systems and procedures' effectiveness, safety and reliability. There is a need to haveR&D projects aligned with targets, are time bound, and have a potential for scale-up.

b) The proposed R&D programme has been drafted in consultation with Council for Scientific and Industrial Research (CSIR). Support is proposed for identified Mission Mode Projects with short-term (0 - 5 years) impact horizon. Development of the final product in partnership with industry will be prioritised, along with leveraging existing capabilities and infrastructure during this period. Projects entailingthe development of domestic modular electrolysers, Type III/Type IV compressed hydrogen tanks and Polymer electrolyte membrane(PEM) fuel cellswill be included under this. Biomass-based hydrogen generation will also be scaled-up for commercial applications.

c) Grand Challenge Projects with a mid-term (0 - 8 years) impact horizon would be initiated parallelly with a focus on critical technologies to mitigate licensing challenges and supply limits. The projects will most likely be in a consortium and would require reinforcement of existing capabilities and infrastructure. Likely Grand Challenges will be built around manufacturing of critical electrolyser and fuel cell components like Membrane Electrode Assemblies (MEAs), electrocatalysts, Catalyst Coated Membranes (CCMs), Gas Diffusion Layers (GDLs), bipolar plates, etc. To scale up domestic manufacturing, improve effectiveness and reduce costs of critical technologies, component-specific research is critical.

d) Blue Sky Projects having a long-term (0 - 15 years) horizon would be taken up with a focus on establishing global IP and competitive advantage for the Indian industry. Blue Sky projects will aim to develop capabilities of the Indian R&D sector within an array of subjects like the development of 3rd generation electrocatalysts (Bunched Nanospheres - BNS, Bunched Nanocages - BNCs, etc.), reversible Solid Oxide Electrolysers (SOECs) and Solid Oxide Fuel Cells (SOFCs), thermochemical water splitting for hydrogen production, seawater electrolysis, thermo-catalytic pyrolysis, plasma pyrolysis, salt cavern surveys, high entropy alloys for reversible hydrogen storage, etc.

e) A public-private partnership framework for R&D (Strategic Hydrogen Innovation Partnership – SHIP) will be facilitated under the Mission. The framework involvesthe establishment of a dedicated R&D fund, with inputs from Industry and Government institutions. Funding from Venture Capital will be looked at to boost innovation for the short and long term. The R&D programme under the Mission will seek to develop globally competitive technologies in various segments. A consortium-based approach, leveraging the strengths of each institution/industry, will be encouraged.

f) The R&D programme will focus on the creation of Centres of Excellence through subject expertise and research infrastructure. A network approach will be undertaken involving the academia-industry-government to ensure the seamless transfer and commercialisation of new technology.

g) The Mission will seek to leverage the inherent strengths and technological experience of institutions such as Bhabha Atomic Research Centre (BARC), Indian Space Research Organization(ISRO), Council of Scientific & Industrial Research (CSIR), Indian Institute of Technology (IITs), Indian Institute of Science (IISc), etc. and the Indian industry. Planning activities under the Mission will take into consideration the available capabilities and build upon prior achievements. Industry-academia-government networks would be important to ensure the technological developments are commercialised, and appropriate policy and regulation support are provided in this regard. Ministry of New And Renewable Energy (MNRE) would play the role of facilitator in this regard to devise policy support for effective industry-academia collaboration that might be required.

h) State-of-the-artMicro, Small & Medium Enterprises (MSMEs) and start-ups working on indigenous technology advancement and adaptation will be encouraged under active Government programmes, as well as various support mechanisms under the Mission.

Chapter 2: Hydrogen Production

2.1. Introduction

Hydrogen can be generated from diverse resources, which include fossil fuel resources such as coal, natural gas, and lignite, and renewable resources such as biomass and water splitting using solar, wind, hydroelectric, and geothermal energy. As shown in fig 1, a wide variety of pathways are available for hydrogen production, which according to the feedstock used, can be divided into two major categories, namely, fossil fuels and renewable resources derived hydrogen. Fossil fuels-derived hydrogen production includes coal gasification, along with hydrocarbon reforming and pyrolysis. Renewable resources-based hydrogen production includes biomass process and water splitting using renewable energy.

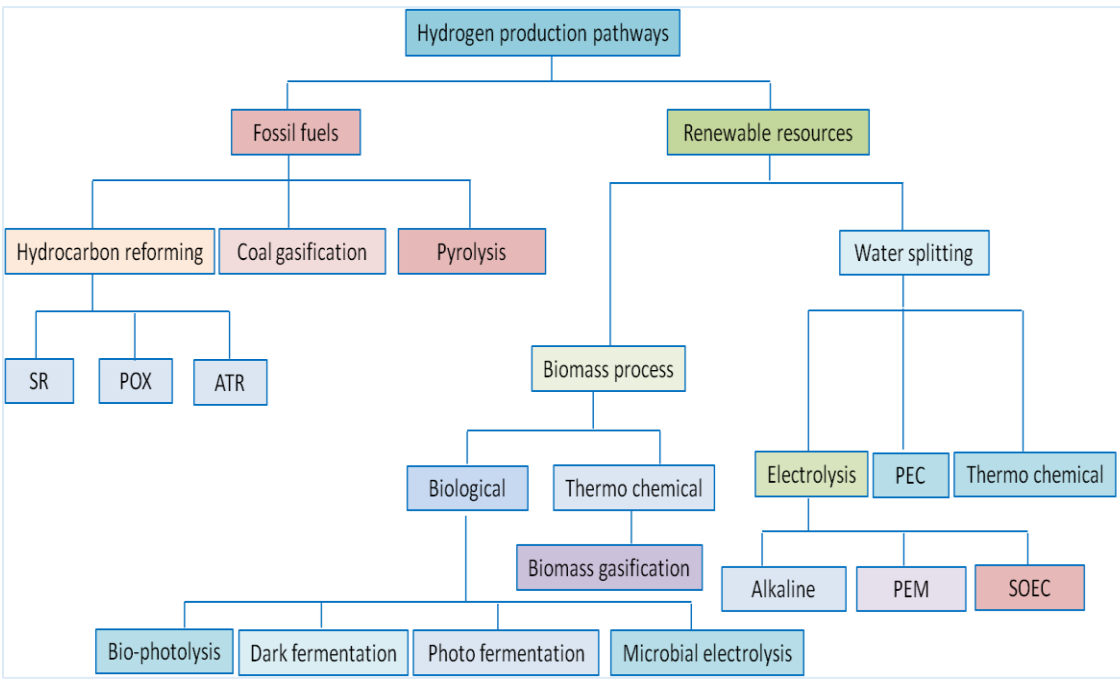

Figure 1: Various pathways for hydrogen production

There are numerous methods for hydrogen production,with the most widely used being steam methane reforming, methanol-reforming, partial oxidation of hydrocarbons, auto thermal reforming, coal gasification, and electrolysis of water. The other methods of hydrogen production including biomass gasification and photoelectrochemical (PEC) water splitting. However, these are still in the research phase.

The quality of hydrogen produced is directly dependent on the cost of the method of production, separation, and purification. India has a current demand of 6MT of grey hydrogen. This usage is concentrated in two main areas – industrial usage in refining and as a feedstock to produce ammonia and methanol. While methanol production requires a small amount of hydrogen, current hydrogen consumption is equally split between refining and ammonia production.With advancing technologies, we have seen a small demand of about 0.3 million tonnes of hydrogen for steel production. Currently, for steel making, hydrogen is not used directly. Indirectly, hydrogen is part of syngas which is produced via coal gasification and used in 1.8 million tonnes vertical shaft DRI plant. Demand for hydrogen from the power and mobility sectors is expected to start materializing from 2025 onwards.

The technologies to produce low-emission hydrogen are at different stages of development. For electrolysis technologies, alkaline and Proton Exchange Membrane (PEM) electrolysers are commercially available (TRL 9), although they are still not competitive with conventional unabated fossil-based technologies. Solid Oxide Electrolyser Cells (SOEC) are still under demonstration (TRL 7), and Anion Exchange Membrane (AEM) electrolysers are at prototype level (TRL 6). However, these technologies are observing rapid development.

2.2. Objectives

Electrolysis, with high capital costs and dependency on electric costs, has made it the most expensive method of producing Hydrogen. Technology advancement to build large capacity and improve the efficiency of electrolysers is also a big challenge. Keeping these problem statements in mind,the key objectives of the 2030 vision are:

- Steep reduction in electrolyser capital and operational expenditure
- Enhance operational capacity and efficiency, keeping in mind durability and reliability, especially when operating dynamically
- Decrease carbon footprint by increasing current density
- Showcase the benefits of adding electrolysers tothe power system through their ability to seamlessly integrate higher concentrations of renewables while providing flexibility
- Reducing the life-cycle carbon footprint of electrolysers by ensuring circularity of material employed as well as for the production process
- Design and develop large-scale (MW) Electrolyser systems, including Stack and BOP
- Build capacity and keep stock of material and critical components of Electrolyser stacks
- Deployment rates to be increased
- Reengineer and improve manufacturing for both water and steam electrolysis

For sustainable development of Electrolyser systems (i.e., short, medium or long term), the targets for Key Performance Parameters (KPP) like current density, specific power consumption, hydrogen purity, degradation rate, CAPEX, stack size, etc., may be mentioned. A KPP sheet is enclosed for reference inAnnex1.

Technological improvements through research and innovation will be key tothe development of more efficient and cost-effective electrolysers. Technological advancements will allow for upscaling electrolyser plants to modules of tens of megawatts and subsequently to electrolyser plants in the range of gigawatts. Rapid technological advancements along with favourable feasibility policy measures which enable renewable energy cost reduction will help achieve India's ambitious green goals. Favourable conditions will allow for producing renewable hydrogen at a levelized cost of hydrogen below INR$H_2$100/kg

2.3. National and international R&D activities

Various research groups in India are engaged in Research, Development, and Demonstration (RD&D) projects on hydrogen production. A brief on the hydrogen production research initiatives by various research organizations in India is given below:

1. Bhabha Atomic Research Centre (BARC), Mumbai

BARC has been exploring several hydrogen production pathways. The technologies are broadly classified into three categories. Hydrogen production using a) only electricity, i.e., Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane (PEM) based electrolysis, b) only heat source, i.e., Thermo-chemical splitting of water like Iodine Sulphur (I-S) process, c) both electricity and heat source like High-Temperature Steam Electrolysis (HTSE), Copper-Chlorine (Cu-Cl) Cycle and Hybrid Sulphur (Hy-S) cycle[2] and d) Sunlight-driven photocatalytic hydrogen generation. The details of the activities undertaken under each production method for BARC are listed in Annex2.

2. CSIR - Central Electrochemical Research Institute, Karaikudi

CSIR-CECRI's research focuses on the generation of green hydrogen by PEM-based water electrolysis, photochemical oxidation of water using a molecular catalyst, and water oxidation by functional electro catalysts and novel composite electrolytes[4]. The design of electrodes and electrolytes for hydrogen generation using sea water has also been explored at CECRI. Reduced Titania was used as a catalyst. The primary challenge with finding the right catalyst for sea water splitting has been balancing the effectiveness of the catalyst and its stability in water. Based on the materials developed, electrolyser technology has been developed by CECRI and transferred to industry[2].

3. ONGC Energy Centre (OEC)

OEC is engaged in developing a green hydrogen eco-system by following a collaborative consortium mode with various national Centres of excellence by mobilizing national resources devoted to various elements of a hydrogen economy with a focus on large-scale green hydrogen generation to develop cost-effective indigenous technology. OEC's focus has been on thermo-chemical water splitting.

From among various possible options of thermo-chemical cycles, OEC has chosen two processes, viz., Copper-Chlorine (Cu-Cl) cycle and Iodine-Sulphur (I-S) cycle due to relatively low-temperature requirement of 550°C and 900°C respectively, and opportunities for efficient integration with other energy systems nuclear or solar power. So far, OEC has established the processes viz. close-loop Copper-Chlorine (Cu-Cl) cycle and close/ open loop Iodine-Sulphur (I-S) cycle at lab/ lab engineering scale, and the next priority is to scale up using engineering materials using indigenous resources [5]. Details are provided in Annex3.

4. Indian Oil R&D Centre, Faridabad

With the objective of assessing different hydrogen production pathways based on indigenously available resources, IndianOil R&D is setting up three hydrogen generation demonstration plants for generating the required hydrogen for undertaking fuel cell bus demonstration trials. Indian Oil R&D and the Indian Institute of Science are jointly working on the development and demonstration of oxy-steam biomass gasification-based hydrogen generation technology, design, manufacturing, integration, supply, installation & commissioning of the solar-powered electrolyser-based green hydrogen production system and dispensing station for refuelling hydrogen and natural gas and bio-CNG reforming-based hydrogen generation plant is being set up for the production of hydrogen for undertaking fuel cell buses demonstration trials. Details of the demonstration plants are given in Annex4.

5. KPIT Technologies

Biomass-to-Hydrogen is not only environment friendly but a sustainable solution which can help in reducing the oil import bill of the country as well as can help in improving farmers' income by providing value to the agricultural residue, which otherwise is being burnt in the country. As the availability of biomass is spread across the country, these technologies are suitable for distributed generation of Hydrogen near the point of consumption. Distributed generation of Hydrogen will reduce the cost associated with handling and transportation of Hydrogen. This is ideal in the case of mobility applications which will potentially be a significant Hydrogen consuming sector in the next 5-10 years. Recognizing this, KPIT has been working on the development of the following two biomass-to-Hydrogen technologies - Microbial dark fermentation process in collaboration with Agharkar Research Institute, Pune, and Hydrogen generation by gasification of biomass in collaboration with Ankur Scientific Technologies Pvt Ltd. Details of the same are mentioned in Annex5.

6. The Energy and Resources Institute (TERI)

To achieve the goal of sustainability, TERI researchers explored intensively on dark fermentation process for hydrogen production with the financial assistance provided by the Department of Biotechnology, Hindustan Petroleum Corporation Limited (HPCL), Center for High Technology (CHT) of the Ministry of Petroleum and Natural gas (MoP&NG), Ministry of New and Renewable Energy (MNRE). In-depth research explorations by TERI researchers, along with the existing state of art large-scale fermentation facilities at TERI, eventually paved the way for the successful development of a pilot 1000-litre scale fermentation process for hydrogen production from sugar cane blackstrap molasses.

Considering food security issues, TERI researchers actively pursued research on hydrogen production from lignocellulosic/woody biomass. TERI researchers explored in isolation of the desired microbe that can utilize both C5 and C6 sugar for hydrogen production. A unique C5 &C6 sugar fermenting microbe was isolated at TERI. This microbe utilizes broad-spectrum C5 sugar-rich biomass samples such as woody biomass (rice straw, wheat straw, sugarcane bagasse, sorghum stover, sugarcane trash), aquatic plant, algal biofilm, and produced hydrogen with significant yield efficiency. Further process parameters were optimized to produce hydrogen through dark fermentation by this microbe from woody biomass. This process was successfully scaled up to a 150-litre scale fermenter at TERI's state of art Fermentation Technology Research Center, TERI GRAM[6].

7. CSIR - Indian Institute of Chemical Technology (IICT)

CSIR-IICT has been working on the dark fermentation process for biohydrogen production process from biogenic waste since 2005. Different wastes, like food waste, vegetable waste, distillery waste, etc., have been used as a source of carbon to produce biohydrogen. Process parameters such as selective enrichment of biocatalyst, retention time, redox microenvironment, and bioreactor configuration, which could enhance yield and hydrogen conversion efficiencies, were optimized. After years of research and overcoming all the process limitations, IICT has successfully developed and demonstrated biohydrogen technology, which can convert biodegradable waste/ wastewater with funding from MNRE. A pilot scale bioreactor with 10 m3 was designed, fabricated, and operated at IICT with abiohydrogen production capacity of 50 m3 per day Hydrogen production through a biological route[7].

8. Indian Institute of Technology, Kharagpur

IIT, Kharagpur, extensively worked on biohydrogen production via dark fermentation. Different organic wastes such as cane molasses, distillery effluent, and starchy wastewaterwereexamined as potential substrates for biohydrogen production by Enterobacter cloacae IIT-BT 08. Groundnut deoiled cake (GDOC) was considered an additional nutritional supplement to enhance biohydrogen yields. The maximum hydrogen yield of 12.2 mol H_2/ kg of COD removed was obtained using cane molasses and GDOC as co-substrates. To further ensure the reliability of the process, bench (50 L) and pilot scale (10000 L) bioreactors were customized and operated. The pilot scale study achieved 76.2 m^3 hydrogen with a COD removal and energy conversion efficiency of 18.1 kg/m^3 and 37.9%, respectively. This study provided an extensive strategy formoving from lab to pilot-scale biohydrogen production, thereby providing further opportunities for commercial exploitation[8].

In addition to above mentioned key research initiatives, multiple other research institutions/ organizations in the country are putting a lot of work intohydrogen production matters.Improve cell design for high performance and increase cell/stack robustness. A brief of the same is presented in Annex6.

Identification of the gap:Industry needs and proposed recommendations

Several of the basic research needs in hydrogen production mirror those of hydrogen storage and use. These needs are discussed in the following sections.

Catalysis

Research is needed around catalysis in all aspects of hydrogen production. Such research includes integrating molecular and heterogeneous catalysts into solar photo-electrochemical and photo-catalytic systems, interfacing biological and bio-mimetic catalysts with chemical and electrochemical systems, improving catalysts for fuel processing, and developing catalysts for use in thermal hydrogen cycles. The areas of hydrogen production and use are strongly linked through catalysis because fuel cell catalysts that are not easily poisoned by CO would enable the use of reformed hydrogen with less extensive purification.

Better fuel processing catalysts would reduce the need for separations processes that remove CO. Similarly, the development of intermediate-temperature fuel cells (200–400°C) that tolerate CO would greatly relax the requirements for fuel processing catalysts. Cost and scale considerations in hydrogen production and use call for the development of all of these next-generation catalysts from abundant raw materials.

Separations

Improved membranes and chemical separation processes are needed in fuel processing, in the separation of hydrogen and oxygen produced by photocatalysis and photosynthesis, and in the high-temperature chemical processes of thermal hydrogen production.

Interfacial Chemistry and Materials

Solar PV/photo-electrochemical and bio-mimetic hydrogen production involve electron and ion transfer at catalyst/electrolyte interfaces and present material problems like those for PEM fuel cells. Corrosion-resistant materials are needed in thermal hydrogen production. Further development of high-temperature materials is needed for thermally assisted electrolysis, like that of solid oxide fuel cells.

Theory and Modelling

Theory has a unique role in many aspects of hydrogen production, storage, and use. In hydrogen production, theory is particularly important in uncovering the mechanisms of heterogeneous, molecular, and biological catalysis, understanding the complex photo-redox processes associated with solar hydrogen production, and in modelling the chemical processes involved in hydrogen-producing thermal chemical cycles.

Life cycle assessment

India needs to undertake a comprehensive Life Cycle Analysis for the hydrogen value chain. This exercise will ascertain the real benefits/constraints of various hydrogen production, storage, and usage pathways thatcan govern the policy planning and channelization of funding support for hydrogen activities.

Key Recommendations

- Mission Mode projects
- Testing / Certification Infrastructure Augmentation
- Key national-level studies
- Fiscal support
- Governing / monitoring mechanisms
- Public Private Partnerships (PPPs)

2.4. R&D priorities: Mission Mode Projects

Projects with short-term (0 - 5 years) impact horizon/Early-Stage Research Action

The following projects are recommended for consideration

- Low PGM catalyst/ electrode development for reduced cost, improved performance, and increased durability of PEM electrolysers
- AEM electrocatalyst development with faster Oxygen Evolution Reaction (OER) kinetics and catalyst activity
- Development of SOEC electrolysers
- Development of feedstock agnostic biomass gasification technology for hydrogen production

The following table recommends performance targets & demonstration projects for the mission-mode category.

Table 1:Mission Mode projects targets

Sl. No.	Technology	Performance targets/Demonstration Projects
1	Indigenous development & scale of PEM electrolysis with	**Current Density** 2 A/cm2 @ ≤ 1.9 V 3 A/cm2 @ ≤ 1.6 V (ultimate) **Durability** 40,000 h (short term) 80,000 h (ultimate) **PGM Loading** 3 mg/cm2 (short-term) 0.5 mg/cm2 (mid term) 0.125 mg/cm2 (ultimate)
2	Solid Oxide electrolytic cell indigenization & scale – up to 25 kW(short-term) / 100 kW long-term having	**Stack Level:** i. Current Density (A/cm2@1.28 V/cell) current status: 0.6 short-term target (5 years): 1.2 ultimate target: 2.0 ii. Degradation rate(mV/kh or %/kh): Current status: 6.4 or 0.5 short-term target (5 years): 3.2 or 0.25 ultimate target- 1.6 or 0.12 iii. Lifetime (Hours) current status: 20000 short-term target (5 years): 40000 ultimate target: 80000 **Electrolyser:** i. Electrical Eff kWh/kg or %of LHV of H_2: Current status: 38 or 88% Short-term target (5 years): 36 or 93% Ultimate target: 35 or 95%
3	Biomass gasification	Development of ultra-efficient biomass gasifiers through improved reactor designs

2.5. R&D priorities: Grand Challenge Projects

Projects with a mid-term (0 - 8 years) impact horizon/ Demonstration Actions for encouraging start-ups and industries to grow

The following projects are recommended for consideration

- AEM electrolyser development
- Power to gas/co-electrolysis technology development with SOEC
- Demonstration of biomass gasification-based hydrogen generation
- Compact bio-methane reformers development for decentralized hydrogen generation
- Development of integrated net carbon-negative solutions for H_2 production in a cost-effective way through indigenous technologies

The following table recommends performance targets & demonstration projects for the grand challenge mode category.

Table 2: Grand Challenge mode project targets

Sl. No.	Technology	Performance targets/Demonstration Projects
1	CBG Reforming+CCS	Setting up 10 pilot plants for CBG reforming to green hydrogen with RE integration Parallel development of Carbon capture technology and sequestration at identified geo-locations (aquifers/basalts/EOR/coal bed methane recovery) **Deliverables:** a. Existing infrastructure of SMR can be utilized without any redundancy b.CO_2 transport and storage network c.CO_2 storage efficiency analysis d. Cost competitiveness
2	AEM electrolyser development with current	**Density** 0.8 A/cm2 @ ≤ 1.92 V& **Durability** 40,000 h (short-term) 1,00,000 h (ultimate)

Sl. No.	Technology	Performance targets/Demonstration Projects
		Cost USD350/kg **Energy** 48kWh/kg
3	Intermediate temperature co-electrolysis of CO_2 & H_2O	Current status: 750-950 ^oC Target: 500-650 ^oC
4	Power to X	1.RE power integrated with intermediate/high-temperature Co-electrolysis for syngas/Green ammonia/Green methanol synthesis Deliverables: a.Optimisation of process conditions and indigenization of reactor design b.Techno-economic assessment of integrated system 2.Demonstration of SOEC integrated with solar thermal technologies
5	Electrolyser scale-up	1.Setting up of small-scale manufacturing plants for electrolyser components with an aim to scale-up in the near future 2.Development of small-scale mobile hydrogen generators for futuristic applications.
6	PEM electrolysis	PEM stack development with optimised PGM loading at par with DOE technical targets (5kW/10kW/50kW)
7	AEM electrolysis	AEM stack development with high membrane durability (5kW/10kW/50kW)
8	RE powered electrolysers	1.Demonstration of Solar PV powered electrolyser operation 2.Development of efficient rectifiers & electronic controllers for the operation of electrolysers on dual inputs- solar & grid
9	Fuel cell demonstration projects	1. Fuel cell (small capacity0.25kW-1.25kW) vehicle (H_2-bicycle, L1 & L2 category vehicles): • Development of indigenous PEM Fuel cell stack & BOP

Sl. No.	Technology	Performance targets/Demonstration Projects
		• Pilot-level demonstrationof Prototypes for standardization • Demonstration and wide-scale trials of hydrogen e-bikes (1000 Nos) 2. Range Extenders (Capacity up to 5kW for category M & M1 vehicles) • Development of indigenous PEM stack & Fuel cell system as a range extender forelectric vehicle • Pilot level demonstration, Validation for standardization purposes (50 Nos) 3. Development of Fuel cell stack/systems for Category M3 &N Vehicles • Development of indigenous stack, BOP components & Fuel cell system and its hybridization for Fuel cell electric vehicle • Pilot-level demonstrations and wide-scale trials, Validation for standardization purposes (50 Nos) • Introduction of fuel cell vehicles in inter/intra city passenger transport 4. Development of Fuel cell stack/systems for Group 1 (small capacity: 1200 ft range) and Group 2 (medium 3500 ft range) Unmanned Aerial vehicle (UAV) • Development of indigenous PEM Fuel cell stack, BOP &system for UAV • Pilot level demonstration, Validation for standardization purpose – 50 Nos

2.6. R&D priorities: Blue Sky Projects

Projects having a long-term (0 - 15 years) horizon would be taken up with a focus on establishing global IP and competitive advantage for the Indian industry.

The following projects are recommended for consideration

- Sea water electrolysis for hydrogen production
- Photo electrochemical water splitting
- Thermochemical water splitting and integration with nuclear/ solar heat source
- Microbial electrolysis system for hydrogen production
- Novel technologies for the conversion of biomass to hydrogen

- Bio-methane pyrolysis for hydrogen production
- Waste to hydrogen

The following table recommends performance targets & demonstration projects for the blue-sky mode category.

Table 3: Blue Sky Projects targets

Sl. No.	Technology	Performance targets/Demonstration Projects
1	Sea water electrolysis technology development	**Current density:** 0.5A/cm2 @1.7V **Activation Overpotential:** 1.5V @ 10mA/cm2 **Durability:** 5,000 h
2	Reversible fuel cell/ electrolyser technology development targets	FC efficiency @ 0.5A/cm2: 80% (ultimate 90%) Electrolyser efficiency @ 1A/cm2: 80% (ultimate 90%) % degradation %/1000 h: <1.5 (ultimate 0.125)
3	Photo – electrochemical splitting of water	Cost USD5.7 per kg (ultimate USD2.1 per kg) Solar to hydrogen conversion ratio 20 % (ultimate 25%) PEC electrode cost: USD 200 per m^2 (ultimate USD 100 per m^2) Electrode replacement time: 2 years (ultimate 10) 1.Mid-scale PEC system development for house-hold application (1kg/d H_2) 2. Development of small-scale mobile hydrogen generators for futuristic applications.
4	Thermochemical cycles	Solar-driven thermochemical cycle hydrogen cost: USD3.7 per kg (ultimate USD2 per kg) Solar to Hydrogen conversion efficiency: 20% (ultimate 26%)

Chapter 3: Hydrogen Storage

3.1. Introduction

Hydrogen has the highest energy per unit mass of any fuel; however, its low-density results in a low energy per unit volume. Therefore, the storage of hydrogen at high volumetric density is considered a critical enabling technology for the successful commercialization of hydrogen-based energy applications, including stationary power, portable power, and transportation. Hydrogen may be stored in the physical form under high pressure at ambient or sub-ambient temperatures or as a cryogenic liquid near its normal boiling point of 20 K. Additionally, hydrogen may be stored as bonded to other elements as in hydrogen compounds or adsorbed as the diatomic molecule in porous solids [1]. Large-scale and long-term storage can be achieved through underground storage in various geological structures like salt caverns, depleted oil and gas reservoirs, and aquifers. However, if the requirement is to store small quantities and for a shorter duration, either liquified, compressed or solid-state storage can be the choice. Each of these methods has its advantages and disadvantages.

The different methods used for hydrogen storage are compressed gas form, liquid hydrogen, and material-based hydrogen storage, i.e., MOF, hydrides, etc. Figure 2:depicts different methods of hydrogen storage, and the following one shows a comparison of different Hydrogen storage methods. Annex7 dives deeper into the above-mentioned methods and their benefits and challenges.

