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 focused 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 while 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 governments 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 have R&D projects that are aligned with targets, are time bound, and have a potential for scale-up.

b) The proposed R&D program has been drafted in consultation with the 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 entailing the development of domestic modular electrolysers, Type III/Type IV compressed hydrogen cylinders and Proton Exchange membrane(PEM) fuel cells will 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 later 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 involves the 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 program 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 program 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 Institutes 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-art Micro, Small & Medium Enterprises (MSMEs) and start-ups working on indigenous technology advancement and adaptation will be encouraged under active Government programs, 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 Figure 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.

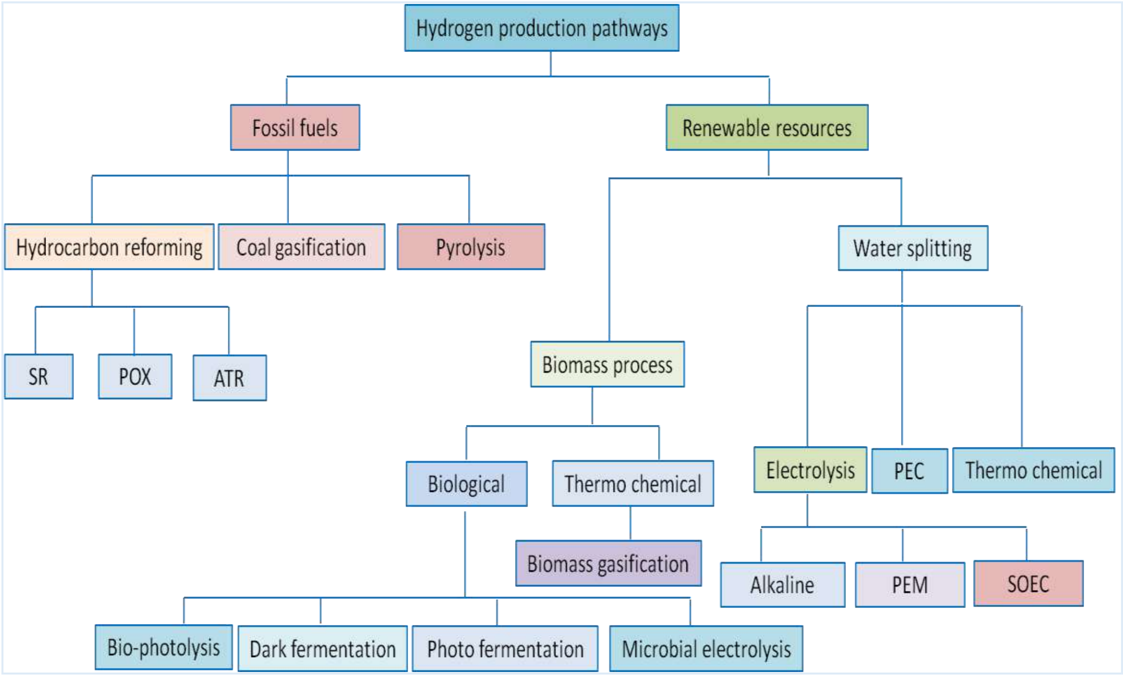

Figure 1: Various pathways for hydrogen production

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 annual demand of 6 MT 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 undergoing rapid development.

2.2. Objectives

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

i. Steep reduction in electrolyser capital and operational expenditure
ii. Enhance operational capacity and efficiency, keeping in mind durability and reliability, especially when operating dynamically
iii. Decrease carbon footprint by increasing current density
iv. Showcase the benefits of adding electrolysers to the power system through their ability to seamlessly integrate higher concentrations of renewables while providing flexibility
v. Reducing the life-cycle carbon footprint of electrolysers by ensuring circularity of material employed as well as for the production process.
vi. Design and develop large-scale (MW) Electrolyser systems, including Stack and BOP
vii. Build capacity and keep stock of material and critical components of Electrolyser stacks
viii. Deployment rates to be increased
ix. 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 in Annex 1.

Technological improvements through research and innovation will be key to the 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 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 100/kg.

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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 Annex 2.

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 their relatively low-temperature requirement of 550°C and 900°C respectively, and opportunities for efficient integration with other energy systems, viz. nuclear or solar power. So far, OEC has established the closed-loop Copper-Chlorine (Cu-Cl) cycle and closed/ 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 Annex 3.

4. Indian Oil R&D Centre, Faridabad

With the objective of assessing different hydrogen production pathways based on indigenously available resources, Indian Oil 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 setting up of bio-CNG reforming-based hydrogen generation plant for the production of hydrogen for undertaking fuel cell bus demonstration trials. Details of the demonstration plants are given in Annex 4.

5. KPIT Technologies

Biomass-to-Hydrogen is not only an environment friendly but also a sustainable solution which can help in reducing the oil import bill of the country as well help in improving farmers’ income by providing value to agricultural residue, which is otherwise 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 Annex 5.

6. The Energy and Resources Institute (TERI)

To achieve the goal of sustainability, TERI researchers researched intensively on the dark fermentation process for hydrogen production with 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) and the 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 scale 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 the 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 and algal biofilms, and produces 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 in 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, in which one can convert biodegradable waste/ wastewater to Hydrogen with funding from MNRE. A pilot scale bioreactor with 10 m^3 capacity was designed, fabricated, and operated at IICT with a biohydrogen production capacity of 50 m^3 per day [7].

8. Indian Institute of Technology, Kharagpur

IIT Kharagpur has extensively worked on biohydrogen production via dark fermentation. Different organic wastes such as cane molasses, distillery effluent, and starchy wastewater were examined as potential substrates for biohydrogen production by Enterobacter cloacae IIT-BT 08. Groundnut deoiled cake (GDOC) was considered as an additional nutritional supplement to enhance biohydrogen yields. The maximum hydrogen yield of 12.2 mol H_2/ kg of DOC 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 for moving from lab to pilot-scale biohydrogen production, thereby providing further opportunities for commercial exploitation[8].

In addition to the above mentioned key research initiatives, many other research institutions/ organizations in the country have put a lot of work into hydrogen production. They have also focused on Improvement of cell design for high performance and increase in cell/stack robustness. A brief of the same is presented in Annex 6.

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 on 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 separation 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.

Catalysts in electrolyzers also need further development, for example low PGM catalysts for PEM.

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 that can 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 (Platinum Group Metal) 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