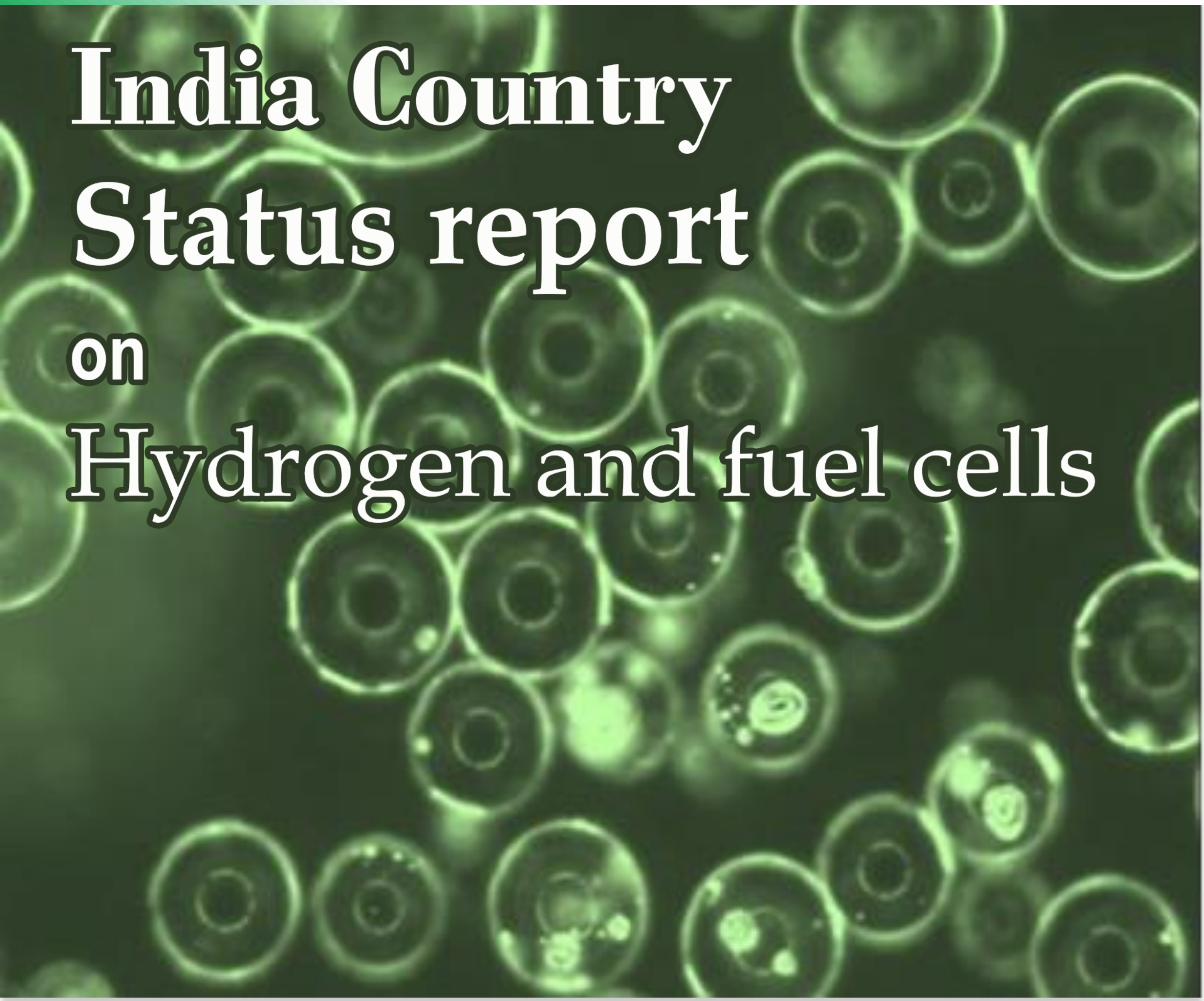
सत्यमेव जयते

Department of Science and Technology

MISSION INNOVATION
Accelerating the Clean Energy Revolution

India Country Status report on Hydrogen and fuel cells



DST@50
1971-2021

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विज्ञान एवं प्रौद्योगिकी विभाग
DEPARTMENT OF SCIENCE & TECHNOLOGY

India Country Status Report
on
Hydrogen and Fuel Cells

Department of Science and Technology
New Delhi
September 2020

सत्यमेव जयते
प्रो. आशुतोष शर्मा
Prof. Ashutosh Sharma

स्वच्छ भारत
एक कदम स्वच्छता की ओर

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सचिव
भारत सरकार
विज्ञान एवं प्रौद्योगिकी मंत्रालय
विज्ञान एवं प्रौद्योगिकी विभाग
Secretary
Government of India
Ministry of Science and Technology
Department of Science and Technology

Foreword

Greater utilization of renewables in our energy mix is our policy objective to achieve decarbonisation. While there are several pathways for decarbonisation varying in time frames, Hydrogen produced from renewables is considered as the cleanest energy source.

Hydrogen has high energy content per unit mass, which is three times higher than gasoline. Hydrogen is being used for energy applications with suitable fuel cells. However, in order to make renewable Hydrogen a viable option, several key challenges related to materials including new material development, electrolytes, storage, safety and standards need to be addressed.

India, as one of the participating country in Mission Innovation Renewable and Clean Hydrogen Challenge IC8 is also committed to accelerate the ushering in of hydrogen economy by identifying and overcoming key technology barriers to the production, distribution, storage, and use of hydrogen at scale. In order to identify and prioritise India specific issues and goals, stakeholders, including experts from academia and from industry, policy makers were brought to a common platform at IISER Thiruvananthapuram during 27-28 February 2020. The brain-storming discussions and presentations pointed to various issues for developing programmes and strategies.

The present report, which is an outcome of these discussions, collates the information on ongoing research activities in the country related to hydrogen been carried by several scientists, industry, utilities and other stakeholders from R&D laboratories and academia.

I hope that this report would be useful for all stakeholders to make informed choices beneficial to advancing research and technology endeavours in this promising area.

(Ashutosh Sharma)

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Editorial Members

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Dr. Sanjay Bajpai graduated in mechanical engineering from Malaviya National Institute of Technology, Jaipur and pursued masters in Business Administration from University of Rajasthan, Ajmer. He was awarded doctorate by Indian Institute of Technology-Delhi for his research work on 'Alternative Fuels for Internal Combustion Engines'. He has managed and shaped several national, bilateral and multilateral research, development and innovation programs. He specializes in management of technology development and socio- economic programs requiring application of S&T. He is currently heading Technology Mission Division of Department of Science and Technology responsible for leading research, development and innovation activities in Water and Clean Energy domain. He has represented India in numerous bilateral and multilateral event and has articulated national and international endeavours in these domains.