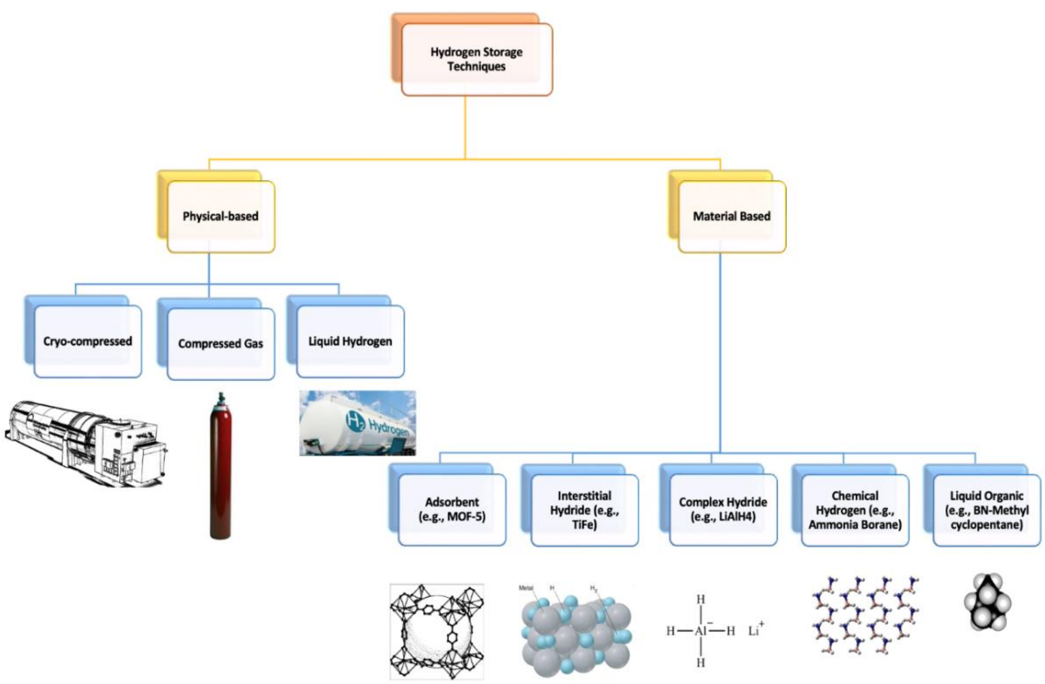

Figure 2:Different Methods of Hydrogen storage [1]

Technique	Gravimetric Capacity (wt%)	Volumetric Capacity (MJ/l | kWh/l)	Operational Pressure (bar)	Operational Temperature (K)
Metal Hydrides	7.6	13.2 | 3.66	20	260-425
MOFs	4.5	7.2 | 2.0	20-100	78
Cryo-compressed	5.4	4.0 | 1.11	300	40-80
LOHC	8.5	7 | 1.94	0	293
Chemical	15.5	11.5 | 3.2	10	298
Liquid	7.5	6.4 | 1.78	0	20
Carbon Nano-structures	20	5.0 | 1.39	100	298
Metal Borohydrides	14.9-18.5	9.8-17.6 | 2.72-4.88	105	130
Kubas-type	10.5	23.6 | 6.55	120	293

Table3: Comparison of different Hydrogen storage methods

3.2. Objectives

- Develop efficient, safe, and cost-effective hydrogen storage methods that enable high-density storage, reduce leakage, and allow for easy and quick refuelling.
- Ensure the long-term durability and reliability of hydrogen storage, transportation, and compression systems to promote their widespread adoption.
- To demonstrate distributed aboveground storage solutions available at a capital cost lower than INR 30,000 /kg by 2030.
- To undertake research activities on underground storage to validate the performance in different geologies, to identify better and more cost-effective materials and to encourage improved designs.
- Demonstrate the large-scale underground storage across various media at a capital cost lower than INR 3000 /kg by 2030.
- Indigenous development of Type III and Type IV compressed hydrogen tanks.
- Developing test facilities for testing of compressed hydrogen tanks.
- Indigenous synthesis of alloys or materials used for solid-state hydrogen storage.
- Materials development with high gravimetric capacity, faster kinetics, the optimum set of operating conditions, low cost, and high cycle life.
- Search for novel materials which could satisfy the above-mentioned conditions like high surface area materials, complex or chemical hydrides, high entropy alloys, composites etc.
- Indigenous development of solid-state materials-based hydrogen storage canisters/tanks includes fabrication and materials synthesis, all being done indigenously.

- ❖ Demonstration of these tanks on a pilot scale for various stationary applications like heating & cooling, hydrogen purification, hydrogen compressors, thermal energy storage, heat transformer, and backup power.
- ❖ Demonstration of solid-state hydrogen storage tanks for vehicular applications in the beginning for the long haul & large distance transport, freight vehicles, train, mining equipment, submarines, forklifts, construction equipment etc.
- ❖ Better materials having low weight and high-capacity demonstration of solid-state storage canisters for various other vehicles for public and private transport applications.
- ❖ Address safety concerns related to hydrogen storage, transportation, and compression. Develop robust safety protocols, standards, and technologies to prevent leaks, mitigate risks, and handle potential hazards associated with hydrogen.
- ❖ Increasing the scale of deployment & thus, widespread use for both stationary and vehicular applications.

3.3. National and international R&D activities

International R&D in Underground Storage Projects:

Hydrogen storage in salt caverns is already used in the United States, Britain, and Germany. The walls of a salt cavern are stable and impervious to gas over the lifespan of the storage facility. The unit physical volume of salt caverns typically ranges from 100,000 to 1,000,000 m3, and, depending on the cavern depth, the corresponding working gas volume may range from a few million to 100 million st-m3.

Figure 3:a). H_2 Storage in a salt cavern, b). H_2 storage in rock cavern (Source: Google)

From a practical viewpoint, the salt cavern storage solution is highly flexible in terms of storage volume and in terms of modularity since several caverns can be reached on a single site to adapt the overall storage capacity to changes in demand. Several examples of hydrogen mixtures and pure hydrogen stored underground are given intable 4.

Table 4: Underground storage of hydrogen in Salt cavern worldwide

	Type	% H_2	*P*, T	Depth (m)
Bad Lauchstadt, Germany	Salt cavern		150 bars	820
Kiel, Germany	Salt cavern	60-64	80-100 bars	1330
Teesside, UK	Salt cavern	95	50 bars	400
Texas: Air Liquid, USA	Salt cavern	95		
Texas: ConocoPhillips, USA	Salt cavern	95		850
Texas: Praxair, USA	Salt cavern			
Beynes, France	Aquifer	50		430
Ketzin, Germany	Aquifer	62		200-250
Lobodice, Czech	Aquifer	50	90 bars, 34 ^{o}C	430
Diadema, Argentina	Natural Gas	10	10 bars, 50 ^{o}C	600

National R&D in Underground Storage Projects

The salt cavern site at Bikaner can be studied for its feasibility of storing hydrogen. Besides this, new sites need to be identified and studied thoroughly. Some experimental and demonstration sites need to be prepared and studied so that these can be used to understand the implications, contaminants in due course, and challenges in storing hydrogen in such underground geological structures. These smaller units can act as case studies for gaining more knowledge about using underground structures.

Studies conducted include:

1. India Hydrogen Alliance, IH2A[15], a member-driven coalition without a legal entity, led by a steering group and work group led by chart industries, is also said to be working on the hydrogen storage and transport aspect of the green hydrogen value chain.
2. Further, as per a report published by the Department of Science and technology[5,] many Indian institutes and organizations are working on Hydrogen storage in India.

Reports of some other studies that were conducted had the following observations:

3. In a publication of the Geological Society of London[16], the potential of geological hydrogen storage in India is predicted to be up to 22 610 terawatt-hours (TWh) in deep saline aquifers. The report further states that the major Indian sedimentary basins, such as the Mumbai offshore, Krishna–Godavari, Rajasthan, Cauvery and Cambay basins, have high storage capacities for hydrogen on the order of 2163, 1788.8, 1211.5, 1666.6 and 342.9 TWh, respectively.
4. A study of underground hydrogen storage conducted by Rajeev Upadhyay et al.[17] assesses the possibility of hydrogen storage in India. As per the report, there are several depleted gas fields in India, and one such field is inthe Tapti daman formation.
5. The Energy and Resources Institute (TERI)[18], in their report "The Potential Role of Hydrogen in India", however, stated that it is unlikely that India has sufficient suitable salt deposits for this to be an option for large-scale Hydrogen storage.

National and International R&D in Metal Hydride Storage Projects

1. Metal Hydride storage system in electric forklift (STILL Gmbh) equipped with fuel cell power module from Plug Power Inc. has been demonstrated by HySA system Competence Centre, South Africa. Materials-based systems like compressors at hydrogen refuelling stations and systems to propel two and three-wheelers developed at HySA.
2. Demonstration of Metal hydride in 2-wheeler at BHU, India, by Prof. Srivastava
3. Vehicle projects LLC demonstrated the world's first fuel cell-powered locomotive – which safely stored hydrogen fuel as a reversible metal hydride[23].

Vehicle projects LLC and its technical consortium developed a 160-kW battery-fuel cell hybrid mine loader (LHD). Hydrogen fuel was stored in a reversible metal-hydride system capable of storing 14 kg of hydrogen [23].

Fuel cell power plants, including reversible metal-hydride storage, for multiple 10-ton mining locomotives and a dozer, were manufactured by Vehicle projects LLC for demonstration in a South African platinum mine [23].

4. Metal hydrides-based system developed by ECD Ovonics and integrated with ICE-based three-wheeler displayed in SAE annual convention [25]
5. Sandia National Laboratory developed the solid-state hydrogen material database under USDOE. The development of AB_2-type metal hydride-based hydrogen storage to power mining locomotives along with various other stakeholders and its implementation in underground mining was carried out in the year 2002.

6. Toyota Motor Corporation used a BCC alloy-based hybrid storage system capable of storing 2 kg hydrogen to propel a car up to a range of 250 km with a maximum speed of 100 kmph [26]
7. Westinghouse Savannah River Company worked on the development, manufacturing, and testing of the world's first hybrid hydrogen-electric transit bus, also called as Savannah River Bus Project, funded by USDOE.
8. National Renewable Energy Laboratory (NREL), USA, has developed different mathematical and statistical models for technological and economic assessment of various aspects of the hydrogen supply chain. NREL has a Hydrogen Infrastructure Testing and Research facility, which consists of a test facility to assess the feasibility of hydrogen storage, compression, and testing capabilities for various applications.

National R&D in solid-state hydrogen storage

Some of the research work being carried out at different institutions in the area of solid-state hydrogen storage in India is summarized below:

A lot of work has been carried out at IIT Bombay on materials for hydrogen storage. Various materials, including different metal hydrides, complex and chemical hydrides (catalyst and support, reversibility), solid solutions, high entropy alloys and LOHC, are being studied. Metal hydride-based systems simulation, design, and optimization of geometric and performance parameters, followed by the development, i.e., fabrication and their performance analysis experimentally, are being carried out at IIT Bombay. In addition, the Hydrogen Energy Centre, instituted which was established at Banaras Hindu University, supported with the funding of MNRE funds,and had several pioneer works in the field of solid-state storage. In BARC, a variety of materials which include main group elements, transition metals/alloys, porous carbon, carbon nanotubes etc., were investigated in detail to develop efficient technologies for storing hydrogen. A large number of metals hydride-based applications have been demonstrated at IIT Guwahati, IIT Mumbai and IIT Tirupati, IIT Madras, IIT Delhi, BARC etc. Details of these activities aredepicted in Annex8.

R&D in MOF materials:

- EcoFuel Asia Tour (in 2007): Volkswagen Caddy EcoFuel car was optimized for natural gas combustion and used MOF-enhanced fuel tanks (sponsored by BASF- Basolite C300 (HKUST-1)).
- BASF has registered prototypes for gas storage (BASOCUBE™ and BASOSTOR™), which have also been studied for hydrogen storage.
- Two patents filed by Ford Global Technologies named: “Hydrogen Storage Materials” (US20110142752A1)211 and “Hydrogen Storage Systems and Method using the same” (US20110142750A1)

Mercedes-Benz: Mercedes-Benz F125® (research) vehicle used hydrogen stored in MOFs.

In all instances, the industrial implementation has been delayed due to technical barriers such as system weight, volume, cost, efficiency and durability.

R&D in Advance/Novel Materials:

In the context of novel materials, the key aspects being looked into arecost-effectiveness and ease of scalable production. Keeping this in view, the focus on research can be the following.

- Mg and Mg-based systems wherein nanoscale can be produced and retained (in service)
- Carbonaceous materials doped with elements can increase the enthalpy of adsorption and invoke spillover mechanism and Kubas interaction. Also, explore Si-based nanostructures.
- System-level hybrid storage methods, wherein the material is filled in a gas cylinder and where the overall storage is enhanced at lower pressures (<50 bar).

Indian Institutes/industry initiatives:

Indian Oil R&D Centre is actively working across the Hydrogen value chain (production, storage, application) and has taken several initiatives to promote hydrogen for automotive and stationary applications in India. Indian Oil R&D Centre, along with IIT Kharagpur, has successfully indigenously designed and developed ~60 L Water capacity Type 3 composite cylinder for storage of compressed Hydrogen gas at 350 bar pressure.

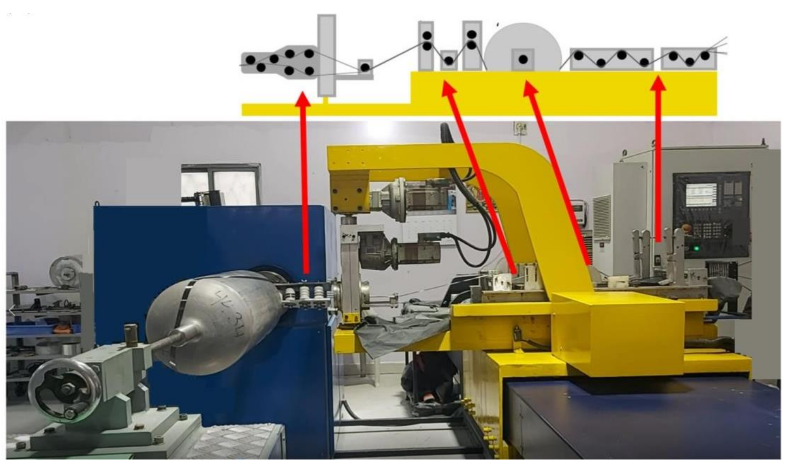

Figure *4*: Filament winding machine

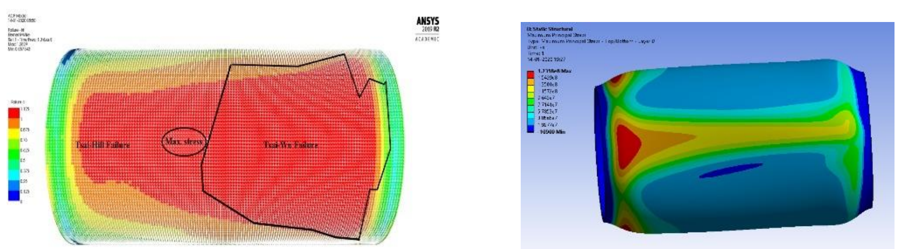

Figure 5: FEM Simulation results of Type III composite Cylinder

For the composite overwrap, carbon fibre, T700, is used as the reinforcement material, whereas epoxy resin, LY556, along with hardener XY54,isused as the matrix material. The cylinder is fitted with a PRD valve HTV350 pressure regulators rated 350 bars and an end seal with TPRD Plug. The design of the cylinders is determined by simulating the burst pressure using an FEA Software, namely ANSYS Mechanical. The feasible winding angles, optimized tension, bandwidth, and fibre winding paths are determined by performing dry and wet trials. About twenty prototypes were manufactured as per the design, materials, and manufacturing technology developed.

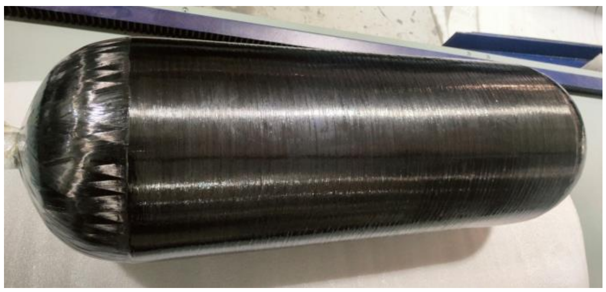

Figure *6*: Fabricated Type 3 composite Cylinder prototype by Indian Oil

The prototype has successfully passed the critical hydrostatic pressure burst and ambient temperature pressure cycling tests as per ISO 15869.

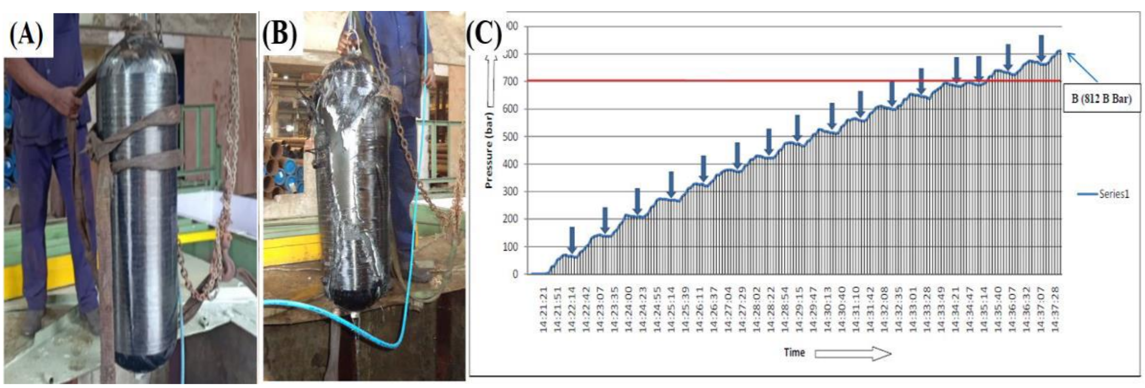

Figure *7*: The prototype of Indian Oil (A) before testing, (B) after burst testing, and (C) pressure

It is anticipated that the entire test conducted will meet the requirement of ISO 15869 and, with this cylinder, will be ready for certification for commercialization as a hydrogen storage vessel.

Initiatives of academic institutes and other organizations in India

The DST – IIT Bombay Energy Storage Platform on Hydrogen has been established with a focus towards the selection, synthesis, and characterization of Metal Hydrides (MH) and other novel materials. It also will be dealing withthe fabrication of MH-based fast reaction beds and testing the performances of various MH thermal management systems for various applications.

The lead organization is IIT Bombay, with four consorting institutions - IIT Guwahati, IIT Kanpur, IIT Tirupati, and NIT Rourkela.

Synthesis of metal hydrides on a large scale, synthesis from industrial grade materials, effect of impurities, metal hydride-based systems simulation, design, development, and their performance analysis are being carried out at IIT Bombay. Metal hydride canisters for various applications are being developed at IIT Bombay.

DST has established the DST- NFTDC Energy Storage Platform on Hydrogen at the Nonferrous Materials Technology Development Centre, Hyderabad, with a core theme of Hydrogen based materials to Energy Devices. TheCentreencompasses scientists from IISc Bangalore, IIT Madras, IIT Bhubaneswar, and Sri Chitra Thirunal College of Engineering, Thiruvananthapuram.

DST-IIT Hyderabad Integrated Clean Energy Material Acceleration Platform on Bioenergy and Hydrogen was recently supported by DST to develop a biomass to H_2 production pilot plant (25 Kg size) that will primarily be operational under thermochemical conditions with an appropriate H_2 storage unit. Additionally, this system will be connected to bio electrochemical and photocatalytic units for improved H_2 production.

Department of Science & Technology (DST) has also initiated the Advanced Hydrogen and Fuel Cell program, which is in line with the National Green Hydrogen Mission and Make in India with an objective to promote and support activities related to the indigenous development of new and existing material in large quantities, catalysts, membrane, components for fuel cells, electrolysers, hydrogen storage materials, materials for type IV cylinders and prototypes for implementation of various applications of hydrogen and fuel cell in the country.

Identification of the gap: Industry needs and proposed recommendations

The needsfora hydrogen systemvary w.r.t. stationary and vehicular applications. For the transportation sector, the weight and size should be low, refuelling should be fast, and the hydrogen storage system should have most of the characteristics which current fossil fuel vehicles have, like range, passenger space, safety, cost, acceleration/deceleration, start and stop, refuelling time, life, and cost etc. Development of high-pressure Hydrogen compressor may be identified as a gap to be addressed since high-pressure compressors are not available from Indian manufacturers. There are several challenges towards storing hydrogen and achieving the above-mentioned criteria.

I. Compressed storage

FCEVs rely on compressed hydrogen. Common fuel cell vehicles like Honda Clarity and Toyota Mirai have pressurized composite vessel-based storage. Most of the composite cylinders currently being used in India are imported and hence are very expensive. Indian Oil R&D has already made significant progress in this direction through the first indigenous development of Type 3 composite cylinders. As per Indian Oil, if the Type 3 composite cylinders are developed and manufactured in India, the cost of these cylinders isexpected to reduce dramatically.

The following are the challenges in the manufacturing of Type 3 composite cylinders in India.

a. **Non-availability of raw materials in India**
   - **Liner**: Aluminium alloy liners used in Type 3 composite cylinders are mostly imported as there are no manufacturing facilities forliners in India. As per the study of IOCL, the liner constitutes around 30-35 % of the cost of the cylinder if imported. If the liner can be developed and manufactured in India, then the cost of the liner can be brought down significantly.
   - **Carbon Fibre**:There areno manufacturing facilities forCarbon fibre in India, and it is mostly imported, hence costly. As per the study of IOCL, carbon fibre constitutes around 20-25 % ofthe cost of a cylinder if imported. If carbon fibre can be developed and manufactured in India,then the cost can be brought down significantly.
   - **High-pressure TPRD valves:**There is currently no manufacturer of high-pressure hydrogen valves in India, and the imported ones are costly. As per the study of IOCL, the valves constitutemost of the cost (40-45 % ofthe cost of the cylinder). This is one of the major bottlenecks in bringing down the cost of the cylinder.

b. **Non-availability of testing facilities as per ISO 15869 and other international standards**

   As per ISO, the developed composite cylinders are required to go through a comprehensive set of tests (Table 5) as per ISO 15869. Such type of testing facilities is not available in India, so the composite cylinders developed in India are mostly sent to USA or Europe for testing. This results in a delay in the overall development cycle of composite cylinders and ultimately results in increasing the overall developmental cost.

Table 5: Cylinder testing requirement as per ISO 15869

Sr. No	Test	Applicable to Type	
		Type 3	Type 4
1	Material Tests for Metal Fuel Tanks and Liners	✓	✓
2	Material test for plastic liners		✓
3	Resin Properties	✓	✓
4	Hydrostatic Burst Pressure Test	✓	✓
5	Ambient Temperature Pressure Cycling	✓	✓
6	Leak-before-break (LBB) Test	✓	✓
7	Bonfire Test	✓	✓

Sr. No	Test	Applicable to Type	
		Type 3	Type 4
8	Penetration Test	✓	✓
9	Chemical Exposure Test	✓	✓
10	Composite Flaw Tolerance Test	✓	✓
11	Accelerated Stress Rupture Test	✓	✓
12	Extreme Temperature Pressure Cycling test	✓	✓
13	Impact Damage Test	✓	✓
14	Permeation test		✓
15	Boss Torque		✓
16	Hydrogen gas cycling		✓

c. **Non-availability of regulations and standards** -Presently, regulations and standards for the development and deployment of hydrogen at high pressure are not available in India. Government and industry should work together to formulate and implement regulations for certification and recertification before the large-scale deployment of hydrogen in India.

For reference, the activities undertaken by BHEL, a PSU under MHI, for the development, manufacturing, and testing of Type-IV cylinders may be mentioned. A reference text is mentioned below:

BHEL has started developing Type-IV hydrogen and CNG cylinders and is making good progress. BHEL intends to set up dedicated CoEs for the development of Type-IV Cylinders, a national testing facility for Type-IV cylinders, and a manufacturing facility in the country.

II. Materials based storage

a. Non-availability of raw materials

Metals required for the synthesis of alloys are either not available in India and are usually imported from China, or else the materials cost for those available in the country is high. Since most of the demonstrations and materials used were carried out with rare earth type, as such it is required to use elements abundantly available in India.

- As the purity of the material increases, its cost increases, so in order to reduce the cost, industrial-grade raw materials can be used to synthesize alloys. Modifications or ways to prevent degradation of performance with such low-cost materials can be studied.

- Large-scale materials, which could be either absorption or adsorption based, need to be synthesized indigenously. The requirement is to develop centralised facilities for scaling up such high-performing materials in the country
- Non-availability of infrastructure for canisters fabrication is another bottleneck.

The economies of scale will work very well when the metal hydride-based canisters are fabricated in large numbers. But currently, in India, such fabrication facilities are not there.

3.4. R&D priorities: Mission Mode Projects

Projects with short-term (0 - 5 years) impact horizon/Early-Stage Research Action

1. Development of materials which could have 4-5 wt% of storage at close to ambient temperature and moderate pressure conditions, with fast de/hydrogenation and good cyclability
2. Cost reduction of the alloys with the use of abundant elements available in the country to synthesize alloys and using industrial-grade materials
3. Indigenous manufacturing of materials-based hydrogen storage canisters and demonstration for various applications
4. Use of AI/ML to find the high performing materials and optimised canister designs to reduce the cost and time in experimentation and development
5. Demonstration of developed materials and systems where weight is not a concern, the rather higher volumetric density of materials-based storage is an advantage and canisters can be used for applications like submarines, construction equipment, mining vehicles, forklifts, freight vehicles or stationary applications like heating & cooling, thermal energy storage, hydrogen compression and purification etc.
6. Indigenous manufacturing of type III tanks
7. Standards and regulations for compressed hydrogen tanks and material-based storage tanks

3.5. R&D priorities: Grand Challenge Projects

Projects with a mid-term (0 - 8 years) impact horizon/ Demonstration Actionsfor encouraging startups and industries to grow

1. Facilities and infrastructure development for the upscaled synthesis of these alloys and materials indigenously
2. Start-ups and Industries can come up with facilities for manufacturing solid-state hydrogen storage canisters
3. Manufacturing of these canisters in large numbers enables commercialization and, in turn, get benefitted with economies of scale
4. Methods to reduce boil-off losses and use the hydrogen which else is lost due to boil-off in case of liquid state storage
5. Manufacturing of liner, carbon fibre, valves and TPD for type III and type IV tanks
6. Indigenous manufacturing of type IV tanks

3.6. R&D priorities: Blue Sky Projects

Projects having a long-term (0 - 15 years) horizon would be taken up with a focus on establishing global IP and competitive advantage for the Indian industry.

1. Research on novel materials, which could give higher gravimetric capacity, reduced cost and weight and have faster kinetics and good reversibility
2. Large-scale deployment of materials-based hydrogen storage systems for industries, domestic and rural areas for both stationary and vehicular applications
3. Better and high-strength materials for compressed hydrogen tanks, which could be cost-effective
4. Indigenous manufacturing of type V tanks with all components manufactured in India
5. Indigenous manufacturing of Type IV cylinders
6. National testing facility for Type IV cylinders

During the transition period, applications which are niche markets, such as urban buses, forklifts, trucks, and stationary applications, can be considered. For India, the transition to hydrogen and fuel cells may happen in cascading steps along 6 major heads: Technology development, Demonstration programs, Capacity building and Applied Research, Fundamental research, and Policy Framework. The broad lines under each pillar of change are discussed below:

Table 6: Mission Mode activities

1.	**Technology development**	
	a. Liner for composite cylinder	Indigenous development for cost reduction and economic viability
	b. Carbon fibre	Indigenous development for cost reduction and economic viability
	c. Valve, TPRD	To develop high-pressure valves and TPRD in a cost-effective way through indigenous technologies
	d. Materials-based storage canisters	Research on Materials for canister construction Indigenous development of hydrogen storage canisters
2.	**Demonstration**	
	a. One pilot project for mobility application	Composite cylinder manufacturers and OEM/vehicle manufacturers are required to work together for the demonstration and use of the developed composite cylinders in the vehicles, as it will also add awareness and address safety issues related to the use of the systems.
	b. One pilot project for stationary/mobility application with materials-based storage	Hydrogen storage canisters at some places have reached higher TRL levels of 5-7;these need to be taken up for demonstration for applications like purification, hydrogen compressors, backup power and mobility applications.
3.	**Capacity building by 2025**	
	Augmenting the storage and supply chain infrastructure at the identified location	Developing the ecosystem for composite cylinders through CNG vehicle
		Proof concepts and demonstrations with metal hydride-based canisters
4.	**Applied research**	
	Pipeline metallurgy compatible withH_2 + NG and neat H_2 Transportation	Critical data to be generated for preparing a long-term roadmap

5.	**Fundamental / Academic Research**	
	Development of advanced material for liner, fibre	Innovative research using material chemistry
	Indigenous development of composite cylinder for 700 bar applications	Higher volume cylinders, i.e., 200-450 Litre, suitable for heavy-duty vehicles
	Development of inexpensive materials with high capacity from abundant elements	Development of metal hydrides-based canisters for various stationary and vehicular applications
6.	**Policy / Regulation / statutory**	
	Incentives for raw materials of cylinder	Taxation / fiscal benefits on localized manufacturing of raw materials, i.e., liner, carbon fibre, valve etc.
	Incentivization mechanism for local manufacturing of cylinders	Accelerating the ecosystem for indigenous manufacturing of components/sub-components related to the H_2 storage system
	Taxes on hydrogen	Evolving mechanisms for taxing H_2 cylinders from different types of cylinders

Table 7:Roadmap for R&D on Hydrogen Storage

Short-term (2025)

- Indigenous development and manufacturing of composite cylinders
- Type 3-cylinder manufacturing for H_2 and CNG storage at 350 bars
- Demonstration trial of the composite cylinder in vehicles in collaboration with OEMs
- Demonstration trial of metal hydride-based canisters in vehicles in collaboration with OEMs
- Demonstration trial of metal hydride-based canisters for backup power
- Development of India-specific codes and standards for Hydrogen storage and safety (BIS / TERI / ARAI / PESO)
- Type IV cylinder manufacturing for H_2 and CNG storage.
- National testing facility for Type IV cylinders

Medium-term (2030)

- Indigenization of raw materials –Liner, carbon fibre, TPRD Valve for composite cylinder
- To set up a facility for manufacturing composite cylinders (up to 700 bar)
- Creation of a testing facility for Hydrogen/CNG cylinders as per ISO standards (up

to 700 bar)

- To ensure commercial availability of composite cylinders made in India
- Indigenization of H_2 storage cylinder to store H_2 at 700 bars (Type 3 and Type 4).
- To set up facilities for large-scale materials synthesis, canisters fabrication and scaling up those canisters for higher capacities of storage
- Development of 2 model cities to promote the concept of an H_2 economy

Long-term (2050)

- Ensuring a mature H_2 market for fuel cell grade H_2 for a target price of USD 2-3 per kg (delivered).
- High-pressure Type I metal tanks up to 1000 bar for bulk storage of hydrogen
- Development of matured H_2 ecosystem with applications in a variety of sectors, including stationary, automotive, shipping, aviation, steel, and railways etc
- Linking the agrarian economy with various bio-H_2 production pathways
- Wide deployment of solid-state hydrogen storage canisters for domestic purification in refineries, light and heavy-duty vehicles, and various places in the hydrogen ecosystem
- Development of Type-V cylinders.

Chapter 4: Hydrogen Transport

4.1. Introduction

Hydrogen can be transported either in gaseous, liquid or solid form. Gaseous hydrogen transportation involves moving compressed hydrogen in pipelines or in tanks/cylinders. Hydrogen can be blended in natural gas pipelines or transported in hydrogen-only pipelines. Similarly, hydrogen cylinders are classified into five categories depending on the operating pressure. Hydrogen can also be liquefied and transported in cryogenic containers. Hydrogen can also be transported under ambient pressure and temperature in liquid organic hydrogen carriers (LOHCs). LOHCs are organic compounds that can absorb and release hydrogen during chemical reactions. Todate, only LOHC or Green ammonia are being considered as possible carriers. It is to be noted that only around 18% of Hydrogen is transported in ammonia, and in LOHC, organic liquor needs to be transported back to the place of the Hydrogen source. Based on the studies conducted so far, the cost of Hydrogen may become nearly 2-3 times more, and thereafter cracking of the same ishighly energy sensitive. Moreover, these may not be applicable for inland transportation within the country. The creation of hydrogen clusters near hydrogen utilization centres may eliminate transportation issues.

Hydrogen can also be adsorbed over metal hydride and transported. Hydrogen is released from metal hydride by desorption. Hydrogen can be converted into methanol, ammonia, or synthetic natural gas (SNG) and transported by using existing infrastructure. These fuels and chemicals can then be reconverted into green hydrogen by dehydrogenation processes like reforming.

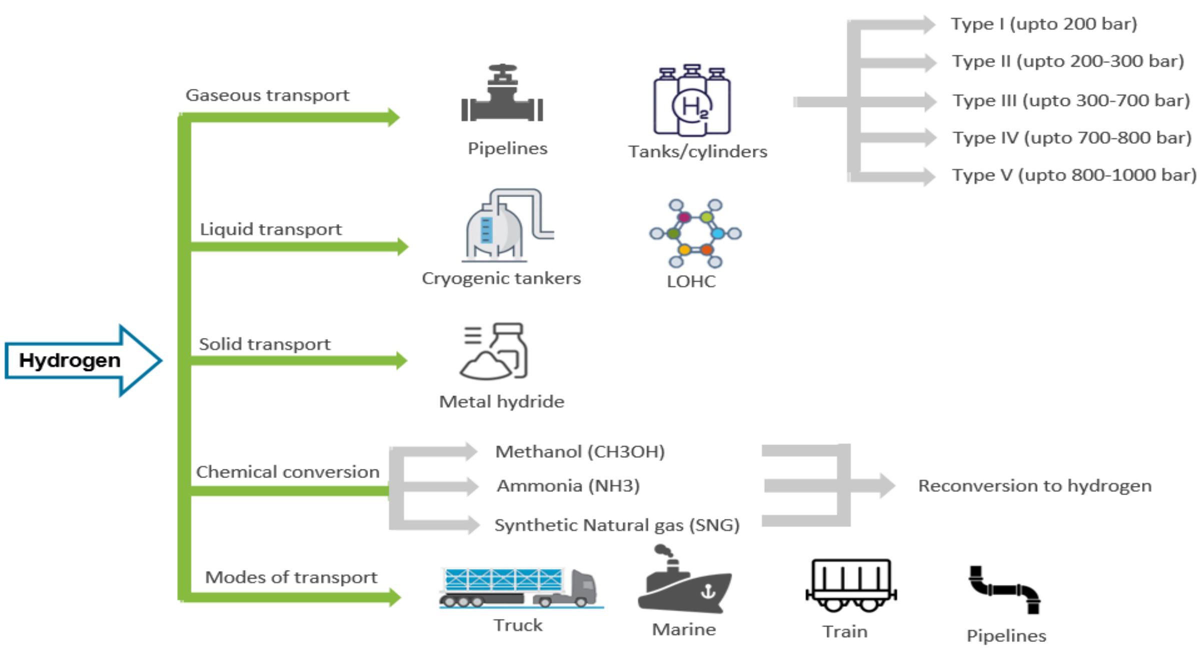

Figure 8: Pathways for hydrogen transport

Hydrogen can be locally transported in tube trailers and trains. Transportation of large quantities of hydrogen over long distances can be done in pipelines. The intercontinental movement of green hydrogen and its derivatives is possible through marine transportation. It should be noted that marine transportation of hydrogen would also need the development of necessary infrastructure at ports. Solid-state transport of hydrogen is not covered in this report since it will be exhaustively discussed in sub-committee II (hydrogen storage).

Marine transport of hydrogen

Shipping is one of the most energy-efficient ways for the transportation of goods. If hydrogen is cryogenically cooled to -253°C, it changes phase from a gaseous state (GH_2) to a liquid state (LH_2), shrinking to 1/800 of its original volume. This reduction in volume allows for the transport of larger energy densities, and consequently, transportation efficiency increases dramatically.

Hydrogen-propelled trains

Hydrogen fuel cell-based rail propulsion technologies powered by PEMFC (proton exchange membrane-based Fuel Cell) along with proportionally sized battery storage systems are being tested across the world. In order to further the cause of decarbonisation in the railway sector, Indian Railways plans to convert the existing 1600 hp DEMU 10-car configuration into a hybrid fuel cell and battery-based distributed power rolling stock (DPRS) with regenerative braking[1]. These futuristic systems are currently in the development phase and are expected to be ready for demonstration in the near future.

Types of cylinders for hydrogen transport

Hydrogen can be stored in many types of pressure vessels, namely type I, II, III and IV tanks. As shown in Figure 10, pressure vessels are classified based on the materials used in their manufacturing. Type I tanks are made of metal, Type II tanks are made of a thick metallic liner hoop wrapped with a fibre-resin composite, Type III tanks are made of a metallic liner fully wrapped with a fibre-resin composite and Type IV tanks are made of polymeric liners fullywrapped with a fibre-resin composite.

Figure 9: Types of cylinders

4.2. Objective

- To increase the efficiency and reduce the costs of hydrogen liquefaction technologies.
- To contribute to the upcoming generation of liquefaction technology for new hydrogen production plants.
- To keep up with the existing research on carrier cycling performance, chemistries, catalysis and reactors with the potential for enhanced roundtrip efficacy and life cycle assessment.
- Build hydrogen carriers for commercial usage to transport and store hydrogen while improving their roundtrip productivity and reducingcosts.
- To strengthen the pressure and capacity for new builds of 100% hydrogen pipelines while reducing their cost.
- To decrease road transport costs of compressed hydrogen by increasing the capacity of tube trailers.
- To enhance the efficiency of road transport of liquid hydrogen while reducing costs.
- To enable scale-up for shipping solutions of bulk liquid hydrogen and its commercialisation.

4.3. National and international R&D activities

The sub-committee evaluated the following existing compendium on research and development (R&D) in hydrogen in India.

- India country report on hydrogen and fuel cell[2]
- Compendium on hydrogen and fuel cell[3]

While hydrogen storage is a well-researched area, it was found that very little progress has been made on the transportation of hydrogen in India.

Table 8shows a comparison of the research status on hydrogen transportation in India and globally and summarises the key technological developments in India and the world for hydrogen transport. In general, it is seen that hydrogen movement in pipelines, tube trailers and marine transportation is at a commercial scale globally. In India, pilots are planned for hydrogen blending in natural gas pipelines, while hydrogen transport in cylinders is limited to Type I and II due to a lack of safety-related permissions from the concerned agencies.

Ammonia and methanol production from green hydrogen are already demonstrated on a commercial scale around the world. In India, there is a pilot plant for producing ammonia, while a demonstration plant is in progress. On LOHCs, a commercial scale operation involving transporting LOHCs over 4000 km has been demonstrated in Japan[4]. There is a lab-scale demonstration of LOHCs in India, and industry research is in the early phase.

Methanol conversion to hydrogen is a commercially available technology, but the conversion of ammonia to hydrogen and dehydrogenation to extract hydrogen from LOHCs is at a relatively nascent stage. India can be a first mover in this space to develop technologies for commercialisation.

Table 8: Summary of technology developments for hydrogen transport

Technology	Technology readiness	Brief Summary
Hydrogen transport		
Pipelines	Global: Commercial scale	Pipeline-based gaseous hydrogen transport is an approved approach. There is roughly 2570 km of hydrogen pipeline in the United States[5]. 1. Corinth Pipeworks[6], a company headquartered in Attiki (Greece), manufactures the steel pipes used in the hydrogen pipeline network. 2. Soluforce[7], based in the Netherlands, manufactures a spoolable Reinforced Thermoplastic Industrial Piping system (RTP, also known as FCP) for hydrogen applications. 3. Pipelife[8], a leading Austrian piping system solution, also manufactures a Reinforced Thermoplastic Piping system (RTP).
	India: Pilot	Gaseous hydrogen transport via existing pipes is a low-cost alternative for transferring vast amounts of hydrogen. Natural gas companies and pipeline network operators in India are currently focusing on the same. 1. GAIL[9] has started hydrogen blending as a pilot project to establish the techno-commercial feasibility of blending hydrogen in the City Gas Distribution (CGD) network in Indore, Madhya Pradesh. Pipeline Infrastructure Limited (PIL) has partnered with DNV[10], an independent energy specialist, to integrate hydrogen into PIL's Indian gas network assets.
Tankers	Global: Commercial	There are numerous cylinder/tank manufacturers in India and around the world.

Technology	Technology readiness	Brief Summary
/cylinders	scale	1. INOXCVA[11], an Indian manufacturer of cryogenic equipment, has supplied the world's largest liquid hydrogen storage tank (238 m^3) to Doosan Crop., which is building a hydrogen plant in South Korea. 2. Chart Industries Inc.[12], an international vessel manufacturing company with a manufacturing facility in India, has constructed over 800 hydrogen tanks. 3. Linde, an international engineering company, provides storage and transport facilities at various operational sites, ranging from specifically insulated tanks for liquid hydrogen (LH_2) to pressure-tight containers (cylinders, cylinder bundles, tanks, and pipes) for compressed hydrogen (CGH_2). 4. Air Liquide[13], the second largest provider of industrial gases after Linde, works extensively on tank material strength. 5. BHEL, one of India's largest engineering and manufacturing organizations, is developing Type-IV hydrogen and CNG cylinders and is making good progress. BHEL intends to set up dedicated CoEs for the development of Type-IV Cylinders, a national testing facility for Type-IV cylinders, and a manufacturing facility in the country
	India: Commercial scale (Type I-II) No technology for type III-V	
Ships	Global: Commercial scale	1. Kawasaki Heavy Industries[14], a Japanese multinational company, has constructed a liquid hydrogen carrier ship capable of transporting 1,250 m^3 of hydrogen. 2. Sirius Design & Integration[15], a ship designer and system integrator in Norway, is working on a hydrogen carrier for Gen2Energy.
	India:	-

Technology	Technology readiness	Brief Summary
Trains	Global: Pilot	1. DB Cargo[16], a rail cargo company based in Germany, intends to construct a rail waggon in the future to transport urgently required hydrogen by a freight train.
	India:	1. Since Indian railways were granted permission to transport LNG only in October 2022, a thorough examination of hydrogen transportation is required. The Indian railways list compressed hydrogen gas in their freight lists, indicated in the 200W rate class, with a transport cost of INR 5,830 per tonne for a distance of 3,500 km.
Conversion of hydrogen		
Ammonia	Global: Commercial	The process of converting hydrogen to ammonia is already a well-established process. In all fertiliser plants, hydrogen is converted to ammonia. They employ the Haber-Bosch process to manufacture ammonia by combining nitrogen (from the air) and hydrogen (from fossil fuel). Furthermore, manufacturers across different industries are attempting to produce ammonia using renewables since it is a clean fuel and helps decarbonise. 1. CF Industries[17] plans to produce 20,000 tonnes of ammonia using green hydrogen at Donaldsonville, United States of America, by 2023. 2. Intercontinental Energy[18] is working on one of the world's largest green ammonia production projects, namely 9 million tonnes of ammonia production utilising green hydrogen in Australia and numerous other green ammonia projects worldwide. 3. A Saudi Arabian plant, a joint venture of NEOM, ACWA Power, and Air Products, plans to commission a 1.2 million tonne ammonia production fuelled by green hydrogen by 2025[19]. 4. Yara International ASA, Aker Clean Hydrogen, and Statkraft ASA formed

Technology	Technology readiness	Brief Summary
		HEryaGReen Ammonia (HEGRA) in 2021 [20], which aims to electrify and decarbonize Yara's ammonia plant in Herya, Porsgrunn, enabling large-scale green ammonia production.
	India: Pilot	1. Avaada Group[21] has signed a deal with the Government of Rajasthan for a green ammonia facility with a production capacity of one million tonnes per annum. 2. ACME Group has established a pilot green hydrogen (314 tonnes per annum) and green ammonia plant in Bikaner, Rajasthan[22]. ACME has also announced plans to build green hydrogen and ammonia plant in Karnataka, Odisha and Tamil Nadu and has signed memorandums of understanding with the state governments.[23]
Methanol	Global: Commercial scale	Similar to the ammonia production process, hydrogen is also necessary for methanol production. 1. CRI has started the first commercial CO_2-to-methanol production plant in China. H_2 recovered from existing coke oven gas, and 160,000 per annum [24] CO_2 recovered from existing lime manufacturing emissions. This methanol production contributes to reducing greenhouse gases by replacing coal-based methanal. 2. Inovyn, an INEOS group European firm, unveiled the 'Power to Methanol' project in Antwerp in 2020[25], which will manufacture 8000 tonnes of methanol per year from captured CO_2 mixed with hydrogen generated from renewable electricity. 3. Thyssenkrupp[26], a multinational chemical and process technology company, is employing its own Uhde Methanol technology to manufacture industrial-scale sustainable methanol in one of its projects.

Technology	Technology readiness	Brief Summary
	India: Early stages for pilot deployment	1. L&T and NTPC have collaborated to build a demonstration plant for CO_2-to-methanol production[27], with CO_2 captured from power plant fuel emissions and H_2 generated in a more environmentally friendly manner, via electrolysis.
LOHC	Global: Commercial-scale	Liquid organic hydrogen carriers (LOHC) absorb and release hydrogen through chemical reactions. Since LOHC does not require compression to carry hydrogen, it is cost-effective. Several firms have reached the commercial level. 1. Spera technology[28] from Chiyoda Group, based in Japan, has been building the supply chain to transport hydrogen from Brunei Darussalam to Japan since 2020 by storing hydrogen in Methylcyclohexane (MCH) which will be commissioned by 2026. 2. Hydrogenious LOHC, a German company, has been developing hydrogen storage and transportation technology using LOHC. Hydrogenious LOHC uses benzyl toluene as a carrier medium. The world's largest LOHC plant is being built by Hydrogenious LOHC in Dormagen, Germany, with commissioning scheduled in 2023[29]. Vopak, a Dutch tank storage company, has formed a joint venture with Hydrogenious LOHC Technologies to pave the way for implementing large-scale pilot projects[30]. 3. Umicore[31], a multinational materials technology firm in Brussels, has announced an incubation and long-term R&D partnership programme focused on innovative PGM-based catalyst technologies.
	India: Laboratory-scale	1. CSIR-NEERI has a technology transfer plan to transport hydrogen using a catalyst abbreviated as Hydrogen Storage and Delivery using Catalytic System (HyStoCat)[32].

Technology	Technology readiness	Brief Summary
		2. In addition to the hydrogen generating and blending pilot project, OIL established an incubation centre in collaboration with a startup company Ohm clean tech Pvt. Ltd., to develop LOHC solutions[33]. 3. Thermax is also working on a LOHC solution. However, only limited information is publicly available.
Reconversion to hydrogen		
Ammonia	Global: Pilot scale	Ammonia is cracked using an ammonia reformer resulting in 70% H_2 and the rest as N_2/NH_3 mixture[34]. H_2 is separated and purified. Pd membrane and Lithium amide-based ammonia decomposition technology areunder research to decompose ammonia. 1. Amogy[35], a firm based out of the United States, has developed proprietary technology for splitting ammonia into hydrogen and is scaling up its technology to decarbonise cargo ships and other heavy-duty transportation systems. It is very close to commercialising its Ammonia-To-Power system. It has formed alliances with several companies, including Yara, Ballard, and John Deere. 2. TyseleyEnergy[36], based in the United Kingdom (UK), in consortium with several companies, including the UK government (BEIS), has been working on ammonia cracking technologies since 2020. The project intends to solve issues in technologies and well-established ammonia supply chains to keep the UK at the forefront of the global market. 3. Siemens Energy, a multinational energy company, is leading a consortium to develop an ammonia cracker prototype plant in Newcastle, UK[37], to produce green hydrogen at an industrial scale.

Technology	Technology readiness	Brief Summary
		4. Northwestern University in the United States has built an electrochemical cell to crack ammonia[38]. According to the researchers, the technology uses renewable energy, is efficient, produces clean hydrogen, and can be scaled up to meet the industrial need.
	India	-
Methanol	Global: Commercial scale	1. Element1[39], a hydrogen company based in the United States, has developed commercial and highly scalable hydrogen generators (fuel cell grade) from methanol. The hydrogen generator developed by Element 1 has been licensed to many partners for fuel cell applications and is in use worldwide. 2. Blue World Technologies[40], a fuel cell company based in Denmark, designed a methanol-reforming process that turns a mixture of methanol and water into a hydrogen-rich gas. They are working with several marine partnerships to create methanol fuel cell-powered workboats.
	India: Laboratory scale	1. Researchers at IIT BHU[41] built a prototype that can generate 900 litres of hydrogen per hour from 0.6 litres of methanol. In addition to this technology, IIT-BHU intends to develop a centre of excellence in collaboration with numerous stakeholders to promote "Make in India" and scale up the device for diverse applications, particularly in the transportation and mobility sectors. 2. CSIR-ACRI[42]developed a method to produce hydrogen with high purity (99.99%) from methanol by electrochemical methanol reformation (ECMR) at ambient pressure and temperature.

Technology	Technology readiness	Brief Summary
LOHC	Global: Commercial-scale	LOHCs act as chemical transporters and can store and release hydrogen under certain conditions (applying temperatures and pressure). The LOHC cycle governs hydrogen conversion and reconversion using organic compounds. Companies working on LOHC technology provide end-to-end infrastructure, including storage and release. Hence, the same firms listed in the conversion of hydrogen to LOHC are also working on the reconversion. 1. Spera technology, for example, is working on hydrogenation (hydrogen conversion) in Brunei Darussalam and dehydrogenation (reconversion) in Japan. Similarly, Hydrogenious LOHC provides end-to-end storage and hydrogen-release solutions at project sites.
	India: Demo stage	

Identification of the gap: Industry needs and proposed recommendations

Table 9lists the concern areas for transporting green hydrogen in India based on feedback received from the subcommittee members. The areas are identified based on industry requirements, the status quo in India, the capability of domestic industry and academia to meet industry requirements and the potential impact of the R&D intervention.

Table 9: Concern areas for green hydrogen transport in India

Area	Industry Requirement	Status Quo	Capability	Impact Potential
Effect of hydrogen transport on pipeline construction material (e.g., embrittlement, seepage)				
Testing infrastructure to study adaptability for domestic conditions				
Domestic manufacturing capabilities for transporting hydrogen and its derivatives				
Regulatory issues for transporting hydrogen at pressures greater than 200 bar.				
Regulatory and safety issues for transportation of products derived from hydrogen.				
Transport of hydrogen in cryogenic conditions				

Area	Industry Requirement	Status Quo	Capability	Impact Potential
R&D on LOHCs for conversion and reconversion - Scale-up potential of LOHCs and theirrepatriation at dispatch - Environmental and health impact of Liquid Organic Hydrogen Carrier (LOHC)				
Catalyst research for ammonia cracker technology - NOx emissions associated with ammonia				
Research on direct conversion of methanol to H_2 by improving chemical kinetics				
Study on the potential of leakage during long-haul transport				

Legend	Highest	High	Medium	Low

4.4. R&D priorities: Mission Mode Projects

Projects with short-term (0 - 5 years) impact horizon/Early-Stage Research Action

- Developing test beds for testing the performance of all types of compressed hydrogen cylinders.
- Indigenous development of type IV and type V compressed hydrogen storage cylinders for movement of hydrogen in India on trucks.
- Pilots and trials for large-scale movement of compressed and liquid hydrogen in trains.
- Early-stage research for the development of LOHCs in India.
- Early-stage research for conversion of hydrogen into synthetic natural gas.
- Early-stage research for the reconversion of ammonia, methanol and SNG to hydrogen.

4.5. R&D priorities: Grand Challenge Projects

Projects with a mid-term (0 - 8 years) impact horizon/ Demonstration Actions for encouraging startups and industries to grow

- Market readiness of type IV and V cylinders developed in India(V)
- Lab and pilot scale demonstration for movement of hydrogen in LOHCs across the road, rail and marine transport (m)
- Lab scale prototype and pilots on the reconversion of ammonia, methanol and SNG to hydrogen (M)
- Pilots and trials for 100% transportation of green hydrogen in pipelines (V)

4.6. R&D priorities: Blue Sky Projects

Projects having a long-term (0 - 15 years) horizon would be taken up with a focus on establishing global IP and competitive advantage for the Indian industry.

The scope of research and development activities can broadly be categorised under three themes. They are manufacturing, testing, and marketing components regarding the transport of hydrogen.

The basis of the proposed R&D efforts stems from four broad sources. They are requirements of the industry at large, the impact potential of research outcomes, the alignment of these research topics with existing competencies of participating institutions and lastly, the technical maturity and depth of research in comparison with global peers.

The recommended projects can be classified according to the serviceability of the research outcomes. Blue Sky research can include projects that are directly oriented in order to potentially engender ideas and solutions in the future. Mission Mode research can include topics that are goal-oriented and whose outcomes have practical implications in the near term. Research topics related to the hydrogen valley could include topics that convene stakeholders of the entire value chain to set up a hydrogen ecosystem. Lastly, the grand challenge category could include topics that seek innovation from start-ups and industries to solve targeted problems.

Proposed recommendations

Table 10lists the various type of R&D approaches and the corresponding projects that can be considered within each project. The table also recommends the institutions and organizations that can contribute to achieving the targets and the corresponding timelines.

Table 10: Targets for green hydrogen R&D in India

R&D approach	Project title	Recommended Institution/ Organization	Target
Mission Mode	• Developing test beds for testing the performance of all types of compressed hydrogen cylinders • Early-stage research for the development of LOHCs in India • Early-stage research for the conversion of hydrogen into synthetic natural gas • Early-stage research for the reconversion of ammonia, methanol and SNG to hydrogen	Academia/ Research institutes	Short term
	• Lab and pilot scale demonstration for movement of hydrogen in LOHCs across the road, rail and marine transport • Lab scale prototype and pilots on the reconversion of ammonia, methanol and SNG to hydrogen	Logistics and Supply chain research institutes	Mediumterm

R&D approach	Project title	Recommended Institution/ Organization	Target
Blue Sky Research			
Hydrogen Valley	• Pilots and trials for large-scale movement of compressed and liquid hydrogen in trains	Industry consortia	Short term
	• Market readiness of type IV and V cylinders developed in India • Pilots and trials for 100% transportation of green hydrogen in pipelines		Short term
Grand Challenge	• Indigenousdevelopment of type IV and type V compressed hydrogen storage cylinders for the movement of hydrogen in India on trucks • Leakage detection in hydrogen pipelines	Central ministry via Section 8	Medium term

Chapter 5: End-use Applications

5.1. Introduction

India currently consumes 10,500 TWH annually of energy in all forms and for all applications from electricity generation, industry, transportation, agriculture, water & wastewater application and buildings. It is expected to go to approximately 45,000 TWH by 2070 based on estimates of India's growth and HDI analysis while also coinciding with the nation's net-zero commitment. If one assumes that all of this energy that is required for the five big application areas mentioned above is electricity, which is becoming a dominant form of energy,then massive investment will be requiredfor building T&D networks across the country. Alternatively, if one assumes that approximately 50% of energy will be carried by hydrogen,then about 22,500 TWH or, equivalently, 500 MMTPA of hydrogen would be required. A more realistic scenario is where all forms of renewable energy will be deployed as dictated by usecases, supply chains and economics.

Green Hydrogen, produced using renewable energy, has the potential to play a key role in low-carbon and self-reliant economic pathways. Indeed, the ultimate deployment of green hydrogen on the ground for a variety of applications is expected to bring down carbon emissions, especially in difficult-to-decarbonize sectors. Green Hydrogen can enable the utilization of domestically abundant renewable energy resources across regions, seasons, and sectors, feedingmultiple usage streams, either as a fuel or as an industrial feedstock. It can directly replace fossil fuel-derived feedstocks obtained from petroleum refining. For example, hydrogen-fuelled long-haul automobiles and marine vessels can enable decarbonisation of the mobility sector, which today contributes about 9-11% of India's GHG emissions. Apart from the mobility sector, green power could be deployed to heat/cool household needs, transport frozen foods/things, operateforklifts/cranes in large warehouses etc.

Hard-to-abate sectors like steel, fertilizers, and cement, which contribute to about 24% of India's GHG emissions,will be immensely benefitted fromthe use of green hydrogen in its decarbonisation efforts. Production of ammonia and fertilizers consume a large quantity of hydrogen, and an estimated few hundred of million tonnes of hydrogen per year is required. The Haber-Bosch process that produces ammonia at high temperature and pressure requires pure hydrogen, and water electrolysis gives an edge. Another important sector is the chemicals sector, including petrochemicals, bulk chemicals, speciality and fine chemicals,and even CO_2 hydrogenation to methanol.For example, hydrogenation leadsto saturated oils and fats – hydrogenated vegetable products – butter; peroxide production by the well-researched, commercial anthraquinone process; methanol and methane production, though not commercially very viable at present, require high purity hydrogen. The chemicals sector can be substantially decarbonized by employing green hydrogen in place of currently used grey hydrogen.

Some of the minor application end-uses include hydrogen balloons for meteorological studies, carrier gas phase in chromatography, chemical analysis by atomic absorption spectroscopy, high-temperature welding, use as a coolant due to high specific activity and thermal conductivity, leak detection, etc.[43-44].

Green Hydrogen can be particularly useful as a versatile energy carrier for meeting the energy requirements of remote geographies, including islands andstrategic locations,in a sustainable manner.The potential associated with hydrogen is immense, and the right deployment to a variety of applications is the need of the hour. Some of the major and critical areas of hydrogen utilization arelisted in this roadmap and discussed in detail. It is also strongly suggested to deploy any colour hydrogen for all the applications listedabove, at least in the initial stages of the energy transition, so as tobuild the critical infrastructurefor hydrogen storage, distribution, and refuelling, as well as to improve the technology and manufacturing readiness levels of green hydrogen.This transition will enable easier switching over to green hydrogen.

Multiple use cases relevant in India domestic market

	Green H_2-based alternatives	Type of opportunity: Onsite/ Captive	Mid-term growth	Merchant	Future potential
Industry — CO_2 Intensive processes	1.1 Ammonia production	✓			
	1.2 Methanol production	✓			
	1.3 H_2 in refineries in HT/HC[3]	✓			
	1.4 Direct reduction in steel	✓			
	1.5 Metal processing			✓	
	1.6 Other industries[1]			✓	
Buildings — Central gas based pipelines for heating	4.1 H^2 blend[2] in city gas network (domestic)		✓		
	4.2 H^2 blend[2] in city gas network (commercial)		✓		
Transport — Internal combustion engine running on fossil fuels	2.1 Fuel cells in passenger cars				✓
	2.2 Fuel cells in comm, vehicles				✓
	2.3 Off-highway				✓
	2.4 Fuel cells in trains & ships				✓
	2.5 HCNG in private vehicles		✓		
	2.6 HCNG in comm. vehicles		✓		
Power — Coal, oil and gas based power backups	3.1 Stationary fuel cells				✓
	3.3 Decentral energy storage				✓

1. Other industries include Edible oils, electronics, diamond cutting, power plants, glass industry
2. A 5% H_2 blend (by energy) with natural gas for city gas distribution
3. HT - hydrotreatment, HC - Hydrocracking

Figure 10: Multiple use cases relevant in India

Hydrogen storage and distribution is arguably the most difficult challenge in scaling the hydrogen economy. In this context, it is important to recognize that hydrogenmight be carried in various forms,such as pressurized hydrogen, cryo-cooled hydrogen, ammonia, ammonia-borane and even liquid organic hydrogen carriers (LOHC). At the user end, hydrogen will be received in more than one form, and appropriate process equipmentwill have to be incorporated at the user end to derive hydrogen at the right temperature, pressure, and purity from the stored forms based on the device connected to it.