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Dr. Ranjith Krishna Pai received the Ph.D. degree in Natural Sciences, from Dr. Othmar Marti's Group, Ulm University, Germany, in 2005. He is Scientist E & Director at Technology Mission Division, Ministry of Science and Technology, Department of Science and Technology (DST), Government of India, New Delhi, India. From 2006 to 2007, he was a Postdoctoral Researcher at University of Chile, Santiago, working on Genetic engineering of a novel protein-nanoparticle hybrid system with great potential for bio sensing applications. 2007 to 2009, he spent two years as a Post-Doctoral Scientist at Stockholm University, Stockholm, Sweden. From 2009 to 2011, he was a Research Scientist at CFN, Brookhaven National Laboratory, New York, USA. After spending 2 years 5 months at BNL, New York, USA, he spent another 2 years 4 months (2011-2013) as a Research Scientist at INL - International Iberian Nanotechnology Laboratory, Braga, Portugal. From 2013 to 2015, he was an Associate Professor and Group leader at Nanostructured Hybrid Functional Materials & Devices, Jain University, Bangalore, India. From 2015 to 2019, he was a Scientist D & Deputy Secretary at Technology Mission Division, Ministry of Science and Technology, Department of Science and Technology (DST), Government of India, New Delhi, India. He published several high impact scientific papers, and author of three book chapters. 15 invited lectures at international conferences. Previously served as an Associate Editor of a Journal "Nano tools & Nano machines" and a Guest Editor of International Journal of Polymer Science. His research interest includes energy conversion technologies, including low cost photovoltaic (Organic, and hybrid solar cells) and electrical energy storage (batteries and super capacitors), synthesis of semiconducting polymers and polymer nanostructures and their application to organic transistors, solar cells, light emitting diodes and other photonic applications, synthesis, characterizations and applications of carbon and inorganic nanotubes, Modeling of the electronic properties of nanostructured semiconductors.

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Prof. Pratibha Sharma is Professor in the Department of Energy Science and Engineering at Indian Institute of Technology Bombay. She is recipient of Gold medal at her master's level and received "Best thesis award" and gold medal for here PhD work in DAE-SS PS, at BARC by Department of Atomic Energy in DAE Solid State Physics Symposium. Her research interests include hydrogen storage materials and systems, hydrogen utilization, low cost earth abundant materials for photovoltaic applications and materials for bio medical applications. She has worked on various types of hydrides for solid state hydrogen storage, their modifications, catalysis, support and tailoring the reactions mechanisms. She has been working on simulation, design and development of hydrogen storage reactors for various applications. She is currently on the editorial board of International Journals, reviewer for several renowned International Journals, serving on the organizing and advisory committees of large number of conferences. She has delivered several invited talks and keynote address in different International conferences. She has supervised 13 PhD students, 30 M.Tech and M.Sc. students. She has more than 65 International journal publications and four patents to her credit. She has been awarded with the "Outstanding Service Award" by the International Association of Hydrogen Energy, for her altruistic contribution towards world hydrogen economy. Prof. Sharma is leading several multi-institutional R&D projects on Hydrogen systems development and integration for different applications. These projects have several IITs and industries as partner which are working together for hydrogen based solutions.

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After obtaining Ph.D in Physics from IIT, Madras, she worked as post doctoral fellow in TH Darmstadt, Germany and University of Geneva, Switzerland for about 8 years. She has worked on various aspects of Hydrogen economy like production, storage and utilization. She has gained vast experience in Fuel cell technology both in Material aspects and Engineering challenges from SPIC Science foundation and Center for Fuel cell Technology for the past 20 years. She was a visiting scientist of Korea Research Institute of Chemical technology, South Korea under the Brain pool program. Presently she is a team leader at CFCT, unit of ARCI, DST at Chennai. She has received the Technology award from Spic Science Foundation for making large area electrodes, Bharat Vikas Award from Institute of self Reliance for clean energy generation, Nature publishing award etc.,

She has chaired many sessions and given invited talks in various International conferences on Fuel cell science, Engineering technology, Gordon Research Conference on Fuel cells, Society of Automobile Engineers etc., in India and Abroad. She is a reviewer for many journals related to Hydrogen and / Fuel cells. Member of Working group, Hydrogen utilization, IEEJ, Japan, American chemical society, International Association of Hydrogen energy, Materials Research society of India, Electrochemical society, and Indian society of Fuel cell Technologists. She has about 170 publications in various International Journals, 10 book chapters and 25 patents to her credit.

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Prof. P. Muthukumar received PhD degree in Mechanical Engineering from IIT Madras during 2005. He joined at IIT Guwahati as Assistant Professor in January 2006 and became Professor in January 2015. He received DAAD research fellowships during September – December 2000, June-July 2008, and June - July 2010. He is the recipient of IEI Young Engineer Award - 2010 in Mechanical Engineering from Institute of Engineers (India). He received Bhaskara Advanced Solar Energy Fellowship (BASE Fellowship) from Indo - U.S. Science and Technology Forum (USIEF), Jan 2014 and also received Er. M.P. Baya National Award 2015 from Instituted by the Institution of Engineers (India), Udaipur. He is also the Fellow of Institute of Engineers (India). He is one of the Commission Member to represent India in the International Institute of Refrigeration (IIR). He also received Fulbright-Nehru Academic and Professional Excellence Fellowship from (USIEF). He served as the President, Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE), Guwahati sub-chapter. He received “Mechanical Engineering Design Award 2017, from National Design & Research Forum (NDRF) of “The Institution of Engineers (India)”, 21st Dec 2017. Recently, he has been honored as Eminent Engineer -2019 from “The Institution of Engineers (India)”, Assam State Centre on 15th September 2019. He served as visiting Professor in many Universities in USA and Germany and having research collaborations with over 20 International Universities. He has been published over 240 research articles in various International Journals and conference proceedings. He is having six national patents for his credit. He has supervised 15 PhD and 45 M.Tech student’s theses. He has successfully completed 5 sponsored research projects worth of 192 lakhs and five consultancy projects worth of 35 lakhs. Currently he is handling seven research projects worth of 760 lakhs. He is the reviewer of more than 50 International Journals in the area of hydrogen energy, energy storage, refrigeration, heat transfer, etc. and also reviewed several research proposals from DST, MNRE, Qatar Research Board, etc. His area of research includes hydrogen energy storage, metal hydride based thermal machines, coupled heat and mass transfer in porous medium, porous medium combustion, sorption heating and cooling systems, etc.

1. Introduction

India with a population of approx. 1.3 billion is the second most populous country and the third largest economy (measured by purchasing power parity) in the world. With significant decrease in poverty level, increased energy access for citizens, availability of cleaner cooking fuel and growing penetration of renewables, the country is advancing on a faster growth path.

The country's total primary energy supply (TPES) is 881.9 Mtoe (coal accounting for 44.3%, oil 25.3%, bioenergy and waste 21.2%, natural gas 5.8%, hydro 1.4%, nuclear 1.1%, wind 0.4% and solar 0.4%)[1]. The TPES per capita is 0.66 toe and energy consumption per capita being 0.44 toe[1]. India's per capita energy consumption stands at 30% of the world's average. With the faster economic expansion in the country, the energy demand is rising in almost all sectors industry, commercial, residential, agricultural and transport. India's energy system is largely dependent on fossil fuels i.e. coal for power generation, oil for transport & industrial sector and biomass for residential heating & cooking. Two thirds of the TPES is meet by domestic production and thus the country is largely dependent on oil and gas imports. In the year 2018, the breakup of India's net import was 205.3 million tons of oil and its products, 26.3 Mtoe of gas and 141.7 Mtoe of coal accounting for 46.1% of the total primary energy consumption (TPEC). Major consumption is in the Industrial sector (42% of the total final consumption i.e. TFC) followed by residential (29% of TFC), transport (17% of TFC) and services (12% of TFC)[1] as shown in Figure1. The rapid growth in the total final energy consumption and electricity demand is currently being met largely by fossil fuels.