As fossil fuel contribution needs to be brought down in India and replaced with renewable energy while catering for the new growth of energy requirements of the future, hydrogen as a mediumto store excess renewable energy may gain huge importance. It can be safely estimated that about 5000 GWh of solar / wind energy may need to be stored per day in order to cater for the energy needed during the lean period of the day. The storage requirement may increase further, considering the excess storage required to overcome the seasonal variation of solar radiation and wind speed. Such high energy storage through conventional batterieslike Li-ion or upcoming chemistries such as Na-ion may not be feasible.In view of this, hydrogen generation through high-efficiency water electrolysis, storing it in suitable forms and reusing it to generate electricity when required(or as a fuel for other applications) may prove to be a cost-effective solution that can possibly be employed at mega scale either in a distributed or a centralised mode.

Hydrogen energy based onsite/centralised power generation is a great opportunity to allow pollution-free, secure powering for on-grid and off-grid sectors. Various technology configurations are feasible to deploy; however, those technologies may find alternate green technologies as competitors. To analyse the performance characteristic of the hydrogen-based power solutions vis-à-vis other non-hydrogen-based green power solutions, a table is provided in Annex9.

Utilizing green hydrogen energy for road/marine/air mobility would reduce environmental pollution in Indian cities and is also a great means for obtaining energy security for the country. Powering of transport vehicles,however, is highly challenging and depends on the class of vehicles and its intended duty cycle, availability of infrastructure for refuelling, maintenance etc. In view of the same, it is essential to further classify the vehicle type and accordingly carry out the technology suitability analysis vis-à-vis competitive green technologies. A comparison of light passenger and commercial vehicles is provided in Annex10.

An alternative scenario using an H_2 / Br_2 fuel cell and HBr-based electrolyser, where the HBr electrolyser is used to generate H_2 and Br and exploitation of the H_2 by oxidising the same in an H_2/Br_2 fuel cell, could allow about ~80% efficiency. This is a significant improvement which is at par with the Li-ion cycle (charging by solar power and discharging to user power). Such a system needs a research focus, especially in the Indian scenario.

Production of iron and steel is one of the vital yardsticks to a country's economic growth and development. India is the second largest producer of crude steel and is aiming to produce around 400 MT of crude steel by 2040, which will generate around 1200 MT of CO_2 along with other polluting gases to the atmosphere. To address this pollution issue, carbon-free futuristic technology is very important. Hydrogen has the potential to replace coal/coke for reducing iron, and water would be the only by-product in the process. A large-scale demonstration of green steel will position India amid the global frontrunners.

The major potential end applications for the deployment of green H_2pathways include:

- Replacing fossil fuel-based grey hydrogen with green hydrogen in petroleum refining and petrochemicals production
- Replacing fossil fuel-based grey ammonia with green ammonia (made from green hydrogen) in fertilizer production
- Replacing coal and coke with green hydrogen and/or natural gas in the production of iron and steel
- Use of green hydrogen and hydrogen-based e-fuels as a transport fuel for speciality & fine chemicals production
- Use of hydrogen and hydrogen-based e-fuels as a transport fuel
- Using green methanol/ bio-methane as feedstock for petrochemicals
- Replacing various fuels used for process heating applications in the industry
- Use of green hydrogen/ mixture of hydrogen and natural gas for heating/ cooling and cooking in residential/ commercial buildings
- Off-grid power generation for remote geographies such as islands and strategic areas
- On-site green hydrogen generation at offshore wind farms and reusing it to generate electricity as required.

5.2. Objectives

Although the production, storage, and distribution of green hydrogen production arecurrently expensive, economies of scale and a further improvement in technologies across the hydrogen value chain are likely to bring down the price of hydrogen at the point of end-use. In order to enable this transition, it is necessary to demonstrate and validate all endapplicationsat pilot scales across various geographies. Towards this goal, it will also beprudent to employ all types of available hydrogen for demonstration purposes and make the technology available readily. This will help to achieve decarbonisation faster and hence,achievethe net zero goal on time. As far as end-applications are concerned, the key objectives towards improving the techno-economics of deployment of green hydrogen-based end-applications are listed below:

- ❖ Increasing the efficiency of hydrogen-based internal combustion engines and reducing their NOx emissions.
- ❖ Improving the reliability, endurance, and safety of hydrogen-fuelled jet engines.
- ❖ Improving overall system performance for fuel cell stack technology in terms of power density, reliability and durability.
- ❖ Reduction or replacement of PGM loadings and development of new materials advancing the performance of onboard storage technology.
- ❖ Improvements in design, health monitoring and manufacturability of core components for fuel cell stacks and onboard storage technology.

- Reducing the cost of core components such as modules and stacks to foster the competitiveness of FC heavy-duty applications.
- Reducing the cost of all other components of drive trains of FC heavy-duty applications.
- Improving overall system performance of FC systems to meet the needs of FCH HDV end users
- Improvements in the design and monitoring procedures of FC systems.
- Supporting and accelerating the wide rollout of FC HDVs through policies, standards, and regulations.
- Improving technologies for the use of green hydrogen in blast furnaces/ DRI processes without adversely affecting the quality of steel.
- Designing safe boilers and heat exchangers for using hydrogen/ hydrogen-natural gas mixtures.

Further research and innovation efforts will entail more efficient and cost-effective fuel cells and upscaling to the higher capacity; simultaneous vendor development to make critical components of fuel cells (such as catalysts and membranes) available within India would make the fuel cells really affordable. Together with efficiency improvements, and capex reduction, the resulting cost reductions should make it possible for wider deployment of fuel cells for many applications.

5.3. National and international R&D activities

a. End-use applications for hydrogen as a fuel

As a blend for direct combustion applications – Internal Combustion Engines

- Hythane-fuelled IC engines potentially present a unique opportunity for decarbonization, considering that the energy conversion technology is robust, less susceptible to gas contaminants (relatively) and exhaustive testing has been carried out.
- A number of projects sponsored by the Government of India have resulted in substantial testing and collection of data. These include 50 hydrogen-enriched CNG (H-CNG) buses in Delhi (by Indian Oil Corporation Ltd. in collaboration with Govt. of NCT of Delhi), 2 hydrogen fuelled Internal Combustion Engine buses (by IIT Delhi in collaboration with Mahindra & Mahindra), fifteen hydrogen fuelled 3 wheelers (by IIT Delhi in collaboration with Mahindra & Mahindra), 2 Hydrogen-Diesel dual fuel cars (by Mahindra & Mahindra) and one fuel cell car (by CSIR-National Chemical Laboratory, CSIR-Central Electrochemical Research Institute and CSIR-National Physical Laboratory).
- The end-use technology is at TRL 9 and can potentially accept 20% of the generated green Hydrogen. The initial emphasis can be on state-run corporations for the operation of bus and truck fleets till 2025/27.
- Standards to be published for quality specifications for Hydrogen.

Development of hydrogen fuel cells for the telecom and automobile sector

- **Telecom sector**

It is envisaged that in the future energy mix, Hydrogen and Fuel Cells will resent immense opportunities to address large-and-long term renewable energy storage and on-demand reliable generation of electricity for various sectors – commercial, residential, industrial, defence and transportation, in a distributed manner using highly efficient combined-heat/cooling-and-power systems that have zero emissions when using green hydrogen. Of the various types of fuel cells, the Low-Temperature Polymer Electrolyte Membrane (LT-PEM) provides a solution that is characterized by high energy density (as much as 3-kWe/Litre), modular scale-up (few watts to megawatts), silent and vibration-free operation, compatibility with various primary fuel sources, and robustness and safety (solid electrolyte membrane) for both stationary and automotive applications. The backup power requirement of Telecom Towers presents an apt opportunity to deploy reliable and on-demand renewable energy solutions.

It is estimated that these towers consume about 2 billion litres of diesel per annum, amounting to an import cost of about USD1 billion and GHG emissions of 5 $MTCO_{2e}$[20]. There were an estimated 400,000 telecommunication towers in India in 2012, and their numbers were expected to grow at a CAGR of 3% for the next few years [21]. Today there are close to 650,000 towers in India. An estimated 85% of telecom towers require 8 hours or more of backup power because of unreliable grid supply. A significant number of these use diesel generators (DG). Tower companies are exploring cleaner options for cutting their carbon footprint in line with the “go-green” initiative of the TRAI [22]. For instance, Reliance Industries Ltd (RIL) has already deployed battery-based backup power systems on several towers. However, batteries become unviable for more than 8hours of backup time and still depend on unreliable grids for power backup. In contrast, Fuel Cell systems generate power continuously if hydrogen is supplied.

Realizing the limitations of battery and DG-based power backup solutions, as mentioned earlier, RIL has already installed nearly 100 imported LT-PEMFC systems on towers, and the same has been continuously tested forthe past three years. RIL’s comprehensive on-field experience suggests that PEMFC systems satisfy all technical requirements of a power backup system for telecom towers. However, the Initial Capital investments and the Total Cost of Ownership (TCO) of PEMFC systems are still higher than desired, and this limits the widespread adoption of Fuel Cell based power backup solutions in Telecom Towers. The only way to reduce the initial capex of PEMFC systems is to develop the technology indigenously and to set up the entire manufacturing ecosystem in India.

CSIR, together with RIL, has successfully co-developed LT–PEMFC stack know-how up to 3-kWe and has validated its durability for long hours in its labs and at RIL’s Fuel Cell Test Facility, as represented in Figure 12. Local vendors for manufacturing and sourcing various components, as well as a system integrator, have been identified. However, large-scale, and commercially viable on-field deployment will require further technological developments in two areas:

i. development of stacks of increased power density and increased durability, which also enable a reduction in the number of components and simpler system-level operation

ii. integrating stacks with suitable hydrogen generation systems.

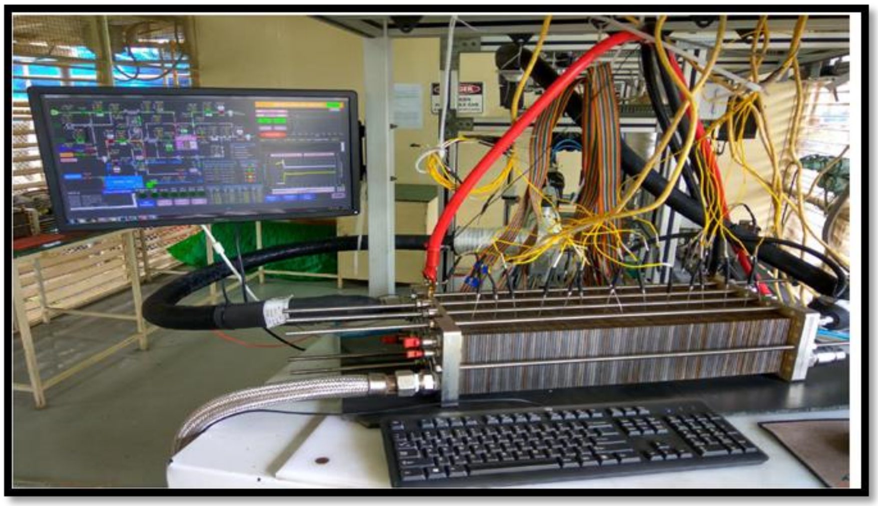

Figure 11: Testing of CSIR-3 kWe Fuel Cell Stack at Industry site (CSIR-NMITLI Program)

The CSIR-RIL team has quantified each of the targets based on the substantial on-field experience of running PEMFC-based telecom power backup systems. The increased attention by many telecom companies in India to deploy PEMFC-based backup power supply systems for telecommunication towers is going to open huge opportunities in this rapidly growing sector in the country.

- **Automobile sector**

As mentioned in the FAME scheme document (Faster Adaption and Manufacturing of (Hybrid &) Electric Vehicles in India by 2020), 85 % of the crude oil is being imported to meet the current energy demand. And transportation sector contributes almost one-third of this, and road transportation accounts for around 80% of the energy consumption. As India is one of the largest emerging economies of the world, its primary energy consumption is expected to increase by 70% in the next ten years, because of which the gap between local crude oil production and consumption will keep on widening. This requires significant investments of resources in investigating, developing and launching alternative energy systems.

The most prominent automotive alternatives are electric vehicles – specifically, battery electric vehicles and vehicles powered by hydrogen fuel cells. Globally, much effort is focused on lithium-ion batteries. India, however, does not possess significant lithium resources. Additionally, lithium-ion batteries are bulky. To overcome these limitations, work is ongoing on alternative battery technology. However, for some applications – for instance, where a long travel range is required – fuel cells are necessary. Also, battery charging takes significant time, whereas refuelling an FCEV is as rapid as conventional fuel-driven vehicles. In general, energy storage technologies, such as advanced batteries and supercapacitors, and hydrogen fuel cells, are important complements to each other. We, therefore, believe that a combination of hydrogen fuel cells, advanced batteries and supercapacitors will be key technologies for India in the coming years.

CSIR's PEMFC program, beginning in 2003, was driven under NMITLI and aimed at reducing the capital expenditure of fuel cells through localization, bringing technology readiness, and creating a platform to drive research and development. CSIR-NCL and CSIR-CECRI were involved in most aspects of developing and testing low-temperature PEMFC stacks. Along the way, it helped to successfully localize the development and manufacture of most components of the system while benchmarking the performance of these components with internationally available components. During 2016-2021, CSIR and KPIT collaborated to develop automotive-grade LT-PEMFC using metal bipolar plates, Fuel Cell system architecture, powertrain integration, control strategy, testing processes, etc. CSIR and KPIT applied this fuel cell expertise specifically to the automotive trials with 3-wheeler and four-wheeler demonstrations, as represented in Figure 13.

Last year KPIT also launched the first indigenously made fuel cell bus based on this fuel cell technology. Currently, KPIT is working on the development of fuel cell-powered marine vessels in collaboration with Cochin Shipyard Ltd. MEA performance is the single most important metric that can influence the adoption of Fuel Cell Vehicles. The analysis of the current MEA indicates that the MEA fabrication approach adopted is not optimal. Even though it achieved the maximum current density of 1 A/cm^2 at the single-cell level in an operating cell voltage of 0.6 V with optimized testing parameters, the current density lies between 0.5 and 1 A/cm^2 at a cell voltage of 0.6 V in a multi-cell fuel cell stack. Secondly, a performance of >1.5 $A/cm^{2,}$ as well as the durability of the stack, is crucial. It is important to achieve the desired power output in minimum fuel cell stack size for the successful deployment of the fuel cell in theautomotive sector.

Figure 12: Testing of CSIR-10 kWe Fuel Cell Stack for Vehicular platform in collaboration with Industry (CSIR-NMITLI Program)

- **Distributed Power Applications**

For applications like residential and small/medium capacity commercial distributed power requirements, a high-temperature polymer electrolyte membrane fuel cell (HT-PEMFC) would be a better candidate owing to its advantage that the system can be conveniently coupled with a reformer unit. The better CO tolerance expected from the system due to its high operating temperature gives HT-PEMFC a clear edge over its LT counterpart. Also, an HT-PEMFC integrated with the thermal system would be the right choice for realizing better energy-efficient installations to simultaneously take care of space cooling and electrical power supply. While high-temperature SOFC systems can also enable excellent thermal integration at the system level, these systems are difficult to run in start-stop modes due to thermal shocks in cycling between operating temperature (> 600 ^{o}C) and ambient temperature. Since the phosphoric acid in HT-PEMFC is confined in the matrix of the PBI membrane, the system (Figure 14) retains a clear technological advantage compared to PAFC, which is based on liquid phosphoric acid. Hence, installations and maintenance will be relatively easy in the case of HT-PEMFCs.

Figure 13: Development of CSIR-5 kW HT-PEMFC system for stationary application in collaboration with Industry

HT-PEMFC has a relatively simple BoP compared to LT-PEMFC due to the absence of the humidifier and the associated components. This makes the HT system more compact and adaptable to many niche applications where size and weight are going to be the important governing factors. Like other fuel cells and alternate energy systems, HT-PEMFC also can play a vital role in establishing hybrid and decentralized energy generation systems.

BHEL's Fuel Cell Research lab is fully equipped with the manufacturing of air-cooled and liquid-cooled Proton Exchange membrane (PEM) Fuel Cell Stack and system up to 5 kW, which Includes:

- Bipolar Plate design with gas and coolant flow fields and their Optimization.
- Design of End Plates, Copper Plates, and other fixtures.
- Design and Development of Sealings for both MEA and Cooling sides of Bipolar plates.
- Design and Development of Humidifiers, Coolants, and Thermal Management Systems.

The in-house developed Fuel cell test bench can test the fuel cell stacks and generate the performance data for the development of fuel cell systems.

BHEL R&D has also developed an electric Golf Cart with a DC motor which has been integrated with an existing in-house developed PEM Fuel Cell system with onboard Hydrogen Storage and a safety system. The hybrid electric golf cart vehicle demonstrates the technology with a payload of 300 kilograms up to a maximum speed of 20 kmph.

BHEL has also developed a liquid-cooled 5 kW high power density PEM fuel cell stack. Under this development, new designs of bipolar plates and sealant materials andsealing mechanism wereadopted to improve the performance of PEM fuel stack significantly.

Currently, BHEL is focusing on the development of a modular 25-kW Fuel cell system, which is inthe advanced stage of development. The 25-kW fuel cell system can address the various capacities by using multiple modules in series/parallel combinations.

BHEL is also focusing on the development of a modular 60 kW fuel cell system.

- ❖ **Electrical power generation using Hydrogen fuelled spark ignition engine generators**

Internal combustion engine generators are used in industries, commercial buildings, hospitals, etc., for standby operations, emergencies, meeting peak load demand, etc. The chloralkali industries produce hydrogen as a tangible product, whereas surplus hydrogen is available in many industries, including ammonia, ethylene, oil refineries, etc., as these industries have already developed the required infrastructure for hydrogen production from natural gas through steam reforming method, storage, transportation, internal dispensing, etc. These industries could generate electrical power using the by-product/surplus available of hydrogen for in-house plant use. The experience gained by the industries could be useful to scaleup the hydrogen in our country.

Hydrogen fuel engines emit zero carbonaceous emissions along with high energy efficiency. However, the major technical challenges in Hydrogen fuel engines are backfiring, oxides of nitrogen, and power drop compared to gasoline or CNG fuel engines/vehicles. Backfire is a preignition phenomenon occurring during the suction stroke of a manifold-based hydrogen fuel spark ignition engine as the minimum ignition energy of hydrogen is very low (~0.02 mJ) compared to hydrocarbon fuels (~20 mJ).

Backfire at high intensity could damage the intake manifold, hydrogen injectors, and injection system, as well as stall the engine operation. Backfires can be eliminated using different techniques/technologies such as retarded hydrogen injection, retarding spark timing, exhaust gas recirculation, increased compression ratio, and direct hydrogen injection. Backfire probability can be decreased with the increase in compression ratio due to the reduction in the temperature of the residual gas [23]. The backfire limiting spark timing and injection timing were 12 ^{0}bTDC and 40 ^{0}aTDC [24]. The temperature of any hot spot must be below 900 K for backfire-free engine operation [25].

Oxides of nitrogen (NOx) forms at a high in-cylinder temperature in spark ignition engines. The emissions could significantly be reduced by exhaust gas circulation, spark timing retardation, water injection, and selective catalyst reduction (SCR) / Lean-NOx Trap (LNT). NOx decreased from 12.1 g/kWh with maximum brake torque (MBT) spark timing (10 °bTDC) to 8.1 g/kWh with retarded spark timing (4 °bTDC) and further decreased to 6.1 g/kWh with 20 % EGR. NOx can be reduced to 0.1 g/kWh using water injection technology at a water-to-hydrogen ratio (WHR) of 9.25 [26]. Hydrogen instead of ammonia as a reductant can be used in SCR as hydrogen can be used for both the engine and after-treatment device. The main problems of usage of ammonia in SCR, such as the need for a separate tank, ammonia slip, formation of bisulphates, fouling, odour, etc., can be eliminated while using hydrogen as a reductant instead of ammonia in SCR.

The calorific value of hydrogen is very high (~120 MJ/kg) compared to hydrocarbon fuels (~44). However, the volumetric heat content of hydrogen is very low (~9.6 MJ/m3), whereas CNG is about 35 MJ/m3 resulting in a power drop. The power drop could be minimized using turbocharger/supercharger technologies and enhancement of swept volume of the engine.

A dedicated lubricating oil that must be used for hydrogen fuel spark ignition engines is developed by the oil industry in India. Industries may develop the required infrastructure developments with high safety for the successful implementation of hydrogen. A photographic view of a hydrogen-fuelled generator developed atIIT Delhi is shown in Figure 15.

Figure 14: A photographic view of a hydrogen-fuelled generator developed in IIT Delhi with MNRE fund support.

b. Difficult-to-Decarbonize End-Use Applications

It is envisioned that hydrogen will play a leading role in different aspects of day-to-day life within the context of a carbon-constrained environment in the future. Experts regularly tout hydrogen as one of the emerging contenders for the leading clean energy source/carrier. There are myriad application areas for Hydrogen in the chemical, metal and processing industries.Many chemical industries might need hydrogen for their hydrogenation or experimental needs, and this is another quick bolt-on use of hydrogen for which we might have to conduct a survey of such users and their current demands. The energy sector is theoretically the primary utilization avenue for hydrogen. It can be argued that the power industry (including captive power generation), followed by the transportation sector through the use of fuel cell vehicles, can potentially be the leading commercial application area and use-cases of hydrogen worldwide. End fuel processor development from kW to MW scale will be needed depending on whether hydrogen is transported as high pressure or ammonia or solid form.

In recent years, ammonia has been branded as a leading panacea to the question. Ammonia liquefies at -33 ºC at atmospheric pressure. The boiling point increases to 25 ºC when compressed to only 10 bars. Furthermore, the energy density of Ammonia is 15.6 MJ/litre,which is even superior to that of liquid hydrogen, the corresponding value of which is 9.1 MJ/litre. The industry is very familiar with the Haber-Bosch process of generating ammonia from hydrogen, and a lot of the infrastructure for handling liquid ammonia already exists, courtesy of the fertilizer industry. Hence, ammonia can be viewed as an extremely cost-effective, practically feasible, industry-ready hydrogen vector that can provide a tremendous impetus to eventual hydrogen usage.

The final piece of the puzzle with ammonia as an energy vector is to use it as a hydrogen substitute or generate back hydrogen just prior to its consumption/utilization. Hydrogen can find wide applications in gas turbine combustors in power plants, anodic feed in solid oxide fuel cells for captive power generation or as a fuel in Proton Exchange Membrane Fuel Cells (PEMFCs) in fuel cell cars. Research should be conducted on employing ammonia as a feed to these devices. As mentioned before, one effective way to approach it is to efficiently decompose ammonia back to nitrogen and hydrogen just before separating the hydrogen and sending it to the target device. This technological arrangement, in principle, can greatly enable the wide adoption of hydrogen in different applications by the industry.

The energy sector alone is responsible for around three-quarters of worldwide CO_2 emissions. According to a recent International Energy Agency (IEA) report, global energy-related CO_2 emissions rose to a record high of 36.3 Gt in 2021. Clearly, employing hydrogen as a clean fuel in gas turbine power plants can go a long way in alleviating this monstrous environmental problem. Employing ammonia as a hydrogen vector in precisely this kind of application can offer a practical method of massively using hydrogen in the final application. Some recent patents have appeared in the literature that provides engineering solutions to use ammonia in gas turbine power plants. One very recent patent proposes a coupled combustor-heat exchanger system to provide hydrogen from ammonia within the combustor of a power plant. Another aspect that needs to be investigated in detail is the suitability of the existing industrial natural gas combustors for hydrogen combustors. A successful demonstration of these ideas in real-life situations can lead to explosive growth of the use of hydrogen with a corresponding reduction in worldwide CO_2 emissions.

Because of the usage of fossil fuels for producing heat and the primary reducing agent being CO, a significant amount of CO_2 is emitted from steel industries. The steel industry is responsible for over 6% of the anthropogenic CO_2 emissions. Hydrogen metallurgy uses H_2 or H_2-enriched gases as the reducing agent instead of fossil fuels to reduce CO_2 emissions. Moreover, the diffusivity of H_2 is considerably higher as compared to CO, resulting in higher mass transfer rates towards the reaction sites and faster reduction rates. Currently, more than 95% of H_2 is produced using fossil fuels as the input in steam methane reforming, coke oven gas (COG, H_2+CH_4+CO) reforming and coal gasification processes. However, H_2 can be produced in a more sustainable and carbon-neutral way through thermochemical routes such as solar water splitting, solar gasification, or solar steam methane reforming. In the steel industry, H_2-enriched products are being researched for use in the blast furnace (BF) production process and direct reduction iron (DRI) process. The BF process does not require high-purity H_2, and H_2-rich gas is acceptable. The DRI process operates with reduction gas having higher H_2 concentration as compared to the BF process. In the BF production process, conventionally, coke is used as an input. H_2-enriched gases such as COG can be injected.However, carbon remains the dominant element for reducing iron oxides, and it is suggested that H_2 can only partially replace coke in BF. Currently, efforts are being directed towards increasing the hydrogen-to-carbon ratio to decrease CO_2 emissions from BF. In the DRI process, both coal-based andgas-based input is used, though gas-based processes are more popular and account for more than 90% of the output from all of the DRI processes. In the gas-based process,usually, natural gas (NG), syngas (H_2+CO) or off-gasses from steel plants (H_2+CH_4+CO) are employed. In the DRI process, the research is targeted towards the usage of pure H_2 or a further increase in the H_2 proportion in input gases. The thermodynamics and kinetics of H_2-based reduction aredifferent fromCO-based reduction, and detailed investigation is desirable to investigate the performance of hydrogen metallurgy both at the fundamental and system level. In addition to technical considerations, economic factors will also drive the direction for moving towards hydrogen metallurgy.

Recommendations for research initiatives

The above-mentioned thermodynamically beneficial and environment-friendly LH_2-based Brayton cycle can be explored as a part of futuristic technology. However, the need for research initiatives is realized. Some examples are as follows:

1. Experimental assessment of such a cycle, using conventional and non-conventional working primary fluid, e.g., air or other gases. This investigation can be performed in a laboratory, and the developed technology can be scaled up by a suitable industry.
2. Developing novel material for addressing hydrogen-related corrosion, embrittlement, etc., at a high temperature.
3. Integration of solar energy systems for the pre-heating of working primary fluid before combustion or for post-combusting heating. This is expected to enhance the system's efficiency.
4. Assessment and adoption of the conventional sub-systems such as heat exchanger, combustor, separator, de-humidifier, and even turbine for such a novel system.
5. Assessment of existing gas turbine-based thermal power plants for possible conversion to hydrogen-based power generation systems. This will enable the re-utilization of widely available and well-trained manpower.

Production of Green and Clean Steel through Hydrogen Plasma Smelting Technique

In India, the production of iron and steel is one of the vital yardsticks to the country’s economic growth and development. Our nation is the second largest producer of crude steel and is aiming to produce around 400 MT of crude steel by 2040, which will generate around 1200 MT of CO_2 along with other polluting gases to the atmosphere and will cause serious environmental concern. If the environment is not protected from this situation, the time will come when India faces a temperature rise concern which will adversely impact the water supply, climate and ecosystem. To address this pollution issue, the development of futuristic technology for carbon-free iron production using alternate reductants like hydrogen with minimum or no CO_2 Emission’, is important. With the increased production iron, the emission of CO_2 is also increasing. The only way to get rid of greenhouse gas pollution is to go for green technology. Hydrogen has the potential to replace coal/coke for reducing iron, and water is the only by-product ofreduction with hydrogen. It is a renewable resource, and we can rely on it compared to coal which is non-renewable. A large-scale (100 kg) demonstration will position India amid the global frontrunners.