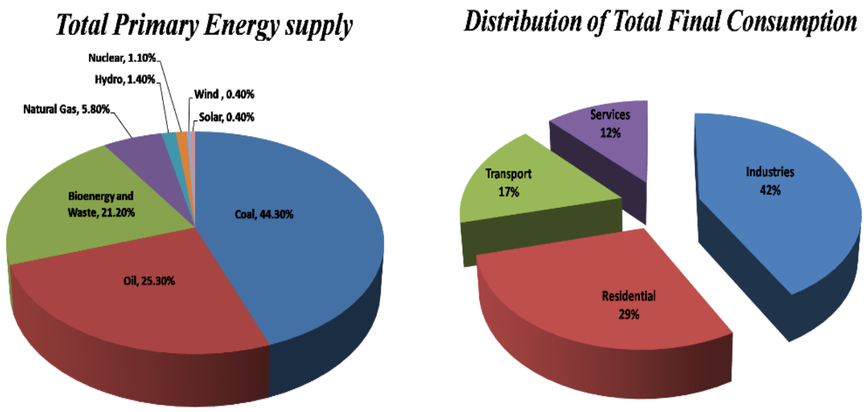


Figure 1. India's total primary energy supply (TPES) and total final consumption (TFC)

India is the world's third largest consumer of oil, for which country has to depend heavily on oil imports. India's oil refining capacity is the fourth largest in the world and the country is a major exporter of the refined products. Government of India is pursuing roadmap to continue being the refining hub and expand its capacity with a plan through 2040. However, currently the dependence on oil import is 80% and is expected to grow further. Another important fuel which is natural gas, is currently 6% in the energy mix the aim is to increase its share to 15%. As per the projections, India's energy demand could double by 2040 and electricity demand triple.

With the rise in energy demand the major impact will be on environment. The energy sector is considered to be the major source for environmental concerns, including the local air pollution, GHG emissions and thus accounting for the implications associated with climate change. Thus, there is a penetrating need of addressing the growth of energy demand, at the same time providing clean energy to the masses and keeping the climate change threats under consideration.

The increasing air pollution in several cities of the country (e.g. Delhi, Gurugram, Noida, Faridabad, Kanpur etc.), is the key concern, energy sector has been identified as the major source of emissions. Sometimes the high concentrations of air pollutants have been reported even due to the non-energy sector related emissions e.g. from crop burning etc. Out of the top 20 most polluted cities in world, ten in the list are from India. The situation is really alarming as in the year 2017 this problem has caused around 1.2 million pre-mature deaths.

The Government of India has laid several policies and is targeting to provide sustainable and affordable solutions, reduce emissions and lay down a path for economic growth. Several steps have been taken to address the climate change and local air pollution threats e.g. The National Green Tribunal has revised the standards in terms of the emission norms for thermal power plants and restricted the particulate matter to 30mg/m^3, NO_x and SO_x emissions to 100 mg/m^3. The major NO_X emissions are arising from transport sector (40% of total), power sector (31%) and industrial sector (20%). The main source being heavy duty vehicles followed by coal-based power generation and use of coal in the industry. The power sector is the major source of SOx emissions (more than half of the total). Figure 2 shows the sector wise percentage breakup of the emissions in the country.

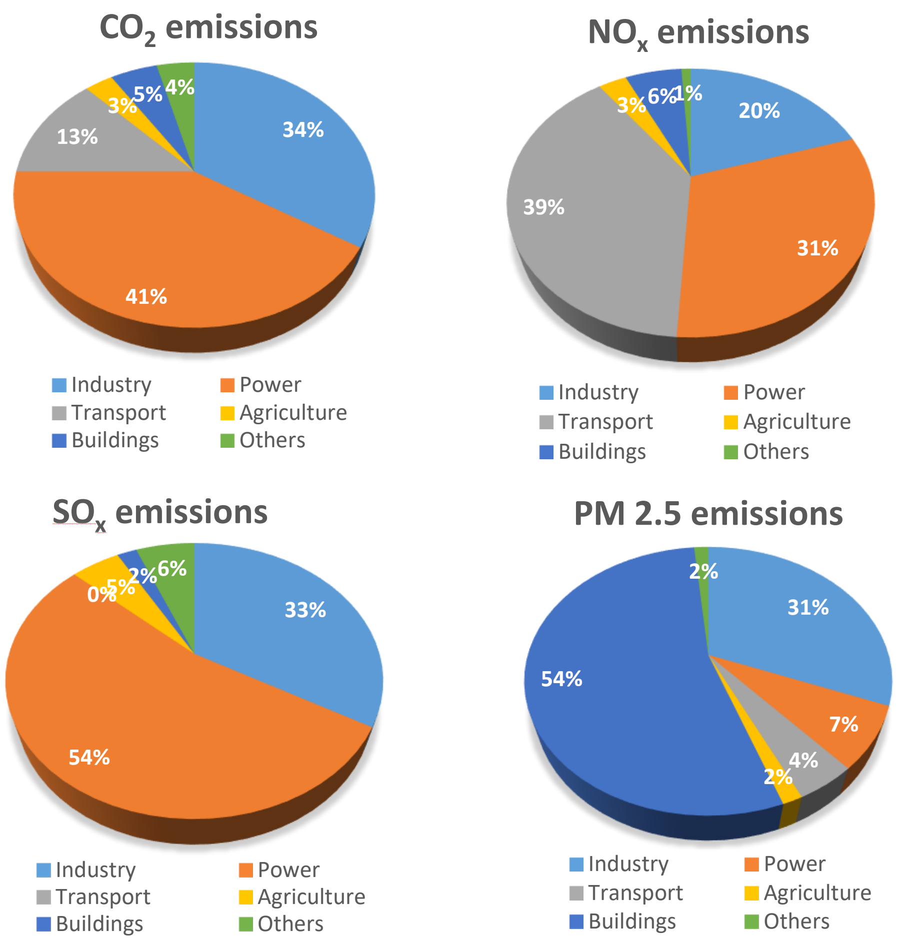


Figure 2. Percentage contribution of the emissions in various sectors

Globally a massive decarbonization is required, if the ambitious emission reduction scenario is to be met and to achieve the 2DS i.e. limit global warming to 2°C above pre-industrial levels. Our country is determined to contribute under the Paris agreement towards reducing the emissions and increasing the share of non-fossil fuels in various sectors.

The National Action Plan on Climate Change was launched in 2008 with not only developmental objectives but at the same time addressing the climate change issues effectively. Building on the National Action Plan on Climate Change, the Government of India has initiated several National missions. Other than the deployment targets and incentive mechanisms, these missions are towards RD&D. These National Missions includes:

- National Mission for Enhanced Energy Efficiency
- National Solar Mission
- National Electric Mobility Mission
- National Smart Grid Mission
- National Mission on Advanced Ultra Super Critical Technology
- National Mission on Transformative Mobility and Battery Storage

An aggressive renewables-based deployment has been seen in the India's energy mix in the past decade, with 84GW of grid connected renewable electricity capacity in December 2019[1]. Next target is towards achieving 175 GW by 2022 and eventually will have 450 GW of renewable energy capacity.

With the Government of India's Ujjala scheme and Prime Minister's Ujjawala Yojana, electricity and clean cooking solutions have been provided to wider mass. The Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY) and the Saubhagya schemes have been very helpful in providing electricity access in villages and thus to the rural households of the country. Between 2000 to 2019, around 700 million people got access to electricity[1]. These schemes have helped in improving the standard of living of the people and addressing the health issues by providing cleaner energy solutions.