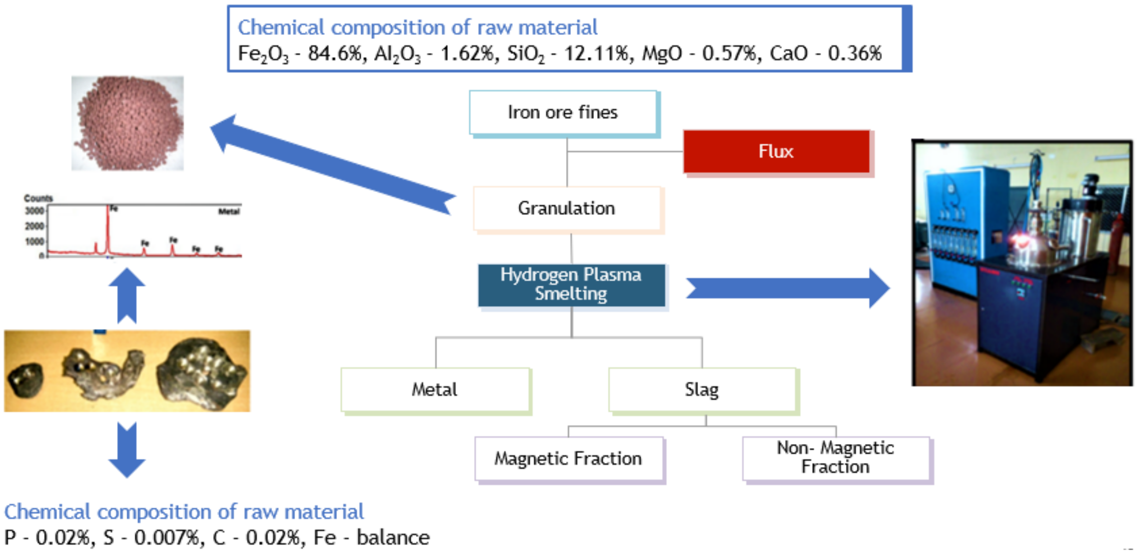

Figure 15:Process flow chart for green steel production

Table 11: Comparison between the Conventional process and Hydrogen Plasma process for clean and green steel

Conventional Process	Hydrogen Plasma Smelting Reduction (HPSR)
CO_2 emission	No CO_2 emission
No. of unit processes are involved in producing iron through the blast furnace route, and the pig iron is processed to make steel	Single unit for production of steel
36 tons of Carbon is required for the production of 112 tons of iron	Only 6 tons of Hydrogen is required to produce 112 tons of iron
CO_2 is produced as a by-product gas and makes the atmosphere polluted	H_2O vapour is the by-product and can be recycled during commercial production
Non-eco-friendly technology	Eco-friendly technology
Iron ore fines cannot be used	Iron ore fines can be used

Staging Hydrogen utilization in India under the Hydrogen Mission

India has promised to cut its emissions to net zero by 2070 at the COP26, and under its broad ambit, the Hydrogen Mission has been launched with the objective of "India the Global Hub for production, usage and export of Green Hydrogen and its derivatives". Regarding the use of Green Hydrogen, the broad charter of this sub-committee is to suggest a pathway for the usage of generated green Hydrogen. It is sought to be emphasized that Hydrogen take remains a key challenge, and the production side can suffer unless a well-oiled system is put in place on the offtake side. Againstthis backdrop and towards setting the course, some basic information is consolidated below.

- Current hydrogen utilization in India accountsfor6 million tones
- The refinery sector accounts for almost 3 million tonnes of hydrogen demand, representing 46% of the total hydrogen demand in the country
- Ammonia production contributes to 48% of the current hydrogen demand
- Steel production via natural gas-based DRI-EAF (Direct Reduced Iron in Electric Arc Furnace) contributes to 0.3 million tonnes of hydrogen demand currently.
- Currently, hydrogen demand for the transport sector is almost non-existent, as no FCEVs exist (commercial basis) on the market in India. While a large number of groups are engaged in the research, development and demonstration activities of PEMFC, it has not reached the stage of commercialization.
    - CSIR-National Chemical Laboratory, Pune and CSIR-Central Electrochemical Research Institute, Karaikudi, along with KPIT, have operated a prototype car.
    - Last year KPIT also launched an indigenously made fuel cell bus based on this fuel cell technology.
    - Currently, KPIT is working on the development of a fuel cell-powered marine vessel in collaboration with Cochin Shipyard Ltd.
    - Toyota Kirloskar Motor Pvt. Ltd., along with International Center for Automotive Technology (ICAT), initiated a Pilot using Toyota Mirai.
- The focus of OEMs (Original Equipment Manufacturers) as ofdate in the country continues to be on Electric / Hybrid Electric vehicles. All efforts related to the adoption of fuel cells as prime movers remain restricted to research and development.
- Fuel cell vehicles are unlikely to hit the road on a commercial scale, at least until 2030, subject to the concurrent development of Hydrogen supply infrastructure (under the consideration of competitive pricing)
- The most optimistic scenario for fuel cells in vehicles corresponds to Reliance & Adani group partnering with Ashok Leyland for the adoption of Fuel Cells on Diesel Trucks.
- Preliminary reports indicate Reliance has contracted the conversion of 45,000 Diesel trucks into Fuel Cells trucks, with the first rollout around 2025 when Reliance proposes to generate green Hydrogen at its Jamnagar refinery.
- Preliminary reports indicate the Adani group is planning to convert mining trucks to fuel cell trucks using 120 kW Ballard PEM fuel cells.
- Current interventions into fuel cells pertain to the adoption of imported fuel cell stacks into existing chassis. The availability of indigenous stacks in the immediate time horizon is unlikely.
- Regarding the use of Hydrogen in conventional engine technology, there are 50 Hythane (18% Hydrogen and 82% Compressed Natural Gas) buses plying on the roads of New Delhi, and there are plans afoot to expand the footprint of such buses across the country.

- Limited work has been carried out by the Metal and Cement sector.

Based on the presented information, from the perspective of the use of generated green Hydrogen in the country, the following key observations are sought to be made for the three routes of Hydrogen utilization: as an industrial chemical with utility as a molecule, as a blend with CNG in combustion devices and as a pure energetic molecule in electrochemical devices.

As an industrial chemical, including reducing agents and inert media

- Currently, with almost all Hydrogen being used as a molecule in chemical processes, sectors like ammonia synthesis, desulfurization etc., are the most suited for the adoption of green Hydrogen.
- For processes involving catalytic synthesis, quality standards would be extremely stringent and need to be published.
- Sectors, where Hydrogen is used as a reducing agent (steel/cement), can potentially be more flexible as compared to catalytic processes, and the initial focus should be on these sectors.
- Mandating guaranteed uptake of green Hydrogen to offset part of grey Hydrogen in conventional industrial processes would be a key requirement.
- Considering that site-specific consumption of Hydrogen is rather substantial, a meaningful offset would require the colocation of green Hydrogen generation plants to minimize transportation cost implications.
- Viability gap funding, if necessary, should be a key point till economies of scale are realized. The viability gap funding provides an opportunity for resolving potential teething problems associated with the blending and utilization of green Hydrogen with grey Hydrogen.
- Establishing / publishing standards for each of the industrieswould be important to enable producers to target the desired quality of Hydrogen.
- Since the end technology is already at TRL 9, the utilization target for more than 75% of any green Hydrogen generated till 2025/27 should be directed tothis sector. Around 50% can be directed at the steel/cement sector, while the balance 25% can be directed at sectors where Hydrogen enters the process as a molecule.

Utilization of Hydrogen in Automotive Engines / Vehicles

BS VI norms for automotive vehicles wereimplemented on April 01, 2020. To further reduce emissions to zero levels along with energy efficiency improvements, hydrogen is one of the best fuel options. The hydrogen blended natural gas (up to 18%) can be used in in-use vehicles. The current vehicles running with natural gas need minimal or no modifications for use of hydrogen-blended natural gas. Hydrogen blended fuel is one of the easiest ways to decarbonize the automotive sector. In the case of 100% hydrogen, a dedicated engine/vehicle needs to be developed. A zero-emission vehicle with hydrogen is the next important step beyond BS VI norms.

Utilization of Hydrogen Use in Compression ignition engines under dual fuel mode

Hydrogen can be used in diesel engines under dual fuel mode. Hydrogen will be injected into the intake manifold of the engine during the suction stroke, and diesel will be directly injected into the combustion chamber at the end of the compression stroke. The thermal efficiency of the engine would significantly improve along with near zero carbonaceous emissions. The engine/vehicle with hydrogen can operate in flex-fuel mode, either diesel or dual-fuel mode (Diesel-hydrogen). Dual fuel technology without major modification can be implemented in-use vehicles. The hydrogen energy share of about 19% could be possible to achieve near-zero levels of CO, HC, and smoke emissions. Hence, hydrogen could be used for the decarbonization of diesel engines/vehicles.

Further Research and Development on hydrogen internal combustion engines vehicles

Research and Development may further be focused on the development of hydrogen direct injection technology, technologies for thermal efficiency improvement, high injection pressure injectors (>50 bar), fuel injection and control systems, hydrogen-SCR systems, etc. Hydrogen direct injection is a promising technology to improve specific power output and torque, backfire elimination of a vehicle as manifold-based hydrogen injection suffers power drop problem. A lot of scopes are available to improve the thermal efficiency of hydrogen engines through the technologies such as charge boost pressure, detonation combustion at part loads, Homogeneous Charge Compression Ignition (HCCI), reduction in irreversibility, including combustion, waste heat recovery, etc.

Identification of the gap: Industry needs and proposed recommendations

Green hydrogen sustainability as fuel perhaps depends upon its ability to provide a solution to store the excess of renewable energy dynamically so that supply is maintained even during lean hours in a cost-effective manner. In view of the same, it is highly important to understand the primary advantages it offers vis-à-vis other green technology solutions and the manner in which the shortcomings can be mitigated.

As it is apparent, rechargeable battery-based solutions, although of high efficiency, may have prohibitive costs for large MWh or GWh installation. Water electrolysis-FC based solution, however, is still plagued by lack of high-efficiency electrolyser. Even today's targeted 1.6V electrolyser, for e.g., can provide only ~50% efficiency, as discussed above. In view of the same, H_2 – Br_2 FC and HBr electrolysis can provide a solution towards high efficiency, allowing lesser installation cost with respect to,e.g., Li-ion system. Another aspect is that of the fuel cell. Since both PAFC / PEMFC depends on Pt, their installation cost could be a problem. Additionally, the PEMFC/PAFC stacks havean upper limit of potential (of about 0.8 V) to prevent carbon corrosion of the electrode, thus limiting the efficiency of fuel cells. Utilizing non-carbon catalyst/electrode system could be an important research impetus. Alkaline fuel cells, which possess better features while not needing Pt as the electrocatalyst, can be operated beyond 0.8V, thus breaking the efficiency ceiling. However, the AFC material issues and low life is preventing unleashing the advantages of AFC; poisoning issues of atmospheric CO_2 also need to be considered. Such cases, from an Indian perspective, are very important to be investigated, considering the expertise available in India with respect to material science.

1. For direct industry-supported implementation:
   a) Deployment of high-capacity electrolyser of about 1.8V operating potential (initially with high non-local content) for distribution of green hydrogen connected to solar / wind power plants for GWH storage application.

2. Research & development impetus:
   a) Development of high-efficiency electrolyser of ~1.6V, both alkaline membrane or acid membrane-based, along with suitable electrocatalyst development. Preference is to be given to alkaline systems considering Pt / noble metal-free electrocatalyst feasibility and better kinetics, thus reducing the cost.
   b) H_2-Br fuel cells and development of HBr-based electrolyser system. FC system could be non-regenerative coupled with a separate HBr electrolyser or regenerative, where both reactions can happen to reduce the cost.
   c) Development of high-efficiency power electronics (>95%) for charging (electrolyser operation) and discharging of FC (to convert FC power to grid quality power)

Inference for Hydrogen energy implementation for onsite power generation

Hydrogen energy based onsite/centralised power generation is a great opportunity to allow pollution-free, secure powering for on-grid and off-grid sectors. Various technology configurations are feasible to deploy; however, those technologies may find alternate green technologies as competitors. To analyse the performance characteristic of the hydrogen-based power solutions vis-à-vis other non-hydrogen-based green power solutions.

To allow a greater level of implementation of hydrogen fuel for power generation, it is apparent that the system needs to be efficient, commercially viable and technologically well-proven. However, there is no hydrogen technology configuration which can meet all the requirements and alternate green technologies also suffer similar issues. In view of the same, a layered approach is required to transition from the present fossil fuel-based power generation to hydrogen or other green technology-based power. Accordingly, the following are proposed:

<u>For direct industry-supported implementation</u>:

a. Green hydrogen + H_2 gas turbine-based power generation for MW to GW level must be tried as it can eventually be proven to become one of the future primary systems. However, unless high-temperature tolerant materials are developed, the efficiency will be low. Round-trip efficiency to improve. Other pollutants like NOx will still be formed, but the same can be easily filtered from the off-gas.
b. Green hydrogen + PAFC based power plant for 100 kWto several MWlevel as the technology is quite mature and the same could be distributed or centralised. Although this may be costly initially, the same has a very long life and great availability. The life can be renewed at a fraction of the cost, and Pt can be recycled. Thus, the capital cost can be subsidised and can be recovered partly during every life renewal. As experienced by DRDO, there could be at least 5 or 6 life renewals feasible.
c. Green hydrogen+PEMFC for several kWto about 50kWrange as distributed power. PEMFC technology is growing fast in India and can be implemented easily. The cost of

the system is a concern, but the same can be managed through subsidiesand recovery during renewals. However, the cost of refurbishing is higher owing to the loss of the costly membrane, although, like PAFC, Pt is always possible to recycle.

d. Carbon neutral, indirect hydrogen sources like biomass gasifier + engine and biomass gasifier + PAFC of Mw scale as distributed power in support of industry needs to be implemented. The engine-based systems will suffer from low efficiency; however, once PAFC or other competitive systems are more available, the engines can be replaced. The initial high cost of PAFC can be managed through subsidies, as discussed before
e. CO_2-sequestrated clean coal-based gasifiers coupled with engine or fuel cells, as discussed above, can be considered for centralised power. CO_2 management may make it site-specific, but considering the huge scope, this should also be considered for implementation.
f. Scale-up of LTPEMFC systems from 10 kW to 100 kW and integration with E-drive/ Storage/ Controls
g. Indigenization and vendor development for all strategic materials and components of PEMFC, such as catalysts, membranes, bi-polar plates, MEA, and GDL.

Research & development:

a. High-temperature H_2 gas turbine research must be on high priority to allow improvements of the existing turbines so that the systems can be gradually upgraded.
b. Alongsimilar lines, H_2 engine upgradation needs to be investigated, maybe by industry-academia interactions. This must include long-hour operation sustaining H_2 – fossil fuel blend as well.
c. R&D efforts must synchronize with the industry implementation plan of various configurations and the technology gaps that need to be filled for gradual upgrades in a timely manner. Moving out of the Pt-based system should be a major focus ofthe research initiatives.
d. SOFC system that can easily get integrated with gasifiers needs to be focussed on MW-level system so that they can be used to replace the engines or low temp FCs for better efficiency. Co-generation to utilize high-quality waste heat of SOFC needs to be investigated, and mini turbine-like technologies need to be developed for the same. This system will allow Pt-free power generation and will allow wide implementation once developed.
e. Highly efficient fuel cells (6 kW/ L)
f. Photoelectrochemical/photocatalytic hydrogen production. Artificial photosynthesis is to be emphasized along Si-PV lines.

Inference for Hydrogen energy implementation for light vehicle mobility

Utilizing hydrogen energy for road mobility is highly important towards environmental pollution prevention in Indian cities and is also a great means for obtaining energy security for the country. Powering of transport vehicles, however, is highly challenging and depends on the class of vehicles and theirintended duty cycle, infrastructure for refuelling, maintenance etc. In view of the same, Annex10 further classifies the vehicle type and, accordingly,carriesout the technology suitability vis-à-vis competitive green technologies.

Annex10 depicts that high-pressure hydrogen with PEMFC is perhaps the most viable option for light vehicle mobility. The main issue will be Pt availability, and till Pt-free PEMFC is developed, this technology will have limited use, at least in India, since Pt is mostly imported. Further, the newer generation Li-ion, Li-metal, and Na-ion batteriesmay prove to be more useful for light vehicles. In view of the same, the following are proposed.

<u>For direct industry-supported implementation:</u>

a. To develop a niche market for PEMFC-based light passenger vehicles and develop hydrogen handling infrastructure as the same will be helpful for distributed power using green hydrogen.
b. Synergistic development of hydrogen infrastructure to support green hydrogen distribution and storage will be helpful for fuel cell-powered light vehicles (may be limited) but will be enormously helpful for distributed power generation using green hydrogen. The distributed power stations running on hydrogen can also be used for battery charging applications to indirectly provide green power for vehicles.
c. Hydrogen-powered ICE power train is worth looking at, considering its quick refilling option, although the range issues will be there. However, the vehicle power train will be light in weight and reliable, allowing neutralizing the range issue to some extent, and the technology cost will be less. This could dramatically change the air quality in the metropolis of India and will also help to kickstartthe hydrogen infrastructure.

<u>Research & development impetus:</u>

a. It is totally necessary to invest effort in the development of either Pt-free or very low Pt (5-10gm of Pt per light vehicle against 30 to 60 gm present situation) based PEMFC catalyst that can be used for the PEMFC since the primary technology is a highly mature.
b. Research of failure analysis of hydrogen high-pressure vessel storage and its relevant safety mitigation is another very important aspect that needs to be considered.

Inference for Hydrogen energy implementation for heavy vehicle mobility

The technologies that can be used for heavy vehicles need to be compliant with long-range (as depicted in Annex11), technology maturity, safety and low cost. Considering the fact that alternate green technology like battery-based power trains may not be able to meet the primary requirement of range and safety, it is worth consideringhigh-pressure bottled H_2 coupled with a PEMFC-like power train. Pt availability limitation may not be so severe aslight vehicles primarily due to the lesser number of such heavy vehicles. However, for a better range, it may be prudent to also explore methanol (a renewable fuel that can be made carbon neutral) reformer coupled with PEMFC or PAFC-like power train. In view of the same, the following is proposed:

For direct industry-supported implementation:

a) The bottled H_2 + PEMFC power train-based heavy vehicles, forklifts etc., application development
b) Bottled H_2 + ICE-based forklifts and small range earth moving vehicles
c) Take advantage of the H_2 infrastructure developed in a synergistic way for multi-use like onsite distributed power, light and heavy vehicle power etc., as discussed before.

Research & development impetus:

a) Reformer coupled PAFC or PEMFC power train for heavy vehicles.
b) Improved low Pt high power PEMFC / PAFC for heavy-duty application.

Inference for Hydrogen energy implementation for locomotive mobility

Railways play a very important role in India both for passenger as well as goods transportation. Considering the extended network of railway tracks and its potential to reduce CO_2 emission, it is quite apparent that a serious focus on hydrogen energy implementation for railways is required. In view of the same, various technologies based on hydrogen energy (direct or indirect hydrogen availability) vis-à-vis other possible green technologies are compared in Annex12.

In many countries' green electric propulsion-based technologies involving Li-ion or fuel cell / bottled hydrogen power train is already implemented in a limited mode. However, on close examination, most of these locomotives do not have more than 2 or 3 coaches. This is unlike Indian Railways, where many coaches are connected to cater to the transportation needs both for passengers and goods. Further, In India, the typical distance the locomotive has to cover is also significantly longer. In view of the same, the power and range requirements, along with the duty cycle, are quite unique in nature.

In view of the same, it is quite apparent that purely battery-driven power trains based on Li-ion or Li-metal may not be quite suitable except for short running like suburban EMUs, shunting engines etc. However, for such short operations, bottled hydrogen with PEMFC-based power trains could also be competitive and worth exploring. For all other cases, hydrogen-based technologies, especially on-board hydrogen generation, that allow longer range and operation cost reduction arepreferred. Thus, onboard methanol /DME or CNG reformers coupled with PAFC (a natural choice) or PEMFC with CO and other impurity filters (that may increase the cost and make it complex) need to be considered for development. Issues like Pt availability etc.,arenot severe in this case owing to lower numbers.

For direct industry-supported implementation:

a) High-pressure onboard hydrogen storage with PEMFC system for EMU & shunting engine applications
b) Focussed hydrogen transportation, filling, and storage infrastructure (high pressure), especially for railway-specific use.
c) Railway-specific hydrogen safety regulations and relevant standards are to be arrived at.
d) Synergy should be there for road-based hydrogen infrastructure for onsite distributed power and automobile powering, along with safety protocols.
e) DME production in refineries instead of methanol to be decided as a policy because all methanol / DME may not be possible to be completely from renewable sources.
f) Infrastructure for CNG, most preferably in LNG form for the railway, needs to be developed based on the already developed CNG/LNG infrastructure for transportation and domestic use. The LNG storage and transportation are expected to be more suitable for railway use considering its storage advantages. Cryogenic LNG storage and transportation tankers are widely available inIndian industries.

Research & development impetus:

a) Focussed research is required for the development of high-capacity PEMFC in the range of 500 kW along with PAFC of several MW levels. PAFC technology thru DRDO up to 500 kW is already available, and such know-how can be further scaled up and configured for locomotive use. Such development of high-capacity fuel cell packs must be done in Academia-industry mode considering the development infrastructure it will be required along with skilled manpower.
b) Packaged methanol/DME and CNG reformers need to be developed again in support of the academia-industry model. DRDO, for e.g., has developed a 50 kWpackaged reformer for defence field use, and such know-how can be used as a seeding for the scaleup. Alternate technologies involving micro channel reformer, deployment method of distributed reformer catalyst etc., are some of the technologies that need to be developed to meet the requirement of space and robustness. Thermal systems, namely burner technology, compact high-temperature heat exchangers etc., are also some of the technology enablers.
c) The development of packaged reformers will have another spin, especially if required to be used for long-distance road transport or off-grid distributed power where extending piped or bottled H_2 networks may not be feasible.
d) Govt must make necessary policy correctionsto allow the free use of methanol. If that is complicated, then the production of DME either by dehydrating methanol or direct production of DME needs to be enhanced.

In addition, the following points are also worth considering for defence applications:

(a) primary driver for usage of H_2 energy in defence – e.g., energy security, low signature, high efficiency causing lower logistic demand etc.
(b) various defence applications
(c) Synergistic development of dual-use technologies that can be used for Hydrogen energy in civil sectors.

Consolidated focus for short/medium/long term technology deployment plan for hydrogen energy

Based on the detailed technology analysis provided above, it is quite apparent that there are various potential technology options that can be considered for different applications. Considering the resource limitation for a developing country like India, it is important to classify and prioritize technologydeployment plans.

In view of the same, the following sections define short-term technologies that can be deployed within the next 5 years, while the midterm ones should be possible to implement inthe next 10 years and long-term ones to be considered for the next 15 years. The short/mid/long term technology deployment plan must have both industry/R&D/Academia involvements and the same will be brought out as well in the following section.

5.4. R&D priorities: Mission Mode Projects

Projects with short-term (0 - 5 years) impact horizon/Early-Stage Research Action

For Industry

1. Obligatory consumption is to be increased rapidly with green hydrogen in sectors such as petroleum refineries, fertilizers, and ammonia.
2. Hydrogen-based ICE for the electric vehicle application and development of light vehicle powertrain and pilot deployments
3. Green Hydrogen generation thru efficient electrolysers (~1.8V or lower) in a distributed scale and coupling the same with Solar PV plants and linking with developing H_2 infrastructure.
4. Development of high-pressure hydrogen storage tanks like type -III to type IV composite cylinders of 350 to 750 bar range, compressor systems, and hydrogen piping network suitable for distributed onsite power/hydrogen filling for vehicles. The technologies to be prioritized are multipurpose.
5. Deployment of distributed power plants
    a. Based on Hydrogen & PAFC /PEMFC in the range of 100kW to 500kW range and linking the same with partly developed Hydrogen infrastructure.
    b. Based on CNG reforming / PAFC or PEMFC in the range of 250 to 1MW power plants using available CNG infrastructure.

For R&D focus

1. Development of high-efficiency electrolysers targeting ~1.6V
2. Development of a biomass-based gasifier/reformer for hydrogen generation with a target yield of hydrogen per unit of biomass based on the Indian scenario.
3. High temp material/configuration of gas turbines for H_2.
4. Development of platform mountable methanol / DME / CNG reformer system for marine and railways application
5. Very low Pt electrocatalyst – tolerant to polluted air – for PEMFC / PAFC use.
6. Development of high efficiency, safe hydrogen high-pressure compressor technology like electrochemical compressors, hydride compressors etc.
7. Development of pilot SOFC stacks for coupling with gasifiers

5.5. R&D priorities: Grand Challenge Projects

Projects with a mid-term (0 - 8 years) impact horizon/ Demonstration Actions for encouraging startups and industries to grow

For Industry

1. Extension of the hydrogen infrastructure with improvements like high-efficiency hydrogen compressors, better safety etc.,
2. Extending green hydrogen generation with improved electrolysers ~1.6V.
3. Deployment of marine vessels powering using onboard H_2 storage / CNG, DME, methanol-reforming and fuel cell system with low Pt catalyst.
4. Deployment of mini hydrogen-powered power plants.
    a. Extended capacity gas turbine based distributed power in the range of several Mw levels.
    b. SOFC / gasifier-reformer (biomass, CNG etc.) power plant of > 100kW range.
5. Deployment of hydrogen-powered locomotives based on stored H_2 / onboard CNG (LNG) or methanol/DME reformers
6. Fuel cell-based low Pt light vehicles with onboard hydrogen (<5gm of Pt per vehicle)
7. Employing evaporated H_2 from cryo-cooled H_2 tanks for operating long-distance marine H_2 shipments with a suitable fuel cell and electrolyser combination.

For R&D focus

1. Pt free or low Pt electrocatalyst for PEMFC / PAFC system.
2. Development of low-cost materials for alkaline fuel cell materials.
3. Development of large-sized low-cost, heavy with Indian component fuel cell stacks of >100 to 200kW.
4. Development of an efficient H_2-Br FC-like system for high-efficiency green hydrogen energy storage and exploitation.
5. Development of prototype-level SOFC stacks for coupling with gasifiers.
6. Multi-fuel processors (for reforming CNG/methanol/DME/ethanol etc.) for onboard hydrogen generation.

5.6. R&D priorities: Blue Sky Projects

Projects having a long-term (0 - 15 years) horizon would be taken up with a focus on establishing global IP and competitive advantage for the Indian industry.

For Industry:

1. Extension of hydrogen infrastructure in a comprehensive manner covering at least 80% of India for onsite power, road/ railway / marine mobility.
2. Extended end-to-end networking of hydrogen infrastructure with solar /wind and other renewable power sources with the user endpoints for completion of the hydrogen grid. It may be required to connect fossil fuel or other H_2 gen sources as well for more efficient management of the hydrogen grid.
3. High-efficiency H_2-Br FC cum electrolyser for GWh energy storage.
4. Optimal deployment of Hydrogen-ICE and hydrogen Fuel cell-based light vehicles vis-à-vis other battery-driven electric vehicles along with indirect hydrogen (onboard multi-fuel processor) based fuel cell heavy vehicles.
5. Deployment of advanced H_2high-efficiency gas turbine and fuel cell based onsite/centralised power stations ranging from several 100 of kWsto 50 -100MW range power plants. Expected to achieve high round-trip efficiency in the long term, which is currently not the case.
6. Deployment of marine hydrogen-fuel cell-based ships and also hydrogen-gas-turbine-based systems for larger marine vessels.

For R&D focus:

1. Low-cost Alkaline fuel cell for domestic and distributed use.
2. Pt-free impurity tolerant (cathode) electrocatalyst for PEMFC / PAFC system and life estimation.
3. Improvement of H_2-Br FC, PEMFC and SOFC system for high power application.

Chapter 6: Enabling hydrogen framework

6.1. Hydrogen purification

Hydrogen purity requirements vary significantly based on the end-use application. While most fuel cells require high purity levels, lower levels suffice for gas turbines, refinery processes and industrial boilers. Further, the Iron and steel sector and fertilizer sector don't require high-purity hydrogen. Concentration levels of many critical hydrogen impurities range from low ppm to low ppb v/v levels, which is quite challenging to measure. Reliable confirmation of a desired H_2 grade product requires the use of specialized sampling equipment, site testing for some highly reactive impurities, and an array of highly sophisticated analytical instrumentation. To address the quality checks of hydrogen in the refuelling network, both the ISO and SAE hydrogen establishes a protocol for testing the quality of the hydrogen fuel dispensed at the nozzle to the vehicle.

The relative abundance of contaminants in hydrogen is highly influenced by the production pathway and the subsequent cleaning steps. Compared to hydrocarbon-derived hydrogen production pathways, water electrolysis has the advantage of producing extremely high-purity hydrogen (>99.9%) and doesn't require rigorous downstream purification. However, hydrogen obtained from water electrolysis also consists of three main pollutants: nitrogen, oxygen and water, which are required to be removed to desired levels using subsequent cleaning processes. Hydrogen generated from the water electrolysis process typically comprises around 40 ppm of nitrogen, 0.2-0.6% of oxygen and 2000 ppm of water.

For the production of hydrogen from the reforming and gasification of carbonaceous feedstocks, the product stream is subjected to a gas purification process for the separation of hydrogen from other gaseous mixtures. Even after subjecting conventional hydrogen purification process,i.e., pressure swing adsorption(PSA), hydrogen is usually associated with traces of several impurities such as CO, CO_2, CH_4, higher HCs, H_2S, NH_3 etc. Typical impurities in the hydrogen produced from different production pathways are given in Table 12. To generate hydrogen from hydrocarbon feedstock complying with ISO 14687:2019 standard for PEM fuel cell vehicular application, either conventional PSA performance is required to be improved or an additional downstream gas cleaning process to be incorporated.