The major five ministries in India responsible for energy and related matters includes the Ministry of New and Renewable Energy (MNRE), the Ministry of Power (MoP), the Ministry of Petroleum and Natural Gas (MoPNG), the Ministry of Coal (MoC) and the Department of Atomic Energy (DAE).

Funding agencies in the area of energy are Ministry of Science and Technology (MoST), Department of Science and Technology(DST), Department of Biotechnology (DBT), Department of Scientific and Industrial Research (DSIR), Department of Atomic Energy (DAE), Ministry of Coal (MoC), Ministry of Earth Science (MoES), Ministry of Heavy Industries (MoHI), Ministry of New and Renewable Energy(MNRE), Ministry of Power (MoP), Ministry of Petroleum and Natural Gas (MoPNG). These are being mentioned in Figure 3.

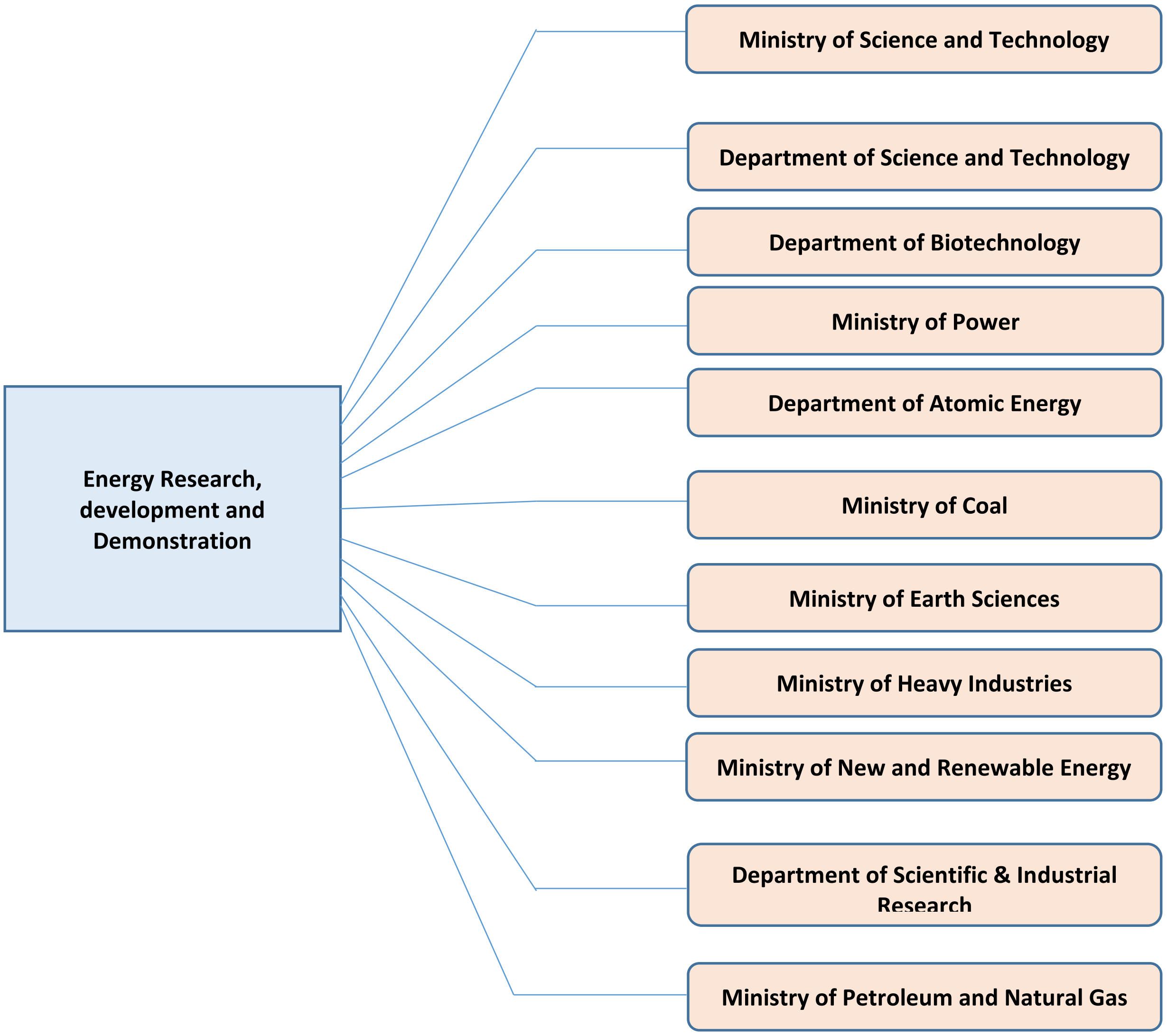


Figure 3. Ministries in the country for Energy related Research, Development and Demonstration

Thus, the pressing need is to meet the rising energy demand, decarbonization of various sectors, providing energy security and having sustainable growth. All these points set up the context for the need of an abundant, non-polluting, efficient and clean fuel which could be used for most of the energy sectors, same way as the conventional fuel or electricity does and the same time could provide energy security to the nation.

Hydrogen is a promising energy carrier, which has the potential to address the various energy sector related challenges and technically from the application point of view can substitute the conventional fuels. Hydrogen with its abundance, high energy density, better combustion characteristics, non-polluting nature etc. have vast advantages over the conventional fuels.

Hydrogen can be produced from a wide variety of primary or secondary energy source and the feedstock can be decided based on the local availability. Appropriate production route can be used for production from locally available feedstock and the hydrogen produced can be used for wide range of end use applications. As such the diversified production routes can reduce our dependence on imports and can assist towards energy security. The use of hydrogen can reduce the CO_2 related emissions significantly at the point of use and if green hydrogen is used then there is capability to decarbonize the entire value chain, enabling reduced emissions and climate change threats. It can even decarbonize the sectors where it is difficult to reduce emissions.

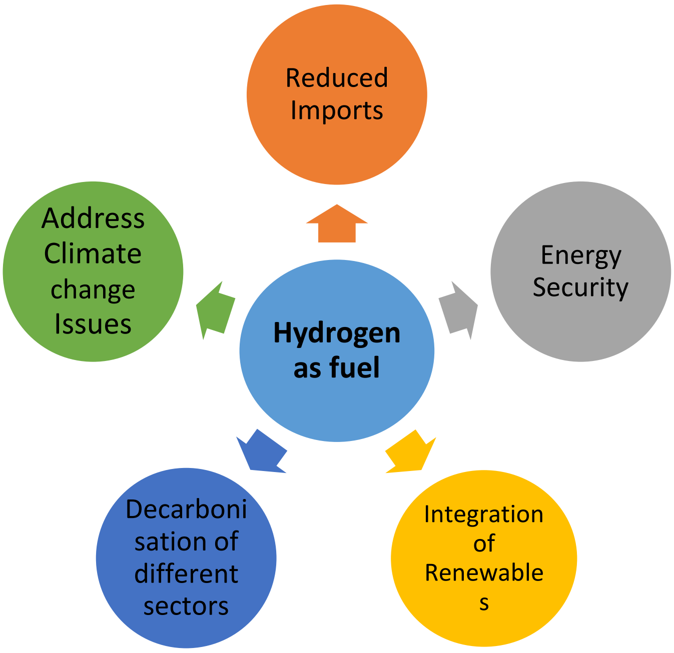


Figure 4. Benefits of using Hydrogen

Hydrogen can provide linkages between energy supply and demand, in both a centralized or decentralized manner, thereby enhancing the overall energy system flexibility. The low carbon energy source can be connected to sectors like transport and buildings or even hard to abate sector like steel and cement industry. A lot of benefits are there in using hydrogen as an energy carrier, some of these for representation are mentioned in figure 4.