Table 12: Typical impurities in the hydrogen produced from different production pathways

Production technique	Impurities
SMR of natural gas/ bio-methane	CO, CO_2, CH_4, higher HCs, H_2S, NH_3
Coal and biomass gasification	CO, CO_2, CH_4, higher HCs, NH_3, SO_2, NOx, Na^+, K^+, Hg, Ar, N2, H2S
ATR of hydrocarbons	N_2, CO, CO_2, CH_4, higher HCs, H_2S, NH_3
Chlor-alkali process	NaOH, Cl_2, Hg

Water electrolysis	H_2O, O_2

For the removal of nitrogen from the hydrogen generated by water electrolysis, generally, no dedicated post-treatment systems are installed; but just venting the initial production generally allowsfor meeting ISO 14687:2019 levels. Oxygen levels below 4 ppm in hydrogen products are obtained by catalytic recombination in the de-oxygenation reactor. Due to the exothermic nature of the reaction, subsequent cooling is needed to remove the water produced by the de-oxygenation reaction. Water is removed from the hydrogen stream by condensation at lower temperatures, followed by adsorption using either pressure swing adsorption (PSA) or temperature swing adsorption (TSA).

Currently, the most commonly used technologies for hydrogen purification are pressure swing adsorption (PSA), cryogenic distillation and amine-based absorption for CO_2 removal from H_2. PSA is the most widely used conventional technique and operates based on the selective adsorption of impurities from a gas stream. The main advantage of PSA is its ability to remove all impurities down to parts per million (ppm), producing hydrogen with high purities > 99.999%. Its main disadvantage is the high H_2 loss (~20%) resulting from the pressure release during desorption (H_2 recovery ~80%). From the adsorption process point for H_2 purification, N_2 and CO are the most problematic impurities of the syngas because of their low adsorption affinity. The presence of minor quantities of CO and CO_2 in H_2 easily poison the Platinum (Pt) catalyst used in fuel cells.

Hydrogen separation using adsorption is usually carried out in two-layered bed adsorption columns using activated carbon as the first layer for the adsorption of CO_2, CH_4 and CO and zeolites as the second layer for N_2 adsorption. The application of PSA for the production of fuel cell grade H_2 has several limitations, which include lower H_2 recovery and productivity, higher cost of production etc. Vacuum Pressure Swing Adsorption (VPSA or VSA) technology is a promising technology for the production of high-purity H_2 because of its high productivity and high H_2 purity compared to the PSA process. VSA process can produce H_2, meeting fuel cell specifications at reasonable production costs with optimum recovery and productivity. VSA technology has better operational performance compared to PSA.

Cryogenic distillation works based on the partial condensation of gas mixtures at low temperatures and high pressures to be separated by distillation. One major disadvantage of this technology is the limited purity levels (~99%) of the extracted hydrogen. In addition, the process is very expensive as it requires the use of numerous equipment and devices. Cryogenic distillation is ideal for large industrial scales but unsuitable for small portable applications.

Membrane technology appears to be a promising energy-efficient alternative for producing the ultra-pure H_2 required for fuel cells. A membrane is a solid physical barrier between two phases (gaseous or liquid), with a certain perm-selectivity towards one or more components of a mixture. In gas separation applications, the force that normally drives the different species to permeate a membrane is the partial pressure difference between both sides of the membrane. Compared to traditional separation processes, the advantages of membrane technology are simpler operation, higher adaptability, compactness and lightweight, modular design with simpler up and downscaling;lower labour intensity, lower operating and maintenance costs, higher energy efficiency and a much lower environmental impact. Typical target values of membrane performance that are considered necessary for the industrial purification of hydrogen are permeability to $H_2$of more than 1000 Barrer and selectivity (H_2/X) of more than 100.

Four emerging technologies that have the potential to become competitive with traditional technologies are membranes technologies in the near future: Carbon Molecular Sieve Membranes (CMSM), Poly (Ionic) Liquid Membranes (PILM), Metal Membranes and Electrochemical Hydrogen Pumping Membranes (EHPM). But, currently, membrane technologies for H_2 purification have still not reached the maturity level required for its wide-scale industrial deployment.

Various promising and widely reported processes for the removal of CO from hydrogen to < 0.2 ppm are Preferential Oxidation (PROX), Selective Methanation (SMET), Selective Membrane Separation, Metal Hydride Separation, Cryogenic Distillation etc. In PROX, oxygen is supplied to the hydrogen-rich reformate gas in the presence of a catalyst. Supported Ru and Pt-based alloy catalysts are mainly used. The main benefit of this is that even a tiny amount of CO reacts in light of large amounts of hydrogen.

Selective methanation is a promising technology as there is no need for the addition of external gas for the reaction to take place. Selective Methanation doesn’t relatetothe danger of explosion and the need for advanced controls that PROX requires. The sidereactions during CO Methanation are CO_2 methanation and reverse WGS. For selective separation of CO from hydrogen, Palladium and its alloys have been the most widely reported membranes for hydrogen separation. Palladium has high catalytic activity for hydrogen separation and high absorbency for the diffusion of hydrogen atoms. Considering that the palladium membranes are susceptible to embrittlement below 300°C and their tendency to suffer sulphur and carbon monoxide poisoning at low temperatures, Pd-based alloy membranes have been developed to overcome these effects and to enhance the hydrogen permeability. Pd alloy-based membranes can generate hydrogen with a purity of up to 99.9999% H_2.

Metal hydrides (MH) are one of the most favourable materials for effective hydrogen storage,considering stationary, mobile and portable applications. The procedureconsiders the selective adsorption of molecular hydrogen on the metal or alloy surface under specific temperatures and pressure. The hydrogen is decomposed into atoms, forming a solid solution MHx, followed by the formation of the metal hydride MHy. During desorption, the impurity gases are eliminated first. The most deployed MH for the separation and purification of hydrogen are the AB5-type. Various benefitsrange from simplicity, low energy consumption, relatively safe use, straightforward operation, and high purity (up to 99.999%). However, certain roadblocks, such as the impact of the composition of the fed gas on the final composition, the rate of absorption and the long-term stability, hinder the process.

Further, there is a need for the development of cheap materials in place of rare materials like Palladium etc. Most of the off-gases in Iron and steel have a substantial percentage of Hydrogen. If cheap membranes or alternative processes are built, large volumes of Hydrogen can be separated and used for Iron making instead of just burning in furnaces or power plants.

6.2. Carbon Accounting Methodology

The Life Cycle Assessment or LCA is a method used to quantify the environmental impact of a product throughout its stages of life, from raw material acquisition through production, use and disposal. Thus, they offer valuable assessment and identification of the most effective alternative feedstocks and processes which suits geographical sustainability and reduction of harmful emissions.

For India to harness the potential of hydrogen, it is imperative to define the contours of green hydrogen. Many countries are defining these boundaries based on the net carbon footprints needed to produce hydrogen from various technologies. A reference figure highlighting the permitted carbon footprints to produce hydrogen can trigger multi-dimensional strategies in addressing the hydrogen production constraints. This would also prevent the dependency on one type of solution, thereby insulating ourselves from geopolitical turbulences, raw material price variations, and supply chain constraints while providing the opportunity to integrate our social strengths with the hydrogen economy.

6.3. Balance of Plant (BoP) component manufacturing and validation

BoP components today are largely imported from other countries. Since the BoP components contribute significantly to the overall system cost, indigenous development and manufacturing arenecessary for cost reduction.

Most of the BoP components have some equivalent component being used in traditional, established sectors in India. Components from the automotive, shipping, and industrial sector can be adapted with ease for hydrogen applications. India has a large ecosystem of ancillary component manufacturing already, servicing various sectors formany decades. It is essential to apprise the component manufacturing industry of the opportunity in this new market.

The committee should clearly define component specifications for components to be used in hydrogen applications. The requirements for components specific to hydrogen applications may vary in terms of environment, gas handling, performance, efficiency, safety, lifetime etc.

Before commercialization, these component prototypes also should undergo validation of environmental, shock and vibration, endurance, EMI/EMC and safety compliance. Mentioned below are key components of BoP.

a. Compressor and Pumps

Air compressors, hydrogen recirculation pumps, water pumps, air filters and mufflers/silencers etc.

b. Valves and piping components

Various valves viz. On Tank Valve (OTV), solenoid valves, 2-way and 3-way valves, check valves, Flashback arrestors, proportional control valves, hydrogen fuel ejectors, back pressure and differential pressure valves etc.

Piping and hoses for handling hydrogen, air and coolant.

c. Humidifiers and Separators

Gas-to-gas humidifiers, water separators and heaters etc.

d. Sensors

Sensors for measuring various parameters, viz. pressure, temperature, mass flow, Relative Humidity, hydrogen leak sensors etc.

e. Power Electronics and Switchgear

DC-DC buck and boost converters, motor controllers (inverters), contactors and switchgear.

Annex

Annex 1 :Target of Key Performance Parameters for sustainable development of Electrolyser systems

Table 13:

Key Performance Parameters	Short term (0-5years)				Medium Term (0-8years)				Long Term (0-15years)			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Nominal current density [A/cm^2]	> 0.7	> 2	> 0.5	> 0.5	> 1.2	> 3	> 1	> 1	> 2	4-6	> 2	> 2
Cell pressure [barg]	> 30	> 40	> 35	> 1	> 40	> 50	> 50	> 5	> 70	> 70	> 70	> 20
Load range [%]	15-100	5-120	5-100	30-125	10-150	5-200	5-150	15-150	5-300	5-300	5-200	0-200
Electrical efficiency (stack) [kWh/Kg H_2]	< 55	< 55	< 60	< 50	< 50	< 50	< 50	< 42	< 42	< 42	< 42	< 35
Electrical efficiency (system) [kWh/Kg H_2]	< 65	< 65	< 70	< 55	< 58	< 58	< 60	< 48	< 45	< 45	< 45	< 40
Lifetime (stack) [thousand hours]	> 60	> 60	> 5	> 20	> 80	> 80	> 40	> 50	> 100	> 100	> 100	> 80
Cold start (to nominal load) [minutes]	< 50	< 20	< 20	< 600	< 40	< 12	< 12	< 450	< 30	< 5	< 5	< 300
Stack Unit Size	> 2MW	> 1MW	>2.5kW	> 5kW	> 5MW	> 5MW	>500kW	> 80kW	10MW	10MW	2MW	200kW
Capital Cost (stack) minimum 1MW [USD/kW]	< 270	< 400	NA	< 2000	< 180	< 250	< 200	< 800	< 100	< 100	< 100	< 200
Capital Cost (system) minimum 10MW [USD/kW]	< 800	< 1000	NA	NA	< 450	< 500	NA	NA	< 200	< 200	< 200	< 300

Annex 2 : Bhabha Atomic Research Centre – R&D activities in hydrogen production

1. Hydrogen production by electrolysis

In alkaline water electrolysis, BARC has successfully developed a complete plant, including the cell module and deployed it in industrial installations. The current plant has 10 Nm^3/hr hydrogen production capacity, and extensive trials have been done on the system. All the operating parameters are optimized, and safety systems are in place. The technology has already been transferred to eight parties, and it is also available for further transfer to other parties. Indigenous membrane diaphragm has also been developed and transferred to industry for commercialisation. Scaled-up technology for a 120 Nm^3/hr system also has been designed and incubated with the industry for commercialization. 10 Nm^3/hr of alkaline electrolyser developed by BARC is very much suitable for chemical industries like fertilizers, pharmaceuticals, metallurgical operations, and food, telecom, and fuel cell industry [3].

BARC is also carrying out PEM-based process R&D and developed an indigenous membrane suitable for this process. BARC has also demonstrated R&D scale membrane electrode assembly (MEA) preparation and tested for its performance, which is close to any other MEA available in the market. BARC has also developed electrode and bipolar plate fabrication and assembly techniques, which can be made commercial for laboratory-scale cell manufacturing and scaling up further.R&D on electrocatalysts for both alkaline water electrolysis and PEM-based electrolysers are underway [42]. Several low-cost electrocatalysts have been developed on the laboratory scale and havepotential for large-scale implementation.

In BARC, research activities on the development of efficient visible light active photocatalysts for assisting sunlight-driven photocatalytic hydrogen generation areundertaken. Titania and carbon nitride-based photocatalysts have been developed [50-54]. Incorporation of cationic dopants, p-n heterojunctions, exfoliation, dispersing metal nanoparticles as co-catalysts, etc., are some of the strategies adopted to improve the photocatalytic properties of parent compounds.

2. Hydrogen production by Thermochemical cycle

In thermo-chemical water splitting, BARC has tested all the reactions present in iodine-sulphur thermo-chemical water splitting. I-S thermo-chemical water splitting consists of three chemical reactions: 1) Bunsen reaction, which is the acid production step (exothermic, T=120^{0}C), 2) sulphuric acid decomposition to produce oxygen (endothermic, T=870^{0}C), and 3) hydrogen iodide decomposition to produce hydrogen (endothermic, T=450^{0}C). Suitable iron-based catalysts were developed to minimize the use of expensive platinum-based catalysts in the high-temperature H_2SO_4 decomposition reaction step[38-41]. A packed bed membrane reactor for HI decomposition was demonstrated. A metallic loop comprised of all reaction and recycle/ purification steps was operated successfully, producing hydrogen at 150 Nlph in July 2022. India is the first country to achieve these feet. Detailed engineering for scaling up the process to 3 Nm3/h is in progress.

BARC has demonstrated two step Hybrid Sulphur process at 10 Nlph hydrogenproduction capacity using industrial material of construction. Stackedtwo cells, SO_2 depolarized electrolyser was successfully operated. Theprocess was operated in a closed loop by recycling Sulphur dioxide and water.

Development of a four-step Copper-Chlorine (Cu-Cl) thermochemical cycle has been carried out at BARC[33-37]. Reaction feasibility has been established in bench-scale reactors for all four steps, viz. hydrolysis, thermolysis, electrolysis and crystallization. Subsequently, process parametric optimization of multi-phase reactors through kinetic and mechanistic studies hasbeen completed resulting in enhanced product yield and selectivity. R&D efforts on the thermal steps of the Cu-Cl cycle provided a thermal degradation pathway of Cu_2OCl_2 and a probable mechanism of $CuCl_2$ hydrolysis using in-situ XAS and TG-MS studies. Phase pure Cu_2OCl_2, which is commercially unavailable, was prepared successfully by alternate methods and was used for studies on thermal steps. In-house developed MEA was employed in offline looping and showed performance comparable to the imported one. The cycle has been integrated in offline mode with the design and development of auxiliary units.Installation, commissioning and demonstration of a metallic integrated facility with reaction and auxiliary steps for closed-loop operation havebeen completed.Installation of an integrated Cu-Cl facility is in progress for demonstration at 50 NL/h hydrogen production. Further, scale-up to 3000 NL/h hydrogen production is planned for coupling with next-generation nuclear reactors and solar heat sources. Thrust has also been given at BARC to develop a high-temperature reactor capable of supplying process heat at a temperature of around 1000°C, which envisage that besides electricity, nuclear energy would play a significant role in the production of alternate transportation fuel such as hydrogen, by splitting of water or steam electrolysis [2].

3. Hydrogen Production by High-Temperature Steam Electrolysis

Bharat Heavy Electricals Limited- R&D activities in the hydrogen value chain

1. Coal Gasification: BHEL has successfully developed and established a Coal gasification combined cycle demonstration plant (CCDP) at Tiruchirappalli, Tamil Nadu. The plant has a coal processing capacity of 168 Tons/day and is capable of generating 6.2 MWe of power. BHEL's expertise in coal gasification technology, particularly in fluidized bed gasification, has provided advantages such as feed size flexibility, high throughput, and no tar formation. The successful demonstration of this technology showcases BHEL's commitment to clean and efficient energy generation.

2. Methanol Production: BHEL has developed indigenous technology to convert high-ash Indian coal into methanol. The establishment of India's first pilot plant in Hyderabad is a significant achievement in this area. The pilot plant, with a capacity of 0.25 TPD, utilizes BHEL's fluidized bed gasification technology to produce syngas and convert it into methanol with 99% purity. This breakthrough technology enables the country to utilize its coal reserves efficiently and promotes the adoption of clean and sustainable energy sources.

3. Fuel Cell Research: BHEL has developed air-cooled and liquid-cooled Proton Exchange Membrane (PEM) Fuel Cell Stack and systems upto 5kW. BHEL focuses on optimizing various components of fuel cells, including bipolar plates, end plates, sealings, humidifiers, coolants, and thermal management systems. BHEL has also developed a hybrid electric golf cart integrated with a PEM fuel cell system, showcasing its capabilities in real-world applications. Ongoing developments include the design of a modular 25 kW fuel cell system, which can be scaled up to meet various energy demands. BHEL is also focusing on the development of a modular 60 kW fuel cell system

4. Center of Excellence for Hydrogen Systems: BHEL intends to establish a Centre of Excellence (CoE) for Hydrogen Systems at Varanasi. The CoE aims to enhance domestic engineering and designing capabilities in the hydrogen value chain for the critical components, specifically in the areas of electrolysers and type IV cylinders. BHEL recognizes the potential of emerging markets and seeks to indigenize the production of hydrogen systems. The CoE will focus on the development and production of high-quality type IV cylinders, establish a dedicated testing facility for cylinders, develop advanced Electrolyser systems, and serve as a knowledge hub for the hydrogen value chain. By establishing this CoE, BHEL aims to contribute to India's self-reliance and promote the adoption of hydrogen as a clean and abundant energy carrier

High-temperature steam electrolysis (HTSE) uses solid oxide cells to split steam into hydrogen and oxygen at an operating temperature in the range of 750 – 850oC. The high-temperature operation decreases the electricity demand (cell voltage), thereby improving the overall efficiency of the process. To realize hydrogen generation through HTSE, a tubular cell approach has been followed in which a porous Ni-YSZ support tube acts as a cathode. The cathode is coated with a thin impervious YSZ electrolyte layer followed by a suitable porous oxygen electrode (anode) layer. Fabrication technology of tubular HTSE cells has been developed. The steady performance of a single tubular cell has been demonstrated for a continuous operation of 150 h at a current density of 0.17 A/cm^2 generating hydrogen at a rate of 4 Nlph at 800^{o}C. Selection of suitable high-temperature sealant and oxidation resistant interconnect materials have been found to be crucial to realize hydrogen generation through HTSE, and R&D efforts are in progress to resolve these issues. In order to demonstrate HTSE technology, the integration of single cells to make a multi-cell stack hydrogen generator of higher capacity and performance evaluation of the stack for a long duration have been planned. The HTSE technology is promising as it can be coupled with high-temperature nuclear reactors / thermal plants from where high-temperature steam can be made available.

Annex 3 : ONGC Energy Centre (OEC) – R&D activities in hydrogen production

1. Closed-loop Cu-Cl cycle in collaboration with ICT, Mumbai

The proof of concept of the Cu-Cl cycle was established, and the laboratory-scale engineering metallic set-up for hydrogen generation at 25 LPH is operational at ICT, Mumbai. The electrodes, molten salt system for subsequent solar thermal storage, materials selection facilities, etc., have been successfully developed. The performance checks of existing systems for a prolonged period, separations, purifications, and integration of molten salt media as solar thermal heat storage are in progress now. Further work on scale-up to 12 MT/year hydrogen production is in progress[5].

2. Closed Loop I-S Cycle in collaboration with IIT, Delhi

R&D on hydrogen production through the iodine sulphur (I-S) thermo-chemical cycle was initiated, and a closed-loop process in quartz set-up was recently demonstrated. Process improvements with modification in electrochemical systems, purification of acids, minimizing cross-contamination, heat integration & process control, etc., are in progress now to plan for the metallic system at 15 bar pressure and 300 LPH hydrogen generation capacity[5].

3. Open Loop I-S cycle in collaboration with CSIR-IIP, Dehradun

The open-loop I-S cycle is an offshoot of the closed-loop I-S cycle that aims at developing a low-temperature alternative route for hydrogen production utilizing H_2S that is produced in refineries/ gas processing facilities. The project has the dual benefit of minimizing the release of H_2S into the atmosphere as well as the generation of hydrogen. The proof of concept in quartz systems has been established recently, and integration of various sub-sections is in progress now, based on which a pilot scale metallic system to produce 10-12 MTD H_2SO_4 is planned.

Annex 4 : Indian Oil R&D Centre, Faridabad – R&D activities

Oxy-steam biomass gasification in collaboration with the Indian Institute of Science, Bangalore

Indian Oil R&D and the Indian Institute of Science are jointly working on the development and demonstration of oxy-steam biomass gasification-based hydrogen generation technology. Proof of Concept of oxy-steam biomass gasification for hydrogen generation was demonstrated. An Indigenous vacuum pressure swing adsorption system (VPSA) was developed for the separation of fuel cell grade hydrogen from other gases at low pressure. Both oxy-steam biomass gasification and VPSA systems were extensively tested. Gas analysis methods have been developed for the quantification of the impurities present in bio-hydrogen to meet ISO:14687 specifications. Fuel cell grade hydrogen generation in a 5 kg/h hydrogen plant using a slipstream has been demonstrated. A small PEM fuel cell system has been extensively tested using bio-hydrogen generated from biomass gasification and ultra-high pure (UHP) hydrogen. Test results indicate that fuel cell system performance using bio-hydrogen exactly matches the performance using UHP hydrogen. Currently, preparation of the basic design and engineering package for the demo plant is in progress, based on which a 10 kg/h hydrogen generation demo plant will be set up at IOC-R&D.

Solar-based green Hydrogen production and dispensing facility

This project involves the design, manufacturing, integration, supply, installation & commissioning of the solar-powered electrolyser-based green hydrogen production system and dispensing station for refuelling hydrogen. The proposed facility consists of a Solar PV plant, Alkaline Electrolyser, Proton Exchange Membrane (PEM) Electrolyser, Solid Oxide Electrolyser Cell (SOEC) for Hydrogen production, Hydrogen compressors, Storage tubes (Type I, III & IV) & dispensers. A solar PV plant (1 MWp) will power the whole Hydrogen infrastructure facility producing green Hydrogen. Alkaline Electrolyser ~4.25 Kg/hr, PEM Electrolyser ~4.25 Kg/hr, SOEC ~0.5 Kg/hr production capacity will generate fuel cell grade Hydrogen at 10 bar pressure, which is compressed using Hydrogen compressors (total ~9 kg/hr) to 500 bar pressure and stored in high-pressure storage tubes of total 7000 L water Capacity (Type I- 3000 L, Type III- 1500 L, Type IV- 1500 L) at 500 bar pressure. The Hydrogen stored in the High-pressure hydrogen storage tubes will be dispensed in the demo Fuel Cell vehicles (both heavy-duty buses and light-duty vehicles) at 350 bar pressure using the Hydrogen dispensers (2kg/min).

Bio-CNG reforming-based hydrogen generation and dispensing infrastructure

Natural gas and bio-CNG reforming-based hydrogen generation plant is being set up for the production of hydrogen for undertaking fuel cell buses demonstration trials. This plant shall have the flexibility to operate with 100% natural gas; 50% natural gas and 50% bio-CNG; 50% natural gas; and 50% bio-CNG. The plant generates hydrogen, meeting ISO 14687:2019 - Hydrogen fuel quality specification. The proposed infrastructure includes a 20 kg/h steam methane reformer, two hydrogen compressors (capacity of 10 kg/h each) to compress hydrogen from 7 bar to 500 bar, and Type-I hydrogen storage tubes to store 200 kg hydrogen at 500 bars. A hydrogen dispenser is also available to dispense hydrogen at a refuelling rate of 2 kg/min to both heavy-duty buses and light-duty vehicles.

Aqueous Phase Reforming (APR) is a low-temperature catalytic reforming process for the production of higher quality hydrogen (with less CO) from weak solutions of bio-carbohydrates in a single reactor at low temperatures. In this process, reacting solution is kept in the liquid phase by using pressures slightly higher than the saturation pressure. IOC-R&D and the Institute of Chemical Technology (ICT), Mumbai, earlier worked jointly on the development of catalysts for APR of methanol and bio-oil. Out of the various catalyst systems tested for APR of methanol, Ni-CuAl hydrotalcite outperformed the rest. For the APR of bio-oil, Pt-NiMgAl (Ni-based hybrid materials from hydrotalcite, promoted with Pt) was very active, selective to hydrogen, and stable under APR conditions. Developed catalysts were scaled up by IOC-R&D and extensively evaluated in a reformer plot plant. Based on the in-house developed process for APR of methanol, BDEP for 5 Nm^3/hr hydrogen generation capacity compact methanol reformer has been developed jointly with L&T, Mumbai.

IOCL R&D is also pursuing research on photoelectrochemical (PEC) water splitting, Proton Exchange Membrane (PEM) electrolysis, and Anion Exchange Membrane (AEM) electrolysis.

Annex 5 : KPIT Technologies – R&D activities

Microbial dark fermentation process in collaboration with Agharkar Research Institute, Pune

KPIT has developed a microbial dark fermentation process for Hydrogen generation in collaboration with the Agharkar Research Institute from Pune, which is an autonomous institute of the Department of Science and Technology (DST). This is a unique two-step process that uses a novel microbial consortium to produce Hydrogen directly from biomass and Methane thereafter – which can also be converted into Hydrogen through Steam Methane Reforming. Along with the Hydrogen, the process also generates other valuable, recyclable products such as organic manure and CO_2.

The process is suitable for cellulosic biomass such as rice straw, wheat straw, Napier grass, energycane, etc.

The technology provides at least 25% more yield than conventional biomethanation processes. Being the first globally, a patent has been filed for the technology.

Currently, KPIT is working on the scale-up of the technology. A pilot plant with a total reactor volume of 15,000 litres will be commissioned in the next two months.

Hydrogen generation by gasification of biomass in collaboration with Ankur Scientific Technologies Pvt Ltd.

The other technology developed by KPIT for generating Hydrogen is based on biomass gasification. KPIT has partnered with Ankur Scientific Technologies, Vadodara – a company which has strong expertise in biomass gasification - to develop this technology. The technology is better suited for woody biomass and MSW. In this technology, the biomass is gasified to form producer gas which is treated further to generate pure Hydrogen. The process produces biochar and CO_2 as by-products which can be used for various commercial applications. Recently a pilot plant with a Hydrogen generation capacity of 125 kg/day has been commissioned for demonstration of the technology. A patent has been filed for this technology as well.