At rural places with limited or no access to grid, the use of hydrogen can provide energy services. With the ambitious targets of achieving the larger renewable deployment, the intermittency being the major drawback, which makes energy storage as inevitable part of the energy system. Hydrogen can be used for small to large scale and short to long term storage to meet both the seasonal or daily supply demand imbalance. Besides various options including power to gas, power to power and power to fuel can be explored with hydrogen being used to meet the supply demand mismatch in case of renewables[2]. The flexibility provided by fossil fuels in terms of use of high-density fuel when and where ever to be used, is lost with the use of renewables. However, the use of hydrogen provides avenues to integrate renewables with energy system and still provide the same set of flexibility through either of the power to X means.

Hydrogen energy is at present at early stage of penetration in energy sector. Many funding agencies are supporting a broad based RD&D projects on different aspects of hydrogen economy including hydrogen production, storage and utilization for stationary, power generation and for transport applications (using either IC engines or fuel cell technologies). The focus of RD&D efforts in this area is towards the development of new materials, processes, components, sub-systems and systems.

The various funding agencies in India are both the Government agencies and public sector companies. Some of these includes the Ministry of Science and Technology, CSIR Laboratories, Ministry of Petroleum and Natural Gas, Defence Research & Development Organizations, Indian Space Research Organization, Oil & Gas companies, Department of Atomic Energy and automobile sector, oil and gas companies are also involved in the research, development and demonstration programme related to hydrogen.

Ministry of New and Renewable Energy constituted a high-level committee to come up with Hydrogen energy roadmap. The National Hydrogen Energy Roadmap was laid in the year 2006 to provide a blueprint for the long-term public and private efforts which was required for hydrogen energy development in the country. The roadmap identified the technology gaps and challenges in the introduction of hydrogen in large scale, in a phased manner. Suitable pathways were suggested and the policies, legislation, financing, support infrastructure required were identified. Two major initiatives were identified namely green energy for transport and for power generation. The key points of these initiatives are listed in Table 1.

Table 1 : National Hydrogen Energy Roadmap: Vision – 2020

Source: NHERM (2006) Report, Ministry of New and Renewable Energy[3]

Green Initiative for Future Transport (GIFT)	Green Initiative for Power Generation (GIP)
• Hydrogen cost at delivery point at Rs. 60-70 per kg, hydrogen bulk storage methods and transport via pipeline to be in place	• Hydrogen bulk storage methods and pipeline to be in place
• Hydrogen storage capacity to be 9 wt%, Support infrastructure- large number of dispensing stations	• Support infrastructure- large number of dispensing stations
• Development of safety regulations, legislations, codes and 1000 MW hydrogen-based power generating capacity setup	• 1000 MW hydrogen based power generating capacity setup standards
• 1,000,000 hydrogen-fuelled vehicles on road- 50MW small IC engine standalone generators	• 50MW small IC engine standalone generators
• 50,000 two/three wheelers - 50MW standalone fuel cell power packs	• 50 MW standalone fuel cell power packs
• 50,000 cars/taxis - 900 MW aggregate capacity centralized plants	• 900 MW aggregate capacity centralized plants
• 1100,000 buses and vans	

Another high level steering committee was constituted under the chairmanship of Dr. K. Kasturirangan on Hydrogen and Fuel cells by MNRE. The committee had sub-committee on different themes like hydrogen production, storage, utilization, transport, IPR, PPP, awareness, safety and standards. These sub-committees in the year 2016 prepared excellent comprehensive reports and suggested the way forward on the above mentioned themes.

A major global initiative involving 24 countries and European Union is the Mission Innovation, which was announced on 30th November 2015. The objective behind Mission Innovation (MI) Initiative is to dramatically accelerate global clean energy innovation – double the Government's clean energy R&D investment over 5 years. There are eight Innovation Challenges (ICs) under MI, which are aimed towards encouraging greater private sector investment in transformative clean energy technologies. IC8 is focused on renewable and clean hydrogen, India is participating in this challenge. The objective will be to accelerate the development of a global hydrogen market by identifying and overcoming key technology barriers to the production, distribution, storage, and use of hydrogen at gigawatt scale. The implementation will be done through multinational research and large-scale demonstration efforts and involvement of public- private sectors on industry-directed breakthroughs. The different activities will be organized under four streams: Making hydrogen, sharing hydrogen, using hydrogen and cross-cutting issues. IC8 is exploring linkages with IC3, IC4 and IC5.

DST has planned for a "Hydrogen Valley Platform" which is a platform being developed to combine together several hydrogen applications into an integrated hydrogen eco-system covering the entire hydrogen value chain (production, storage, distribution and final use). The objective of this platform is to bring together industry and policy makers to exchange their respective experiences and trigger dialogue between them so as to identify the key factors of success and jointly discuss how to best capture, process and disseminate high quality learnings through the IC-8 platform. This platform will be providing opportunity to learn from leading hydrogen valleys across the globe and would enable understanding of issues and barrier to providing the technology.

Department of Science and Technology has taken up development of hydrogen and fuel cell technologies in a mission mode. The focus is towards creating volumes and infrastructure, towards demonstration of niche applications, provide facilitative policy support and provide symbiotic international linkages. The hydrogen mission will be directed towards advancement of hydrogen and fuel cell technologies through R&D and validation, to make technologies competitive in cost and performance, to reduce institutional and market barriers towards commercialization.

The Hydrogen and Fuel Cell program by Department of Science and Technology is focused to develop transformational technologies that reduce the cost of hydrogen production, distribution & Storage, diversify the feedstock available for economic hydrogen production, enhance the flexibility of the power grid, and reduce emissions through novel uses of low-cost hydrogen. Thirty research projects have been supported under this program.

2. Hydrogen Production

The term hydrogen economy was coined way back in 1970 by John Bockris and he mentioned that hydrogen economy can replace current hydrocarbon-based economy. This replacement will lead to more of energy security and lesser negative effects on the environment.

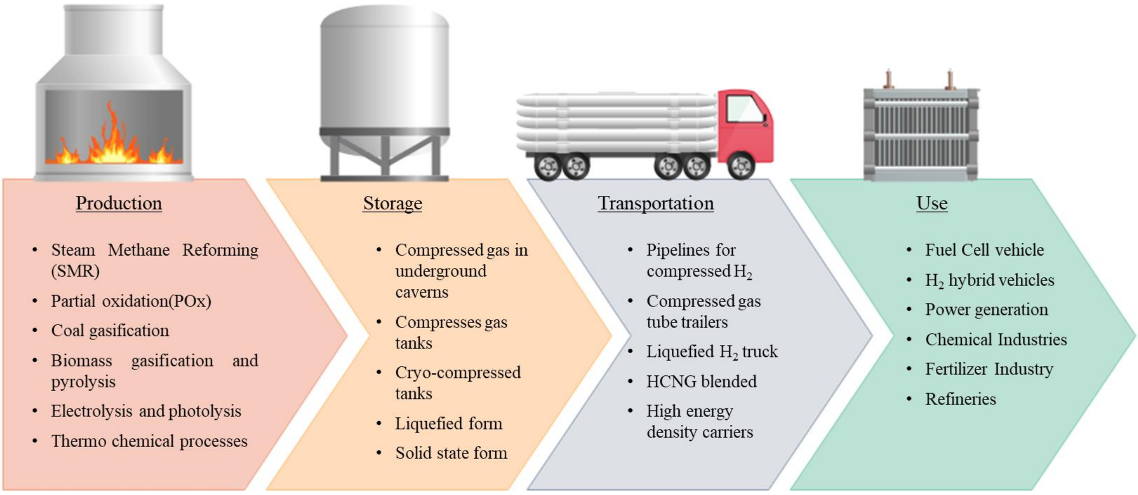


Figure. 5 Pathways to Hydrogen economy

The recent renowned interest in the use of hydrogen is an indication of the benefits of use of hydrogen in the entire energy ecosystem. The different pathways to hydrogen economy include hydrogen production, storage, transport and utilization, and the different options for each of these are included in figure 5.

The current global demand of hydrogen is 70 million metric tons per year, in energy terms its around 330 million toe[4]. Most of which is being produced from fossil fuels (76% from natural gas and around 23% from coal, remaining from electrolysis of water) which consumes 6% of the global natural gas and 2% of the global coal[4]. All this results in CO_2 emissions of around 830Mt/year. Most of this CO_2 produced is not captured, only around 130Mt of this is being captured and used in fertilizer industry. The situation will change when the hydrogen production from non-fossil fuel-based production will increase and with greater renewables deployment, the shift will be towards green hydrogen production. The production methods are basically dependent on the feedstock which in turn also depends on the local availability. Depending on which feedstock is used, the different routes for hydrogen production can be reforming, gasification, pyrolysis, fermentation and electrolysis or photolysis. However, the most widely used method for hydrogen production includes steam methane reforming, methanol reforming, partial oxidation of hydrocarbons, auto thermal reforming, coal gasification, electrolysis of water and thermochemical processes as mentioned in figure 6.

The other methods of production including biomass gasification and photocatalytic or photoelectrochemical are still at the research scale. The cost of hydrogen produced depends on the method of production, separation and purification to achieve the required purity. Hydrogen is an important raw material for chemical industry, petroleum refining, food processing, metal processing etc. Partial oxidation of oils stands to be one of important segment which produces large quantities of hydrogen and is also an efficient method (70-80%). Demand of hydrogen in refineries has increased due to stringent emission norms and hydrogen is being used for various hydrotreatment processes like hydrodesulphurization, hydrodenitrogenation and hydrocracking processes.

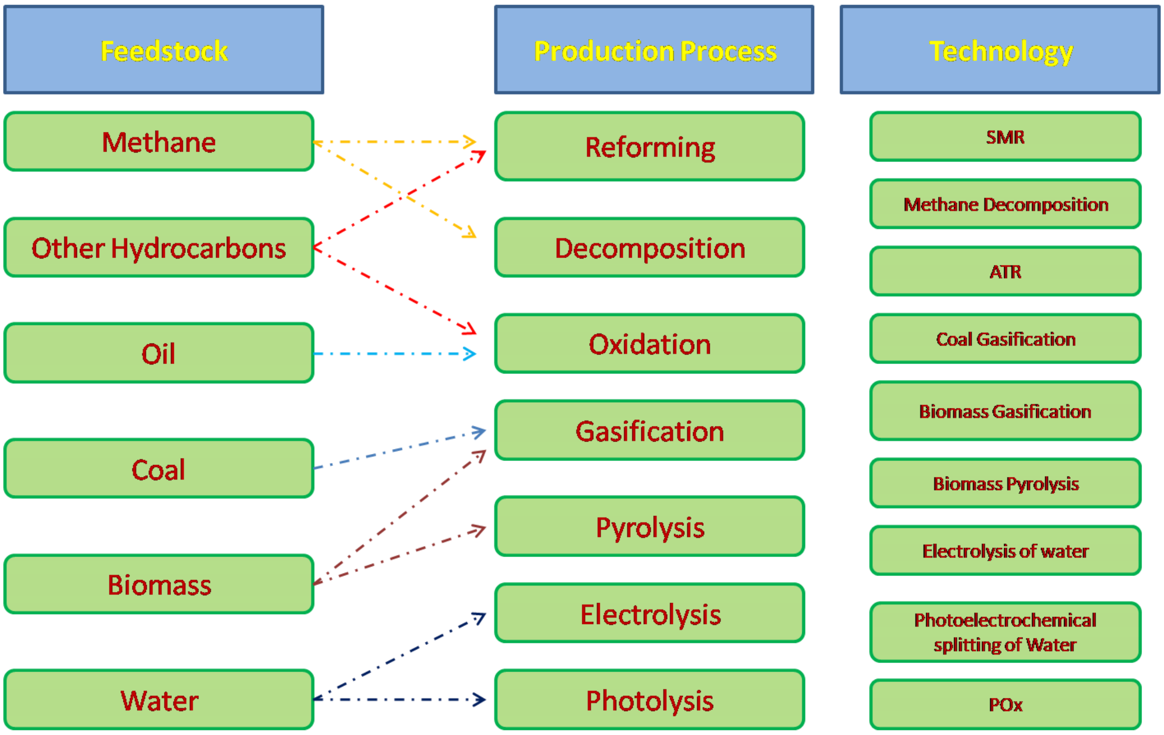


Figure 6. Hydrogen production routes based on feedstock used

Most of the hydrogen produced is used for oil refining (33%), ammonia (27%), methanol production (11%), steel production via DRI (3%) and others. Hydrogen can be produced either centrally and then subsequently transported and distributed at the point of use or in a distributed manner where it is being produced at the point of use.

The estimated hydrogen production and consumption in the country during 2007-08 as per a study undertaken by the University of Petroleum and Energy Studies, Dehradun is mentioned in Table 2.

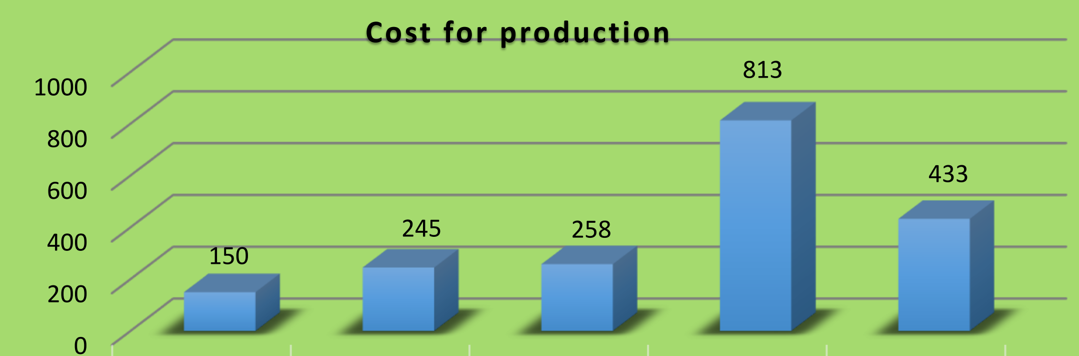
Table 2: Estimated hydrogen production and utilisation in the year 2007-08