Annex 6 : Hydrogen production at different institutions in India

Table 14: Hydrogen production-related work at different institutions in India [11]

Sl No.	Institution	Nature of work
1	IIT Delhi	• Studies on the catalytic decomposition of sulfuric acid in the I-S process for hydrogen production • Studies on Bunsen reactor for the production of sulfuric acid and HI using electrochemical cell, the concentration of HIx solution using electrodialysis, catalytic decomposition of Hydrogen Iodide (HI) into I_2 and H_2, development of hydrogen transport membrane reactors for hydrogen iodide decomposition followed by hydrogen removal. • Modelling of a membrane electrolysis cell for Bunsen reaction and electro-electrodialysis unit for the concentration of HIx solution • Mechanistic studies on the catalytic decomposition of sulfuric acid in the I-S cycle for hydrogen production • Areas of design of nanostructured materials with applications in water purification, hydrogen generation, photoelectrochemical studies, superconducting materials (oxides, oxypnictides and oxychalcogenides)
2	IISc, Bangalore	• Hydrogen and liquid fuels from biomass gasification • Hydrogen generation using biomass gasification for a fuel cell application, multi-fuel gasification system to accept woody biomass or biomass briquettes, • Development of semiconductor nanocomposites for photo-catalytic water splitting into H_2 and O_2 under solar light irradiation, TiO_2-based photocatalysts for organic waste degradation
3	IIT Madras	• Electrocatalysis and photocatalysis for hydrogen production, generation of solar hydrogen
4	IIT Guwahati	• Optimized production of bioethanol and biohydrogen from lignocellulosic biomass in a fluidized-bed reactor

Sl No.	Institution	Nature of work
5	IIT Kharagpur	• Mission Mode project on hydrogen production through biological routes, maximisation of gaseous energy recovery from organic wastes through bio-hythane process, pilot scale packed bed reactor configuration for a high rate of hydrogen production, biological hydrogen production using distillery effluent and kitchen waste.
6	IIT Kanpur	• Photoelectrochemical water splitting and fuel cells
7	IIT Hyderabad	• Non-thermal plasma assisted direct decomposition of H_2S into H_2 and S • Transformation of greenhouse gases like methane and CO_2 into syngas/H_2 by low-temperature plasma catalysis
8	IIT Indore	• Hydrogen generation through catalytic route
9	CSIR-NEERI	• Development of an efficient hydrogen supply system through liquid organic hydrides
10	Banaras Hindu University	• Photocatalysis for water splitting • Conversion of methanol to hydrocarbons, catalytic cracking of Methane
11	UPES, New Delhi	• Establishment & demonstration of hydrogen production and utilisation facility through photovoltaic-electrolyser system at NISE located in Gwalpahari. • Survey on inventory and quality of by-product hydrogen potential in selected major sectors in India
12	IICT, Hyderabad	• Methanol reformer to produce 10kL/hour hydrogen coupled with 10kW fuel cell, 50kL/h reformer for 50kW fuel cell. • Catalysts for reformation of glycerol, generation of hydrogen from biomass-derived glycerol
13	C-MET, Pune	• Hydrogen generation by photocatalytic decomposition of toxic hydrogen sulphide, development of prototype

Sl No.	Institution	Nature of work
		• Photo-reactor for hydrogen production from hydrogen sulphide under natural sunlight, photocatalysts development
14	NIT, Calicut	• Investigation ofbio-hydrogen production by thermochemical method in fluidized bed gasifier under catalytic support and its utilisation
15	IACS, Kolkata	• Bio-inspired catalysts for the reversible conversion • $H+ + e- \rightarrow ½ H_2$
16	NIT Rourkela	• Production of hydrogen gas from biomass and wastes • using fluidized bed gasifier
17	CSIR-IMMT, Bhubaneswar	• Development of transition metal tantalates and oxynitrides for water splitting and pollution abatement • Functional hybrid Nanostructures for photoelectrochemical water splitting
18	ICT, Hyderabad	• Generation of hydrogen from biomass-derived. • Glycerol
19	ICT, Mumbai	• Process analysis for copper-chlorine (Cu-Cl) thermochemical hydrogen production process, ICT–OEC Process for copper-chlorine (Cu-Cl) thermochemical hydrogen production • The reaction of metals with HI, decomposition of certain transition metal iodides and biomass conversions
20	CECRI, Karaikudi	• Oxidation of CuCl and recovery of Cu, CuCl& recovery of Cu – energy optimisation, electrolysis of CuCl – HCl system for the preparation of $CuCl_2$& H_2, electrodes • Electrolytes for water electrolysis to generate hydrogen and hydrogen
21	ARCI-CFCT, Chennai	• Novel electrocatalysts, depolarisers for water electrolysis, seawater electrolysis

Sl No.	Institution	Nature of work
22	Tata Energy Research Institute	• Technology packages for woody and briquetted biomass using a throat-less gasifier with a closed top, large-scale bioreactor facility for bio-hydrogen production.
23	Naval Material Research Laboratory (NMRL), Mumbai	• Bio-hydrogen with chemical fuel cells for electricity generation, hydrogen generation by autothermal reforming
24	NIT Raipur	• Design of electrolytic cell for economic and energy efficient biohydrogen production from leafy biomass by electro-hydrogenases
25	NIT Tiruchirappalli	• Combined pyrolysis and steam gasification to establish multifuel Quraishy production with a maximum hydrogen yield
26	CSIR-IIP, Dehradun	• Open loop thermochemical S–I cycle of H_2S split for carbon-free hydrogen production in petroleum refinery
27	OEC, Mumbai	• Thermochemical hydrogen production, iodine-sulphur • & copper-chlorine cycle for hydrogen production
28	CIMFR, Dhanbad	• Production of hydrogen from renewable and fossil fuel-based liquid and gaseous hydrocarbons by nonthermal plasma reforming
29	Sardar Patel Renewable Energy Research Institute, Vallabh Vidhya-Nagar, Gujarat	• Dual fuel and thermal application, forced and natural drafts biomass gasification processes.
30	IACS, Kolkata	• Hydrogen evolution reaction (HER) by the [Fe-Fe]-hydrogenase enzymes, graphene oxide modified aza terminated ITO supported graphene as electrode material, catalyst development

Sl No.	Institution	Nature of work
31	ONGC	• Thermochemical hydrogen generation
32	University of Rajasthan	• CNT-doped polymeric membranes for hydrogen purification
33	JNTU Hyderabad	• Hydrogen production through biological routes • PEM-based water electrolysis, catalysts for hydrogen from glycerol • Studies on novel ways of enhancing CO_2 utilization in catalytic oxidative dehydrogenation reactions
34	SPIC Science Foundation, Chennai	• PEM methanol electrolyser for the production of 1 Nm3/hour of hydrogen
35	Shiksha 'O' Anusandhan University, Bhubaneswar	• Porous graphene-modified metal oxide photoanode for electrochemical water splitting
36	Thapar university, Patiala	• Reforming of biogas for hydrogen production and its • utilization in CI engine under dual fuel mode
37	DEI, Agra	• Synthesis and characterization of nanostructured metal oxides and quantum dots for solar hydrogen production, • Photoelectrochemical generation of hydrogen
38	BARC, Mumbai	• Thermochemical Hydrogen Generation by I-S process: Development of materials, and reactors for closed loop operation of I-S thermochemical closed loop. • Thermochemical Hydrogen Generation by Cu-Cl process: Development of materials and reactors for closed loop operation of Cu-Cl thermochemical closed loop • Electrolysis: Hydrogen Generation by Alkaline water electrolysis

Sl No.	Institution	Nature of work
		• Hydrogen production by High-Temperature Steam Electrolysis • Hydrogen production by Photocatalytic water splitting: Sunlight-driven hydrogen generation using low cost, visible light active photocatalysts in the presence of co-catalysts and sacrificial agent.

Annex 7 : Indian Patents in Multiple Hydrogen Production Pathways and Key Institutes

Table 15: Indian Patents in Multiple Hydrogen Production Pathways and Key Institutes

Pathways	No of Patents in Indian Jurisdiction	Key Institutes
Electrolysis • PEM • AEM • Alkaline • SOEC	322	• Council of Scientific & Industrial Research (CSIR) • Shell International Research MaatschappijB.V
Fossil fuel conversion • Coal gasification • Pet coke gasification • Natural gas/Methane reforming • Methanol reforming • Other hydrocarbon reforming • Pyrolysis	28	• Praxair technology inc • University of Southern California
Biomass and waste conversion	53	• Shell International Research Maatschappij B.V Indian Institute of Technology, Guwahati • NTPC limited • KPIT Technologies, Ankur Scientific Technologies
Thermal water splitting	17	• Council of Scientific & Industrial Research (CSIR) • International Advanced Research Centre for Powder Metallurgy and New Materials
Biological hydrogen production	375	• Council of Scientific & Industrial Research (CSIR)

Pathways	No of Patents in Indian Jurisdiction	Key Institutes
		• Bayer • KPIT Technologies, Agharkar Research Institute
Photochemical and photocatalytic	2	-
Nuclear	170	• Indian Institute of Science • Jawaharlal Nehru Centre for Advanced Scientific Research

Annex 8 : Methods for Hydrogen Storage

1. Underground Storage:

Hydrogen can be stored in large quantities and for longer duration in underground geological formations like salt caverns, depleted oil and gas reservoirs and aquifers. Storage of hydrogen in salt caverns is a relatively mature technology, while aquifers-based storage will require much more research before these can be used for storing hydrogen. Underground storage in salt caverns and salt domes are large volume, low-cost, natural storage options, but local availability can be a challenge. Indeed, underground hydrogen gas storage is about two orders of magnitude cheaper than tank storage when applied to volumes of several million Nm^3 of hydrogen [4].

As stated in the National Hydrogen Roadmap 2006, depending on the geology of an area, underground storage of hydrogen gas may be possible. For underground storage of hydrogen, a large cavern or area of porous rock with an impermeable cap rock above it is needed to contain the gas. A porous layer of rock saturated with water is an example of a good cap rock layer. Other options include abandoned natural gas wells,solution-mined salt caverns, manmade caverns and depleted or abandoned coal or mineral mines.

The Hydrogen Technology Collaboration Program (Hydrogen TCP) [5] (part of the International Energy Agency) states that subsurface reservoirs such as gas fields, aquifers and solution-mined salt caverns represent proven and mature options for large-scale storage of natural gas and its components carbon dioxide and nitrogen.

In many places in the world, these gases have been trapped in porous and sealed reservoirs over geological time intervals of millions of years. Even though hydrogen is the most abundant element inthe universe, natural accumulations in the subsurface are rare. Hydrogen could be stored in gas fields, but there is little experience with this option.

How does it work?

Engie[6]explains that Salt caverns are artificial cavities which are created in geological salt deposits, generally located at a depth of 500 to 1,500 metres. To create such a cavern, it is first necessary to drill into the salt. The second stage consists in injecting water into the salt to dissolve it. The resulting brine (water mixed with salt) is extracted and leaves room for a large, tight cavern where hydrogen can be stored under pressure.

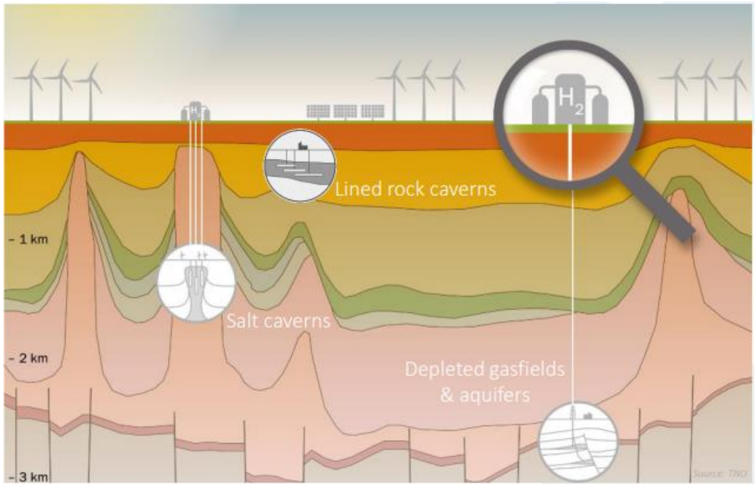

Figure 16: Depiction of Salt Caverns for Hydrogen Storage.

The advantages of hydrogen storage in salt caverns are as under:

- **Vital chain link**: Underground hydrogen storage will support the development of the renewable hydrogen sector by ensuring the security of renewable hydrogen supply.
- **Flexibility**: Salt cavern offers flexibility regarding itsinjection and withdrawal cycles to respond to the needs of the hydrogen market. Depending on their depth, salt caverns may be operated at pressures up to 200 bars and allow for large-volume hydrogen storage (from 9 to 6,000 tons).
- **Safety**: Due to their tightness, salt caverns allow for the safe storage of large quantities of hydrogen under pressure. The first hydrogen storage cavern, which was built in the United Kingdom in 1972, is still in service.
- **Resilience**: It is reported that Engineers India Limited[8] has a strategic Alliance with M/s DEEP.KBB GmbH, Germany, for salt cavern projects to jointly pursue basic design, detail engineering, project management and construction supervision services for underground and above-ground salt cavern storage facilities for hydrocarbons and other products like hydrogen & carbon dioxide for Indian and international clients. Based on the discovery and suitability, caverns could be converted into a cost-effective hydrogen storage facility to achieve the desired scale.
- **Economical**: Due to the low capital cost of the cavern, underground storage is among the cheapest methods, especially for very large quantitiesof storage.
- **Large Quantity Storage**: A very large quantity of Hydrogen can be stored in underground storage, which may be a constraint in above-ground storage options due to inherent safety concerns in above ground storage systems.

Some of the disadvantages of hydrogen storage in salt caverns are as under:

- **Under the developmental stage**: Engie[6] report highlights that there are 4 hydrogen storage sites in salt caverns existing in the world. These storage facilities are strategic reserves for use in hydrocarbon refineries. The frequencies and quantities used are low. For energy uses, injection and withdrawal cycles will have to be quicker and offer greater amplitude. Experimental evaluations of the consequences of such more intensive modes of operation would be required to confirm the concept and viability of future salt cavern hydrogen storage projects.
- **Purity of the hydrogen**: Another potential problem linked to the operation of a cavern with hydrogen is the development of the composition of hydrogen contained in the cavern. If the hydrogen is expected to absorb moisture (as is the case for natural gas), it is also possible that bacteriological and chemical reactions take place, thus transforming some of the hydrogen and modifying the overall composition of the gas. A specific treatment to purify the hydrogen at the cavern outlet could thus be necessary (in addition to dehydration).
- **Geographical scarcity**: The issue with salt caverns is the relative scarcity of salt deposits. In India, there are salt caverns available in Bikaner, which areunutilized until a solution for the disposal of the brine is found [7]. Indian Strategic Petroleum Reserves Limited (ISPRL)[8],whichoperates storage facilities of strategic significance, has commissioned crude oil storage at three locations, namely, Visakhapatnam, Mangalore and Padur (near Udupi). Notably, the crude oil storages are constructed in underground rock caverns and are located on the East and West coast of India.

Areas of Investigation:

Bringing together national and international research projects creates a need to answer questions such as: how does hydrogen interact chemically with the rocks it is stored in? Will microbes in the underground reservoirs consume the hydrogen, introducing impurities? How does the hydrogen move in the pores of the underground reservoir? How much hydrogen is lost when it is injected and extracted?

Apart from the above, broadly, the investigations should be carried out on the following categories:

- H_2 Conversion & Contamination: Impacts of reservoir and fluid processes on quality and recovery ability of stored H_2
- Storage Integrity: Integrity and stability of subsurface reservoirs and seals under H_2 storage operations
- Storage Performance: Estimation, ranking and optimization of H_2 injection, production and storage capacities in subsurface reservoirs
- Surface Facilities & Wells: Concepts, designs and materials for safe and effective storage of H_2
- Economics & System Integration: Pathways and business models for Commercialization and Integration of H_2 storage in the future energy system

❖ Planning, Regulation & Safety: Tools, guidelines, and best practices for safe and responsible subsurface H_2 storage development and operations

The next most cost-effective options to Salt Caverns are either rock cavern storage or reusing depleted hydrocarbon reservoirs. Depleted oil and gas reservoirs tend to be larger than salt caverns, but they are more permeable and contain contaminants that would have to be removed before the hydrogen can be commercially used [9].

2. Physical Hydrogen storage

When the stored hydrogen doesn't interact with the storage medium, then this is a physical method of storage, while in the chemical method of storage, the hydrogen interacts with the storage medium. The current near-term technology proven and being demonstrated for onboard automotive applications is the physical storage at 350 and 700 bar workingpressure in compressed gas vessels- "tanks." While low-pressure liquid hydrogen is used for bulk hydrogen storage and transport. "Cold" (sub-ambient but > 150 K) and "cryogenic" (150 K and below) compressed hydrogen storage are being investigated due to the higher hydrogen densities that can be achieved at reduced temperatures [2].

a. Compressed Hydrogen

Compressed hydrogen storage is one of the most established, technically viable and mature hydrogen storage technology. Compressed Hydrogen storage vessels can be classified into four standard types: Type I, Type II, Type III, and Type IV.

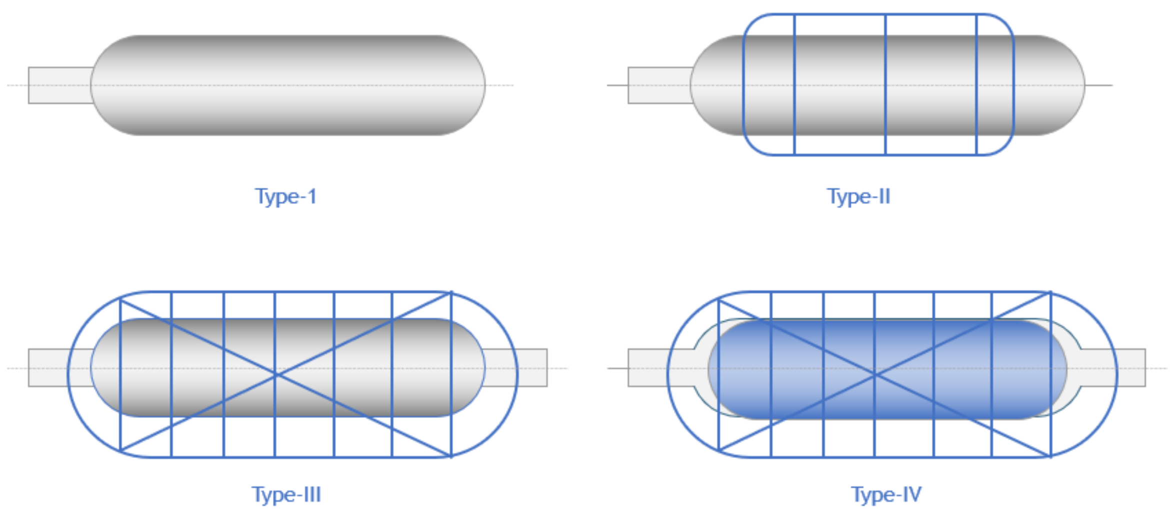

Figure 17: Different Types of Cylinders

Type I is an all-metal vessel (usually steel) and hence the heaviest, typically employed in industry for stationary use. Type II is a metal liner hoop-wrapped composite cylinder weighing less than a Type I cylinder. However, both Types I and II vessels are unsuitable for vehicle and transportation applications due to their weight. Type III vessels comprise a fully wrapped composite cylinder with a metal liner made of Aluminium alloy. The composite overwrap (usually carbon fibre embedded in resin) acts fully as the load-bearing component. Type III vessels offer a 25%–35% mass reduction over Type I and II hence more suitable for vehicle and transportation applications; however, they are more costly. Type IV vessels comprise a fully wrapped composite cylinder with a plastic liner (typically high-density polyethylene), which acts solely as the hydrogen permeation barrier. The composite overwrap serves as the load-bearing structure and is typically made up of carbon fibre or carbon/glass fibre composite in an epoxy matrix. Type IV vessels are the lightest of the pressure vessels, making them most suitable for vehicle applications;however, they are too costly.

Presently the largest manufactured compressed hydrogen tanks in the world (about 15000 m^3) can be pressurized only up to 12-16 bar. These tanks can be buried to save ground space and to provide improved protection against radiation from adjacent fires or damage caused by explosions. However, this is rarely used as it makes inspection of the vessels and interconnection of pipes less easy, and it requires a preventive measure to prevent corrosion. Nevertheless, to overcome the difficulty of inspection and pipe interconnection, it has been proposed to place the tanks in a basin and submerge them afterwards with a liquid such as water so that tank protection from heating and explosion is compatible with an easy inspection simply by lowering the water level in the basin.

For transportation applications, compressed Hydrogen types III and IV could be considered due to their comparatively lightweight, but the cost of the storage system is also important; hence there is an urgent need to bring down the cost of these cylinders for widespread adoption of Hydrogen fuel in India.

b. Liquid Hydrogen

The liquefaction of hydrogen is much more energy intensive than compression. The liquefied hydrogen storage suffers fromboil-off losses, and the evaporated hydrogen is released to maintain the tank pressure. Therefore, liquid hydrogen storage is impractical for hydrogen vehicles because of unavoidable losses [20]. However, this method of storage can be used for transporting hydrogen in larger volumes due to increased volumetric density. The requirement of super-insulated vessels is to maintain the temperature of 20K for the entire duration of storage and avoid any heat inflow leading to boil-off losses are the major concerns. Besides, around 30-40% of the energy content of hydrogen goes into liquefaction since the pressure of storage is ambient. As such, these tanks are designed to hold cryogenic hydrogen but not higher pressure.

c. Cryo-compressed hydrogen storage

To combine the advantages of compressed gas (in order to reduce the storage pressure) and liquid hydrogen storage (to improve the volumetric density), cryo-compressed hydrogen storage is used. In this method, the tanks store hydrogen gas at cryogenic temperatures under 250 – 350 bar pressure. The storage density is ~15% higher than liquid hydrogen storage. Nevertheless, this technology requires thorough research and development as the boil-off issues and expensive materials usage is inevitable. Thus, the tanks are made to hold both high-pressure and cryogenic temperature liquids[21].

3. Material based Hydrogen storage

In this method of hydrogen storage, hydrogen either gets absorbed chemically or gets adsorbed on the surface of various materials. The advantage of this method of storage as against compressed storage is the operating conditions are quite moderate. In compressed-state storage where hydrogen is compressed to high pressures, e.g., Type III (350bar) or Type IV(700 bar), the operating pressures in the solid-state storage materials can be ambient or close to ambient. The release temperature can vary depending upon the choice of the materials selected (again can be ambient or higher). Further, if we compare with liquid state storage, then the operating temperature, in this case, is close to ambient, while in liquid state storage, it's at 20K, and the boil-off losses are inevitable. The major advantages of solid-state storage methods are high volumetric density, moderate operating temperatures (room temperature to 80^0C depending on application) and pressure (ambient to 30 bar or more depending upon the application), and safe to operate. Safety is a prime advantage in the case of hydrides since the hydrogen release reaction is endothermic. If there is any hydrogen leakage, the reaction stalls on its own, making the system safe.

Based on the mechanism of hydrogen uptake, the materials can be broadly classified into physisorption-based or chemisorption-based materials. The different high surface area materials which can store hydrogen include zeolites, metal-organic frameworks, covalent organic frameworks, carbon-based materials etc. Since the bond formed in these materials is a weak Van der Waals bond as these materials have high capacity at low temperatures (preferably 77K), and at room temperature, the storage capacity is low. Although the kinetics and reversibility of these materials aregood, the storage capacity under NTP is low.

Another class of materials include materials where hydrogen uptake or release takes place chemically. These chemisorption-based materials can again be metal hydrides, chemical hydrides, complex hydrides, high entropy alloys etc. The bonding of hydrogen with the host in such materials is comparatively stronger than the physisorption-based materials. Metal hydrides are being widely studied and have the advantage of reversibility, better thermodynamics, and kinetics. Chemical and complex hydrides suffer from the challenges like high desorption temperature, sluggish kinetics and poor reversibility or irreversibility. Hydrogen is chemically bonded in the metal hydrides. These bonds are much stronger than the bonds involved in the adsorption of hydrogen. Consequently, more energy is needed to release the chemically bonded hydrogen. On the other hand, the stronger bonding allows hydrogen to be stored at high density even inambient conditions. This is an attractive alternative because of its versatility and because solid compounds can store more hydrogen per unit of volume than liquid hydrogen, and the biggest advantage is that it is a safe method of storage.

a. Metal Hydrides

Almost all the elements of the periodic table form hydrides;depending on the nature of the bond, these can be either ionic, covalent, or metallic hydrides. Metal hydrides have been specifically shown to be used for various applications like thermal applications, heating and cooling, heat pump, heat transformer, hydrogen compressors, for hydrogen purification systems.

There are several exhaustive reviews available in which the different types of hydrides, including the intermetallic, BCC solid solutions, and complex and chemical hydrides, have been discussed in detail.

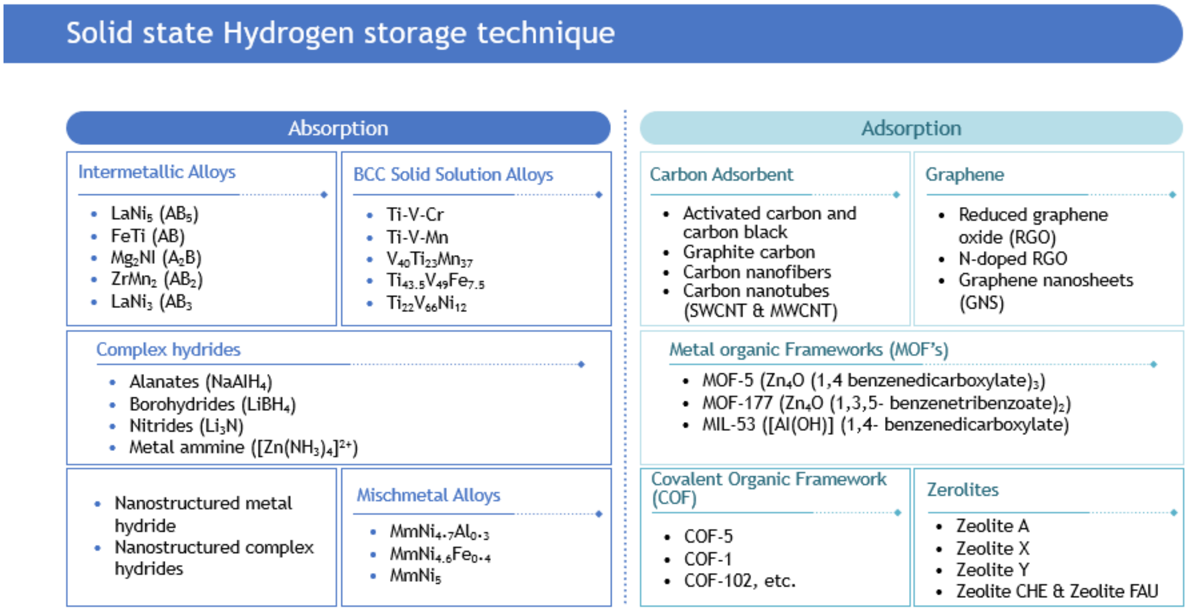

Figure 18: Different classes of materials for solid-state hydrogen storage [22]

The requirements forthese materials are quite different for stationary and vehicular applications. For vehicular applications, the weight and size should be low, refuelling should be fast, and the hydrogen storage system should be able to provide most of the characteristics which current fossil fuel vehicles have, like range, passenger space, safety, cost, acceleration/deceleration, start and stop, refuelling time, life and cost etc. when used in an FCEV. While for stationary applications, size and weight are not the major constraints, the cost, safety, stability, and life cycle are the main requirements.

b. Hydrogen storage in adsorption-based materials

Storage of hydrogen via adsorption exploits physical Van der Waals bonding between molecular hydrogen and a material. Due to the weakness of the van der Waals bonding, low temperatures and elevated pressures must typically be applied to achieve significant hydrogen storage densities. Most developed adsorption-based storage vessels have yet only been on the laboratory scale. The most significant challenges of an adsorption-based hydrogen storage system are heat management. While the interaction between the adsorbent and the adsorbed hydrogen is weak, typically 3–10 kJ/mol (hydrogen), the adsorption process is still exothermic. This produced heat must be removed efficiently to ensure that an adequate degree of adsorption can be reached.

c. Metal Organic Frameworks (MOF) & Covalent Organic Frameworks (COF)

These materials, which are based on the physisorption of molecules, remain more of a scientific curiosity and widespread applications are not expected soon. Some MOFs (like MFM-132a) can store a good amount of hydrogen >6 wt.% at 77 K and 20 barbut typically suffer from low storage capacity under ambient conditions. Synthesis methods of many of these MOFs arenot easily scalable, and hence their use is currently limited. Covalent Organic Frameworks (COFs) are also being investigated currently,but exciting results are awaited. Hybrids based on MOF have been synthesized (e.g., Pd-MOF hybrid), but these materials have not demonstrated any significant utility so far.

d. Advanced/Novel Materials

Advanced and Novel materials include non-conventional materials for hydrogen storage, many of which are still in the research stage and have not found widespread use. Their importance stems from the fact that some of these investigations may provide acritical breakthrough, which is urgently needed in the area for widespread applications. In this class, traditional materials in novel forms may also be included, e.g., Mg/MgH_2 in nanoscale form or hybrids based on carbon. Complex hydrides, Amides, Imides (& their Mixtures), Ammonia Borane and Related Compounds, and Aluminium Hydride (Alane) are some other materials which have been investigated in the context of hydrogen storage and may provide solutions to the existing requirements.

Nanomaterials and clusters rely on a high surface/volume ratio for good kinetics and, in the case of hydriding materials, to lower the activation barrier for hydride formation. These include unsupported clusters, nanoparticles, nanostructures, and 3D-supported (or scaffolded) nanomaterials. Typically, the crystallite size of the materials discussed is below 10 nm. Sandia National Laboratory developed a 3 kg $NaAlH_4$-based hydrogen storage system for vehicular applications with General Motors in 2012.

e. Carbonaceous materials

These include graphene-based materials (reduced graphene oxide, Boron-doped rGO, etc.), carbon nanotubes (including those decorated with catalysts like Ni), activated carbon, etc. Carbon in various forms, including mesoporous and nano hollow sphere forms, can be doped with nitrogen, boron and other elements to increase the binding energy and hence improve the storage capacity under ambient conditions. To improve the storage capacity of carbonaceous materials, hybrids have been synthesized (with Ni, Co, etc.),wherein the spillover mechanism and Kubas interaction effects are invoked.

In spite of some encouraging results published in recent times, intense research is required to produce these materials in large quantities for hydrogen storage applications.

Novel forms of Mg/MgH_2 and other nanostructures

In nano-form, researchers have shown that Mg can absorb hydrogen close to ambient conditions. Mg-C and Mg-Ni composites have also shown promise. In spite of the nanoscale structure, good cyclability has been demonstrated by some investigators. Some of the methods proposed seem amenable to scaled-up production, and hence the traditional material Mg (which in bulk form suffers from the high temperature of operation and slow kinetics) seems to be making a comeback and may be worthwhile investigating further (given that system is simple and inexpensive). One of the most significant results is by Hongge Pan and co-workers, wherein they have demonstrated a high storage capacity at 30°C along with good cyclability in a sample with non-confined Mg nanoparticles. Hollow nano and microstructures have also been used for the storage of hydrogen. These have so far been limited to the research level. Si-based nanostructures may offer exciting possibilities, and intense research is required in this area.

It is noteworthy that none of the materials iscurrently in large-scale production or widespread use.

System-level hybrid storage strategies

Currently, the three main hydrogen storage strategies are storage as compressed gas, storage as liquid (cryogenic) and storage in a material (solid-state). The higher the pressure of storage, the higher the volumetric (and gravimetric) capacity, and hence cylinders up to 700 bar are being used currently. High-pressure cylinders require high energy for compression and additionally pose a safety risk. The materials involved in the construction of the cylinders are also costly. A hybrid approach may yield good results, wherein moderate pressures (<50 bar) are used for the storage of hydrogen in a cylinder filled with a material. Herein, the molecular form of hydrogen is stored along with other adsorbed and absorbed forms of hydrogen to yield the desired capacity.