Sector	Estimated Production during 2007-08 (Million Tonnes / Year)	Utilization during 2007-08 (Million Tonnes / Year)
Fertilizer Industry	1.99	1.99 (Captive Use)
Petroleum Refineries	1.69	1.46 (Captive use)
Chlor Alkali Industry	0.073	0.064
Total	**3.753**	**3.516**

Hydrogen production from natural gas without the carbon capture, use and sequestration (CCUS) is currently the most economic method and the lowest cost is USD1/kgH_2 in Middle East, while the electrolysis of water is the most expensive route. However, at places where power from renewables or nuclear is available to meet the heat or electricity requirements, hydrogen is produced using electrolysis or thermochemical route rather than depending on import of natural gas. Currently in India most of the hydrogen produced, is the byproduct of either the refinery processes or chlor-alkali plants. There were around 40 chlor-alkali units in 2013-14 producing 66000 tons of by-product hydrogen out of which 6600 tons was not utilized. Most of it is internally used for various processes and very less quantity is available for utilization for other applications. However, the major rise in demand of hydrogen will be in the end user industry, further with stringent environmental regulations, its demand will foresee an increase in both transport and power generation sectors. The hydrogen energy market was valued around USD 50 million in the year 2017 and further as per the Applied Market Research Report[5] it is estimated to grow to USD 81 million by the year 2025, thus experiencing a CAGR of 6.3% from 2018 to 2025.

It is also pertinent to mention that H_2 produced from fossil fuel sources will not be green hydrogen i.e. it will result in the formation of CO_2 as a by-product. Major hydrogen player, Japan has demonstrated the production of green hydrogen from coal by using carbon sequestration and ensuring net zero greenhouse gas emission. Greener methods of hydrogen production are actively being explored in India as well and on to this end, research is being carried out from materials to systems level. Cleaner methods of hydrogen production chiefly constitute electrolysis, via chemical or photoelectrochemical routes.

In India, hydrogen is being commercially produced in the fertilizer industry, petroleum refining and chemical industries and also as a by-product in chlor-alkali industries. Some limited hydrogen is also produced through electrolysis for commercial use. Most of it is captive hydrogen however less merchant hydrogen is available for utilisation. The cost of hydrogen from different methods of production as per the MNRE analysis is included in Figure. 7.



	Steam Methane Reforming	Coal Gasification	Biomass gasification	Biomass microbial	Electrolyzer Alkaline
Rs/Kg	150	245	258	813	433

Figure 7. Cost of hydrogen production

Department of Science and Technology activities on Hydrogen production are mainly focused on:

- More efficient reforming processes and development of newer membranes
- Improving the efficiency of water splitting reaction
- Development of cost efficient and earth abundant catalyst for photo-electrochemical water splitting
- Newer materials, catalysts and electrodes to accelerate the reaction
- Sorption enhanced reforming for improved hydrogen production from biogas.

Various research groups in India are engaged in RD&D projects on Hydrogen production, following is a brief on the developments in the country on hydrogen production:

- At Bhabha Atomic Research Centre (BARC) Mumbai, several approaches are being explored towards hydrogen production technologies. The technologies can be broadly classified into three categories. Hydrogen production a) using only electricity i.e. Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane based water electrolysis (PEM), b) using only heat source i.e. thermo-chemical splitting of water like Iodine Sulphur (I-S) process and (Cu-Cl) process and c) using both electricity and heat source like High Temperature Steam Electrolysis (HTSE) and Hybrid Sulphur (Hy-S) cycle. The objectives have been materials development and technology demonstration of the processes towards a sustainable hydrogen production from water. In alkaline water electrolysis, BARC technology is available for commercialization, which involves 10 Nm^3/hr of hydrogen production. This is very much suitable for chemical industries like fertilizers, pharmaceuticals, metallurgical operations, food, telecom and fuel cell industry.

In the high temperature steam electrolysis (HTSE) using solid oxide cells, operating temperature in the range of 800-1000°C, suitable microstructure and processing conditions have been developed for a number of MIEC electrode materials like PSCF, Nd_2NiO_4, LSCM, BSCF etc. and its suitability in electrolysis mode of operation have been studied. To realize the HTSE cell, tubular cell approach has been followed in which Ni-YSZ support tube acts as hydrogen electrode along with impervious coating of YSZ electrolyte and suitable oxygen electrode have been fabricated and tested for its performance. In order to have technology demonstration of HTSE, integration of single cells to fabricate multicell stack hydrogen generator of higher capacity and performance evaluation for a long duration are being planned.

In iodine-sulphur process of thermo-chemical splitting of water for hydrogen production, which consists of three chemical reactions: 1) Bunsen reaction, which is the acid production step (exothermic, T=120°C), 2) sulphuric acid decomposition to produce oxygen (endothermic, T=870°C) and 3) hydrogen iodide decomposition to produce hydrogen (endothermic, T=450°C). All these reactions have been tested at BARC. Suitable iron based catalysts have been developed to minimize the use of expensive platinum based catalysts in the high temperature H_2SO_4 decomposition reaction step. Numerical simulations to evaluate different approaches for scaling up of packed bed membrane reactor for HI decomposition and other reaction steps have been carried out. Extensive research are being also carried out for other hydrogen productions technologies like Hy-S process, Cu-Cl process, PEM based electrolysis process at BARC. Thrust has also been given at BARC to develop 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.

- Design of electrodes and electrolytes for hydrogen generation using sea water has been explored at CSIR-CECRI, Karaikudi. Reduced Titania was used as 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 and transferred to the industry.

- H_2 production via sorption enhanced reforming process is being carried at Institute of Chemical Technology, Mumbai. Hybrid bi-functional materials which combine the benefits of both the reforming catalyst and CO_2 absorbent are being explored. The feedstock used includes biomass surrogates (such as bio-ethanol, bio-butanol, bio-oil and bio-gas). The bi-functional materials being studied includes hydrotalcite along with Ca, Zn and Cu as promoters. Cu-based materials results in the highest production of high purity H_2 and fast removal of CO_2. Other aspects of SER including process configurations, reactor engineering, reactor systems and materials are also investigated.

- The use of transition metal mixed oxides for Alkaline water Electrolysis is being explored by the Chemistry research group at University of Lucknow. Low temperature synthesis routes have been explored to synthesize Spinel (ferrites and cobaltities) and Perovskite oxides. Electrodes are being prepared on conducting support using suitable techniques. Improved electrocatalytic properties have been observed for these materials.

- Hydrogen generation via catalytic route, explores the on-board generation of hydrogen from liquid organic compounds. Liquid Organic Hydrogen Carriers (LOHCs) such as formic acid, methanol etc. can be catalysed to release hydrogen at attainable operating condition and is being explored at Thermax.