Chemical Hydrogen

Ammonia (NH_3) is an attractive hydrogen storage medium, it has a very high hydrogen storage density, 17.7% (wt) gravimetrically and 123 kg/m^3 volumetrically for liquid ammonia at 10 bars, and its synthesis, handling, and transportation is very mature. The most challenging technical aspect of using ammonia as a large-scale hydrogen storage medium is the dehydrogenation process. Ammonia starts to decompose spontaneously at temperatures exceeding 200^0C. Heat at high temperatures, typically above 650^0C must be supplied to achieve complete conversion. The most active catalysts for ammonia decomposition are based on ruthenium (Ru) that unfortunately, is likely to be too expensive for large-scale use, leading to catalysts based on cobalt, nickel, or iron being explored.

Liquid Organic Hydrogen Carrier

One of the promising hydrogen storage techniques relies on the reversibility and high selectivity of liquid organic hydrides, in particular, methylcyclohexane (MCH). The use of liquid organic hydrides in hydrogen storage provides high gravimetric and volumetric hydrogen density, low potential risk, and low capital investment because it is largely compatible with the current transport infrastructure. The concept of MCH (methylcyclohexane) and LOHC (Liquid Organic Hydrogen Carrier) has been explored since long back in 1979. The concept of hydrogen storage in liquid organic carriers has not been commercially established because of technical limitations related to the amount of energy required to extract the hydrogen from LOHC and the insufficient stability of the dehydrogenation catalyst, added cost and energy required to hydrogenate the spent carrier molecule to get back the parent LOHC

Annex 9 : National R&D in solid state hydrogen storage

Some of the research work being carried out at different institutions in the area ofsolid-state hydrogen storage in India is summarized below:

A lot of work has been carried out at IIT Bombay on materials for hydrogen storage. Various materials, including different metal hydrides, complex and chemical hydrides (catalyst and support, reversibility), solid solutions, high entropy alloys and LOHC, are being studied. Metal hydride-based systems simulation, design, and optimization of geometric and performance parameters, followed by the development, i.e., fabrication and their performance analysis experimentally, are being carried out at IIT Bombay. In addition, the Hydrogen Energy Centre, which was established at Banaras Hindu University with the funding of MNRE, had several pioneer works in the field of solid-state storage. In BARC, a variety of materials which include main group elements, transition metals/alloys, porous carbon, carbon nanotubes etc., were investigated in detail to develop efficient technologies for storing hydrogen[38-40]. A large number of metals hydride-based applications have been demonstrated at IIT Guwahati, IIT Mumbai and IIT Tirupati.

Studies on materials like TiVCr-based solid solutions o with Zr and Ni additives resultedin around 3.8wt% of storage capacity. Studies on the impact of heat treatment, particle size reduction, cooling rate during synthesis, the effect of additives, thermodynamics studies, kinetics and cyclability of metal hydrides like BCC solid solutions TiVCr with different additives, AB type alloys with additives Zr, V and Mn. Various low-cost and efficient catalysts and support materials were developed for complex hydrides like NaBH4, which have a high hydrogen generation rate (approx. 16.8 L/min-g) and good cyclability. Chemical hydrides like ammonia borane with high storage capacity, reversibility, suppression of undesired product species with the use of catalyst and support and with an 85% reversible capacity achieved (showing >16wt% storage). The synthesis of metal hydrides on a large scale, synthesis from industrial grade materials and the effect of impurities is being carried out, and it is found that the use of industrial grade materials reduced the cost by 83% as compared to the commercially available materials. Other materials like hollow glass microspheres have been studied, and ways to improve their pore size, pore density, thermal conductivity to enhance their hydrogen storage capacity havebeen studied and, with dopant 3.3 wt% hydrogen storage capacity reported for 10 bar and 200 ºC.

Metal hydride-based systems simulation, design, and optimization of geometric and performance parameters, followed by the development, i.e., fabrication and their performance analysis experimentally, are being carried out at IIT Bombay. Large-scale canisters for hydrogen storage have been developed and are at TRL 6, which can store upto 100 kg of alloys. The canisters have been developed for applications like backup power, heating & cooling, thermal energy storage and for vehicular applications and can be stacked to achieve higher capacity. Currently, canisters which can store 100g, 700g and 1 kg of hydrogen have been demonstrated and integrated for various applications. Also, studies on Mg-based hydrides and their composites are being carried out at IIT Bombay.

Hydrogen Energy Centre which was established at Banaras Hindu University with the funding of MNRE, had several pioneer works in the field of solid-state storage. This Centre, under the guidance of the late Dr O. N. Shrivastava, has worked extensively on various novel materials, carbon nanotubes/nanofibers, graphene and composites. Extensive studies were carried out on several hydrides, including the Mg-based hydrides for reducing the desorption temperature with the use of Mm or Fe_3O_4 on graphene sheets.

In BARC, a variety of materials which include main group elements, transition metals/alloys, porous carbon, carbon nanotubes etc., were investigated in detail to develop efficient technologies for storing hydrogen. Based on these studies, transition metal-based ternary alloy, Ti_2CrV, is found to be quite promising for developing hydrogen storage modules for vehicular applications. The alloy absorbs around 4 wt.% hydrogen under ambient temperature and sub-atmospheric pressures, while hydrogen desorption starts around 70°C. Detailed cost calculations using the IAEA-developed Hydrogen Economic Evaluation Program (HEEP) also confirm the cost-effectiveness of the alloy-based hydrogen storage technology compared to the one based on gas storage cylinders.

On the applications side, the group demonstrated hydrogen-fuelled Internal Combustion (IC) engine-based two-wheelers, which was further extended to three-wheelers and small cars. The hydrogen-fuelled vehicles were developed at Hydrogen Energy Center, BHU, and those were demonstrated. The developed vehiclespl had a range of ~60–80 km for two-wheelers and ~60 km for three-wheelers (at a top speed of ~50 km/hr) for single charging.

In the metal hydride-based storage systems, the reactor design is very crucial because of the exothermic and endothermic absorption and desorption processes resp. As such, the design requires efficient thermal management to ensure better performance, fast charging/discharging and achieving close to the theoretical capacities. A lot of system-level simulation and optimization work has been carried out at IIT Madras, IIT Guwahati and IIT Tirupati.

On metal hydride-based systems side thermal modelling to study the effect of various parameters on absorption rate in a cylindrical reactor with finned tube heat exchanger made of copper pin fins and tubes, also a single stage four bed cooling system was studied at IIT Mumbai.

Thermal conductivity studies required for thermal management in metal hydride systems are carried out for a wide range of materials at IIT Tirupati. Novel concepts of metal hydride compact with the incorporation of graphite flakes and heat enhancement surfaces have been developed and tested for improving effective thermal conductivity and achieving better heat transfer. Synthesis, characterization and thermodynamic studies of different intermetallic compounds and their utilisation in the development of solid-state hydrogen storage systems for combined heating and cooling systems, compressors, and thermal energy storage has been carried out at IIT Tirupati.

The DST – IIT Bombay Energy Storage Platform on Hydrogen has been established with an aim to carry out materials and systems research, prototype demonstration, technology development, incubation of innovative ideas, industry interactions, collaborations, manpower development and information dissemination in the field of hydrogen. The focus of the Centre is towards the synthesis of large-scale materials, i.e., Metal Hydrides (MH) and other novel materials, fabrication of MH-based fast reaction beds and testing the performances of various MH thermal management systems for various applications. The lead organization is IIT Bombay and has four partnering institutions,includingIIT Guwahati, IIT Kanpur, IIT Tirupati, and NIT Rourkela.

Metal hydrides, including AB_2, AB_5 and other alloys synthesis and their characterization work,havebeen extensively carried out at the University of Rajasthan. The analysis has been utilized in the development of large-scale hydrogen storage systems such as compressors.

At IIT Delhi Microgrid powered by an MH-based hydrogen storage system (5000 litres) has been installed in the Centre for Energy Studies IIT Delhi. The 5kW PV works as the primary power generation unit. The institute is involved in active research in the field of hydrogen storage materials at the atomic level using first principal methods, development and detailed study of different classes of hydrides.

At IIT Kanpur, development of various classes of hydrogen storage materials ranging from intermetallic compounds, high entropy alloys and nanohybrids are being carried out at Hydrogen Energy Systems Lab. The utilization of this form of hydrogen storage system hasbeen demonstrated for applications such as refrigeration and compressors.

Studies on borohydrides, intermetallic compounds and high entropy alloys, experimental studies on the determination of thermal conductivity of hydrogen storage alloys and the development of metal hydride-based cooling systems and hydrogen storage systems have been done at IIT Indore.

Synthesis, characterization, and thermodynamic studies of hydrogen storage materials such as MOF, intermetallic compounds, etc., studies on the hydrogen embrittlement on various materials and development of Type III and Type IV tanks arebeing carried out at IIT Ropar. At IIT Ropar, the focus is on in-house manufacturing of all major components of these tanks, such as a plastic liner using a rotomolding process, metallic boss using hydrogen embrittlement-resistant metals and precise carbon fibre winding using a robotic fibre winding system.

Together with IOCL, a lot of work towards manufacturing Type III and Type IV tanks is being carried out, especially the design and development of the compressed gaseous cylinders at IIT Kharagpur, which is mentioned in the section below. Besides, research on adsorption-based gas storage systems was done at IITKGP.

Numerical and experimental analysis on solid-state hydrogen storage systems has been carried out at IISc Bangalore for hydrogen storage, thermal energy storage systems, etc.The group at IISc is working on analysingthe performance of solid-state hydrogen storage-assisted standalone polygeneration microgrids for various climatic zones of India. The components of a polygeneration stand-alone microgrid are optimized in a way to utilize the maximum electricity generated by solar PV to meet the electrical load demand.

A lot of studies on Engines at the Unconventional Fuels laboratory of IIT Delhi werecarried out, and the use of hydrogen for both the spark ignition as well as compression ignition engines without any major modifications in the existing systems was demonstrated. A novel manifold injection system to address undesirable combustion phenomena such as backfire and rapid rate of pressure rise in the case of hydrogen was demonstrated.

Hydrogen storage in silicon-based materials is being carried out at NIT Rourkela.

Annex 10 : Overview of technologies with their respective power generation capacity

Table 16: Overview of technologies with their respective power generation capacity

Technology	Power generation capacity	Distributed centralised	Remarks
Hydrogen based technologies			
Green Hydrogen / other sources generated clean hydrogen / PEMFC system	kW to MW level	Distributed & centralised use	Cost of PEMFC is an issue considering Pt availability. BoP, like Power electronics, control systems etc., needs customization – expertise widely available in India. Low life (<6000 hrs) of PEMFC is a concern. Govt policy required for stack renewal. Tank-to-wheel efficiency is ~45-55%.
Green Hydrogen / other sources generated clean hydrogen / PAFC system	kW to GW level	Distributed & centralised use	Cost of PAFC is an issue considering Pt availability. BoP, like Power electronics, control systems etc., needs customization – expertise widely available in India. High life (> 60,000 hrs) of PAFC is an advantage. All technology available in India thru the DRDO initiative. Govt policy required for capital build-up. Overall tank/wheel efficiency ~ 45-55%
Green Hydrogen / other sources generated clean hydrogen / SOFC system	MW to GW level	Centralised use	Technology maturity is low, and more research initiatives required. Cost of present system ishigh but can be brought down;life expectancy is moderate, Tank-to-wheel efficiency ~60%. Do not require Pt

Technology	Power generation capacity	Distributed centralised	Remarks
Green Hydrogen / other sources generated clean hydrogen / AFC system			Technology less mature. Research initiative required. Cost of the present system could be low;life expectancy is low, Tank-to-wheel efficiency high ~60%. Do not require Pt.
Green Hydrogen / other sources generated clean hydrogen / ICE engine	kW to MW	distributed	Low cost, Easily configurable by Indian industries, poor tank-to-wheel efficiency ~25-30%.
Green Hydrogen / other sources generated clean hydrogen / H_2 gas turbine engines	MW to GW	centralised	High-temperature material required, new technology, High tank-to-wheel efficiency possible ~45-50% Academia-industry model can be deployed. Various technology developed by DRDO for jet engines can be useful for the same
Non-hydrogen green technology alternatives			
Direct solar PV / Li-ion battery storage	kW level	distributed	High battery cost, matured technology, only for small, distributed power
Direct solar PV / Na- ion battery storage	kW level	distributed	new technology to be developed, only for small, distributed power
Air-borne tethered wind mail / Li-ion battery storage	kW level	distributed	Site limitations, technology to be developed directly thru industries, and DRDO Aerostat technologies may be useful. Low power use
Biomass gasifiers / Fuel cell	kW-MW	Distributed	High potential technology, carbon neutral, FC type selection critical: a) PAFC: very well suited due to CO tolerance and very long life. Cost is high, Pt availability an issue

Technology	Power generation capacity	Distributed centralised	Remarks
			b) PEMFC: lower life and low CO tolerance, requires gas cleaning technologies that increase cost c) SOFC: technology well suited and overall efficiency increase if coupled with co-generation to utilize the waste heat. Technology needs development. Pt free option.
Biomass gasifiers / Engine	kW-MW	Distributed	High potential technology, carbon neutral, mature technology since the engine can be easily configured. Low efficiency of engines makes the process less viable however can be introduced in the initial phase in support of the industry.
Green coal gasifier technology + engine	MW-GW	centralised	High potential technology, mature technology since the engine can be easily configured. Low efficiency of engines makes the process less viable. CO_2 sequestration can be an issue causing low implementation, however, can be introduced in the initial phase in support of industry.
Green coal gasifier technology + fuel cells	MW-GW	centralised	High potential technology, CO_2 sequestration can be an issue causing low implementation, FC type selection critical: a) PAFC: very well suited due to CO tolerance and very long life. Cost is high, Pt availability an issue b) PEMFC: lower life and low CO tolerance, requires gas cleaning technologies that

Technology	Power generation capacity	Distributed centralised	Remarks
			increase the cost c) SOFC: technology well suited and overall efficiency enhances if coupled with co-generation to utilize the waste heat. Technology needs development. Pt free option.

Annex 11 : Technology comparison for light passenger/ commercial vehicles

Table 17

Technology	Remarks (considering power generation capacity of 50 to 200kw
Hydrogen based technologies	
High-pressure bottled H_2 + PEMFC	Cost of the PEMFC drive is an issue. Pt availability for even 50 lakhs car may be an issue considering about 30 to 50 gm of Pt requirement per vehicle. BoP, like Power electronics, control systems etc., needs customization – expertise widely available in India. Tank-to-wheel efficiency is ~45-55%. Safety protocols for operation and maintenance and regulation procedures with respect to hydrogen storage need to be arrived at.
High-pressure bottled H_2 + PAFC system	Cost of PAFC is an issue considering Pt availability. Too heavy and not suitable for light vehicles.
High-pressure bottled H_2 + ICE engine	Simple technology but low tank-to-wheel efficiency of ~18-22% may limit the range and cost of operation owing to the high H_2 need per km of travel. The safety protocol forH_2 storage needs to be developed. NOx pollution is still possible.
Onboardgenerated hydrogen-based technologies using fossil fuel	
Methanol / DME onboard reformer + PEMFC /PAFC	Complicated technology, high cost and not flexible for short irregular use. Tank-to-wheel efficiency is ~37-42%, and overall suitability not existing.
CNG onboard reformer + PEMFC /PAFC	Complicated technology, high cost and not flexible for short irregular use. High temp process not suitable for quick start-up etc.
Non-hydrogen-based green technologies	
Li-ion battery	Highly matured technology already implemented. Range of operation and additional charging time, charging infrastructure needs to be developed. Future will depend upon the reduction of Ni, Co type metal requirements along with the availability of Li to allow heavy scale deployment.
Na-ion battery	High potential, especially with respect to lower cost possibility and high availability of Na metal. New technology and also need reduced use of Ni and Co.
Al/air battery	Single-use primary batteriesmay not be cost-effective for general-purpose use. Continuous battery replacement after a short span of time may cause supply chain problems as well.

Annex 12 : Technology comparison for heavy commercial vehicles, special purpose vehicles like material moving vehicles, e.g., cranes, forklifts, etc., light passenger/ commercial vehicles

Table 18

Technology	Remarks (considering power generation capacity 300kW to 1MW
Hydrogen based technologies	
High-pressure bottled H_2 + PEMFC	Cost of PEMFC, along with Pt, could be an issue. BoP like Power electronics, control systems etc., needs customization – expertise widely available in India. Tank-to-wheel efficiency is ~45-55%. Safety protocols for operation and maintenance and regulation procedures for hydrogen storage need to be arrived at.
High-pressure bottled H_2 + PAFC system	Cost of PAFC is an issue considering Pt availability. Although heavy compared to PEMFC, however owing to its long life and considering regulated use, this is worth considering for the higher power end requirement.
High-pressure bottled H_2 + ICE engine	Simple technology but low tank-to-wheel efficiency of ~18-22% may limit the range and cost of operation owing to the high H2 need per km of travel. Safety protocol forH_2 storage needs to be developed. NOx pollution is still possible. Considering the dramatic increase inH_2 storage requirement and the longrange required for such vehicles, this may not be a feasible option. However, for short-range use like forklifts, cranes etc., this may be useful.
Onboard generated hydrogen-based technologies using fossil fuel	
Methanol / DME onboard reformer + PEMFC /PAFC	Complicated technology, high cost but good Tank to wheel efficiency ~37-42% may be attractive for regulated use vehicles like buses and long-range heavy trucks. Pt availability will be an issue.
CNG onboard reformer + PEMFC /PAFC	Complicated technology, high cost but good tank-to-wheel efficiency ~37-42% may be attractive for regulated use vehicles like buses and long-range heavy trucks. Pt availability will be an issue.
Non-hydrogen-based green technologies	
Li-ion battery	Highly matured technology, however, considering the high-power need, the range may be an issue since the weight of the battery will also be high. Safety concern for high-capacity battery, especially when parked in a crowded area, needs detailed study and safety adaptations.

Annex 13 : Different technologies considering the power generation capacity

Table 19

Technology	Remarks (considering power generation capacity 500kW to several MW
Hydrogen based technologies	
High-pressure bottled H_2 + PEMFC	Limited range, more suitable for shunting engines and other EMU coaches etc. Cost of PEMFC, along with Pt, could be an issue. BoP, like Power electronics, control systems etc., needs customization – expertise widely available in India. Tank-to-wheel efficiency is ~45-55%. Safety protocols for operation and maintenance and regulation procedures for such hydrogen storage, both for onboard and land storage, need to be arrived at.
High-pressure bottled H_2 + PAFC system	Similar issues like PEMFC, although heavy compared to PEMFC, however owing to long life and considering regulated use this is worth considering for the higher power end requirements.
High-pressure bottled H_2 + ICE engine	Simple technology but low tank-to-wheel efficiency of ~18-22% may limit the range and cost of operation owing to the high H_2 need per km of travel. May not be very suitable owing to the low range.
Onboard generated hydrogen-based technologies using fossil fuel	
Methanol / DME onboard reformer + PEMFC /PAFC	High cost but good Tank to wheel efficiency ~37-45%. Considering the renewable methanol /DME fuel that could be carbon neutral as well, this may be an attractive proposition for locomotives of any type. Considering regulated use, this system is highly feasible. Cost issues of PAFC/PEMFC need to be managed thru appropriate govt subsidies, as discussed before.
CNG/LNG onboard reformer + PEMFC /PAFC	High cost but good Tank to wheel efficiency ~30-37%. Considering the high availability of CNG, which is less polluting in nature and for FC power trains, actual CO_2 is further lowered owing to better efficiency;this may be an attractive proposition for locomotives of any type. Considering regulated use, this system is highly feasible. Cost issues of PAFC/PEMFC need to be managed thru appropriate govt subsidies, as discussed before.
Non-hydrogen-based green technologies	
Li-ion battery	Highly matured technology;however, considering the high-power need, the range may be an issue since the weight of the battery will also be high. Safety concern for high-capacity battery, especially when parked in

Technology	Remarks (considering power generation capacity 500kW to several MW
	a crowded area, needs detailed study and safety adaptations.

Annex 14 : Literature review

Summary of Global WTT Studies

The comprehensive analysis reveals that the findings vary from region to region and are extremely influenced by other factors like the primary energy basket of that region/country, electric grid efficiency, feedstock availability and prices, distance between the production and demand centres and purity requirement for end-use application.

Koroneos et al. reported a study on the comparison of WTT emissions of various hydrogen production pathways, including SMR and other renewable options like solar PV, wind, hydropower and solar thermal energy. The analysis reported H_2 from solar PV as the most environmentally hazardous solution in the renewable category owing to its higher (50-80%) CO_2, SO_4, PO_4 and SPM equivalent emissions. Centinkaya et al. compared WTT emissions and energy usage for five H_2 production processes-SMR, coal gasification, water electrolysis via solar and wind, and thermochemical water splitting with the Cu-Cl cycle with Canada-specific considerations. The study revealed wind electrolysis as the most environmentally benign method of H_2 production, followed by solar PV power. Studies conducted in different parts of world-China, Spain and the EU concluded that WTT CO_2 equivalent emissions for grid electricity are 7-10 times more intense than conventional diesel. When compared with H_2 from NG, diesel was reported to be less emission-intensive by 70-80% at the WTT stage. These studies also reported that the CNG fuel pathway is 30-50% less emission-intensive than diesel.

Hwang et al. compared WTT emissions of various conventional and alternate fuels for coastal ferriesin the Republic of Korea. The work reported NG to be less emission-intensive than Marine Gasoil (MGO) and H_2 from SMR in the WTT phase. It also reported that H_2 from renewable energy is at par in terms of CO_2 emissions when generated through the nuclear route. However, the H_2 produced via coal gasification or grid electricity was concluded to be 25-45% more emission-intensive than renewable-based H_2.

Wong et al. presented that WTT emission for conventional gasoline is 50% lower than H_2 from SMR based on data in UK, Germany and Denmark, whereas H_2 becomes an attractive solution if routed through wind electrolysis as it reduces GHG emissions by 60-70% when compared to conventional gasoline at WTT stage. Ozawa et al. compared different renewable H_2 supply chains originating in Australia and Norway. The study concluded that wind or solar-based liquid hydrogen (LH_2) is less emission-intensive compared to reference SMR-based H2 by 50-60%. Analysis by Schönsteiner et al. on alternative marine and aviation fuels in Singapore inferred that WTT energy consumption of LNG is similar to conventional bunker fuels, and LH_2 based on renewable energy sources would lead to near complete avoidance of GHG emissions.

As apparent from the above-cited literature survey, there is a wide variation in the outcome of several studies conducted in different parts of the globe to compare a variety of energy pathways at the WTT stage.

Summary of Indian WTT Studies

In India, a limited number of studies have been reported comparing hydrogen fuel cells with other mobility options. Also, such analysis was restricted to only the passenger car segment.

Patil et al. presented well-to-tank energy and emission analysis for gasoline, diesel, CNG, LPG, electricity, and H_2 from NG from the Indian perspective. The data indicated that the WTT efficiency of conventional gasoline, diesel, CNG and LPG (>70%) is much higher than H_2 (~45%) and electricity pathways (~20%). The study further inferred higher WTT emissions for electricity mix (20 times than conventional diesel) in India due to the larger pie of coal.

Chugh et al. investigated well-to-tank energy consumption and CO_2 emissions for hydrogen production using multiple pathways and its transportation to the point of use. It was found that out of all pathways investigated for hydrogen production, minimum energy consumption (220 MJ/kg) is reported for the Solar to hydrogen pathway, followed by natural gas reforming (267 MJ/kg). Air gasification of biomass process consumes 367 MJ/kg and while 478 MJ/kg is required by the bio-methanation process.

While Solar based H_2 generation pathway emits 18 kg of CO_2 /kg of H_2,equivalent emissions for steam methane reformed H_2 pathway wasreported to be 24 kg/kg of H_2. Biomass gasification technology emits 13 kg/kg of H_2 of emissions, followed by biomethane reforming.

The above investigation highlights the potential of biomass as a promising alternative to fossil fuels along with solar energy for the Indian scenario.

In the Indian context, where multiple alternatives are emerging to address the energy conundrum, it is imperative to present a fresh outlook by comparing such potential pathways for hydrogen production for well-to-tank emissions and energy consumption, which can be further extended to include the CO_2 footprints and energy consumption from end use application to derive an overall well to wheel landscape.

In order to realize a hydrogen-based economy, hydrogen needs to be produced on a mass scale in a sustainable way. To achieve this, hydrogen needs to become cost-competitive with conventional fossil-based fuels, and its technologies need to be scaledup. Challenges and gap areas for large-scale sustainable hydrogen production and proposed short-term, mid-term and long-term initiatives

Annex 15 : Hydrogen safety: focused Research areas

Investing in research and development in the areas mentioned below is crucial to ensure the safe and effective use of hydrogen in various applications, ultimately leading to a sustainable future.

I. Potential Research Topics based on knowledge gaps

- Hydrogen explosion modelling refinement: There is a need for more accurate modelling of hydrogen explosions to better understand blast waves, flame speeds, and other explosion characteristics.
- Development and evaluation of wide-area hydrogen sensing technology: Current sensing technology is limited in its ability to detect hydrogen leaks, especially in large areas such as refuelling stations.
- Hydrogen effects on materials, specifically fatigue loading: The long-term effects of hydrogen exposure on materials, including fatigue loading, need to be better understood to ensure the safe use of hydrogen in various applications.
- Hydrogen gas cabinets: There is a need for more information on the design and operation of hydrogen gas cabinets to prevent hydrogen leaks and ensure safe storage.
- Hydrogen deflagrations in partially enclosed areas: The behaviour of hydrogen deflagrations in partially enclosed areas is not well understood, which is critical for designing safe hydrogen storage and transportation systems.
- Pressure relief device reliability: There is a need for more reliable pressure relief devices to prevent overpressure and potential explosions.
- Confined release mitigation strategies: There is a need for more effective strategies to mitigate the consequences of confined hydrogen releases.
- Design, installation, testing, and maintenance of hydrogen detection systems: There is a need for standardized guidelines for the design, installation, testing, and maintenance of hydrogen detection systems.
- Ignition limits/criteria for large leak (dynamic) scenarios: There is a need for more information on ignition limits and criteria for large hydrogen leaks to prevent explosions and ensure the safe use of hydrogen.
- Hydrogen safety study on infrastructure: There is a need for a comprehensive study of hydrogen safety in infrastructure, including fuelling stations, storage facilities, and transportation systems.
- Fire barrier effectiveness: The effectiveness of fire barriers in preventing the spread of hydrogen fires needs to be better understood to ensure the safe use of hydrogen in various applications.

II. Broad research areas

- Review of the risk assessment tools for predicting and preventing process accidents in the hydrogen industry
- Approaches to managing human factors in hydrogen production, transmission and application - Human reliability analysis, Human factors lab
- Recent advancement of experimental techniques and measurement diagnostics for risk and reliability analysis of hydrogen handling
- Advanced computational simulations and modelling software for hydrogen accidents' consequence modelling (e.g., fire, explosion, thermal radiation) - predicting leak frequencies and ignition frequencies allow for estimating risks and comparing those to acceptance criteria.
- Sensing and monitoring advancement toward hydrogen safety
- Machine learning applications and data-driven models in risk assessment and management of hydrogen process

(i) Blending Hydrogen into Natural Gas Pipeline Networks: addressing Key

Issues and challenges

- Lifecycle assessment
- Impact on End-use System
- Safety assessment
- Leakage assessment
- Material compatibility and durability assessment
- Material Embrittlement
- Modelling of Hydrogen injection into NG pipelines
- Codes and Standards Assessment for Hydrogen Blends into the Natural Gas Infrastructure
- Current Status and Novel Approaches

(ii) Safe storage of hydrogen

- **For gaseous hydrogen (GH_2)**
    - gas cloud build-up in ventilated rooms
    - a study on the properties of GH_2 jet fires
    - spontaneous ignition and flame propagation in congested environments, including deflagration-to-detonation transition
    - tunnel safety
    - explosion mitigation

- **For liquefied hydrogen (LH_2)**
    - BLEVEs of storage vessels
    - releases of LH_2 on and underwater

  - combustion and dispersion of clouds developing from LH_2 pools
  - ignition by electrostatic charging during releases of LH_2 and
  - effect of temperature on combustion properties of H_2 and
  - LH_2 jet fires

- **Determination of the Safety Integrity Level of hydrogen systems to determine the requirements for instrumented risk reduction measures**

(iii) Safe generation of hydrogen

- Electrolyser and component performance, quality, manufacturing, and safety
- Green H_2 production project design, construction, and operation (including Ventilation, Leak Detection: H_2 sensors, Electrical Equipment Consideration, Outdoor separation and varying pressure, and Selection of materials)
- Hydrogen uses in Industrial applications
- Green H_2 certification and trade-related regulation

(iv) Safe transport/utilization of hydrogen

- Measurement of Green H_2 production and utilization
- Safety response due to normal and hazardous environmental conditions
- Emergency Response
- Safety requirements for retrofitting green hydrogen in the existing infrastructure of refineries and the fertilizer sector
- Safety aspects (fire explosion hazards, QRA, impact radius, hazardous area classification, etc.) for blended hydrogen for transportation, utilisation
- Principles and approaches for the safety assessment of Hydrogen vehicle

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