- ONGC Energy Centre (OEC) has been involved in collaborative research to further the transition to hydrogen energy. OEC is investigating thermochemical water splitting for large-scale hydrogen generation. The four-step Cu-Cl that operates at 550 °C and the I-S cycle that operates at 900 °C have been designed and developed for electrolysis of water. The group has developed a new patented Cu-Cl cycle and also demonstrated a closed loop I-S cycle. Besides these the open loop I-S process is at advanced stage of development. The research groups at OEC are involved in various other research activities, including improvement of the processes, development of materials used in construction of reactors and electrodes, membranes of electrochemical processes and gas separation, catalysts, high temperature corrosion testing and integration of heat source with thermochemical cycles

- Another major activity is the multi-institutional project on Generation of Solar Hydrogen, which is initiated and supported by the Technology Systems Development Program of Department of Science and Technology. The project is running in a consortia mode comprising of IIT Kanpur, IIT Madras, Dayalbagh Educational Institute Agra, IIT Jodhpur, CECRI, Karaikudi and BARC Mumbai. The project aims at developing scalable designs of solar hydrogen generation systems using multiple technologies. Besides bridging the technical challenges that exists at multiple length scales in the development of a solar energy conversion technology, the initiative was planned to bridge the complementary strengths of different Indian universities and national laboratories so as to map the laboratory-scale prototype to the corresponding field-scale device.

The central emphasis of the project has been to design, synthesize and characterize the best possible solar-chemical-materials combination suitable for large scale applications. The goal of the project is towards integrating the materials developed into a photoreactor to generate hydrogen and oxygen with water as the feed. Materials close to international standards and general heuristics for material design are being developed. Apart from the photocatalytic and photo-electrocatalytic route, an electrolyser integrated to photovoltaic modules will be fabricated.

- Few groups are working on the hydrogen generation from methanol in the country. Considering the present investment made by Government of India on Methanol, generation of hydrogen from methanol will play a key role in near future

Other than the above-mentioned key research initiatives, a lot of work on hydrogen production is being carried out at several other institutions in the country, a brief mention of the same is being presented in Table 3.

Table 3: Hydrogen production related work at different institutions in India

	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 production of sulfuric acid and HI using electrochemical cell, 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 membrane electrolysis cell for Bunsen reaction and electro-electrodialysis unit for 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, photo-electrochemical studies, superconducting materials (oxides, oxypnictides and oxychalcogenides).
2	IISc, Bangalore	Hydrogen and liquid fuels from biomass Gasification, hydrogen generation using biomass gasification for fuel cell application (HBGF), multi-fuel gasification system to accept woody biomass or biomass briquettes, development of semiconductor nano-composites for photo-catalytic water splitting into H_2 and O_2 under solar light irradiation, TiO_2 based photocatalysts for organic waste degradation

	Institution	Nature of work
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
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 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 for syngas/H_2 by low temperature plasma catalysis
8	IIT Indore	Hydrogen generation though catalytic route
9	CSIR-NEERI	Development of 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 photo-reactor for hydrogen production from hydrogen

	Institution	Nature of work
		sulphide under natural sunlight, photocatalysts development
14	NIT, Calicut	Investigation on bio-hydrogen production by thermo-chemical 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 Nano structures for photo electrochemical 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, reaction of metals with HI, reaction of metals with hydroid acid, 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 and electrolytes for water electrolysis to generate hydrogen and hydrogen
21	ARCI-CFCT, Chennai	Novel electro catalysts, depolarisers for water electrolysis, sea water electrolysis
22	Tata Energy Research Institute	Technology packages for woody and briquetted biomass using throat-less gasifier with 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-hydrogenesis

	Institution	Nature of work
25	NIT Tiruchirappalli	Combined pyrolysis and steam gasification to establish multifuel Quraishy production with 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 non-thermal 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
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 Nm^3/hour of hydrogen
35	Shiksha 'O' Anusandhan University, Bhubaneswar	Porous graphene modified metal oxide photo anode for electro-chemical 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

Various Institutions/ Industries/ Organizations working in India on Hydrogen Production are mentioned in the country map in figure 8. Several research groups are actively working in the field of hydrogen production, the list of scientists and researchers working at these organizations on hydrogen production and their contact is included in Table 4.

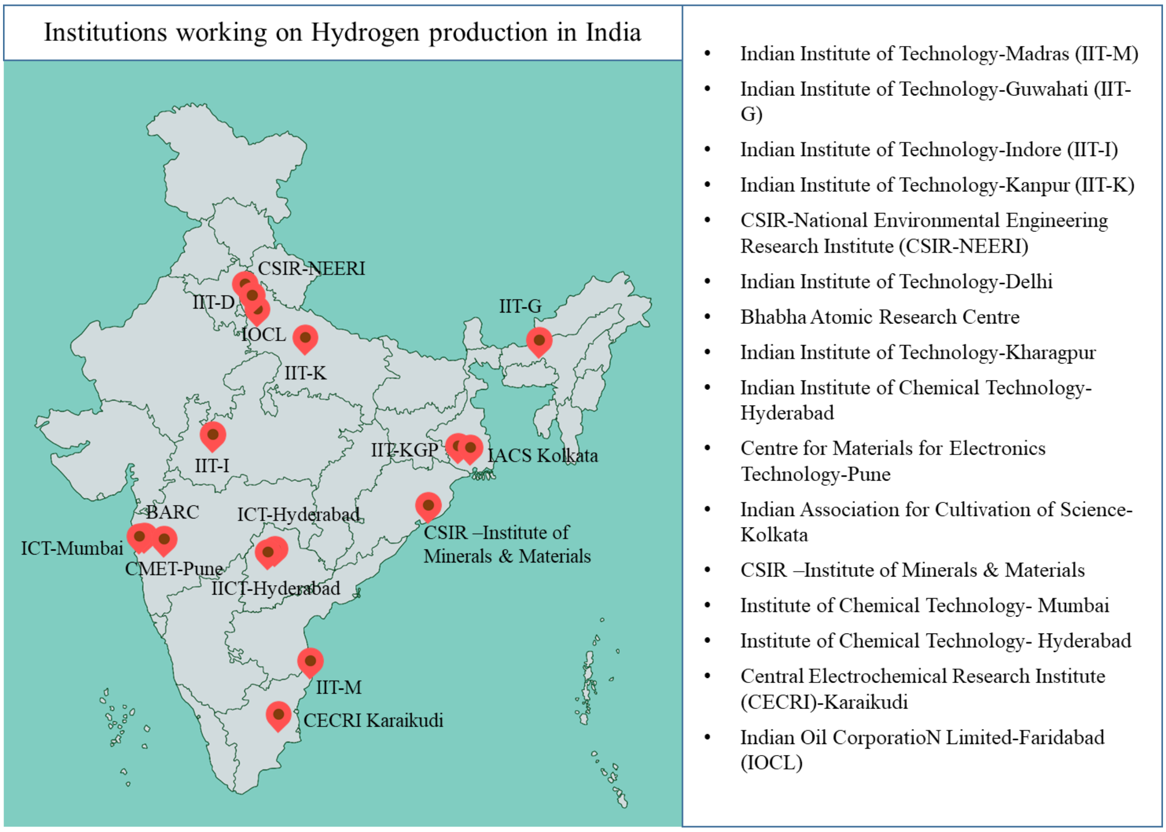


Figure 8. India country map showing various institutions and companies working on hydrogen production

The key players in the Indian hydrogen market are Linde India Limited, Praxair India Private India Limited, Inox Air products, , Air Liquide India, Gujarat Alkalies And Chemicals Limited, Bhuruka Gases Limited, Aditya Birla Chemicals (India) Ltd., TATA Chemicals Limited, , DCW Limited (DCW), and GHCL Ltd.

Table 4. List of scientists working on hydrogen production at various institutions /organizations in the country with their email

Affiliation	Name	Email ID
IISc, Bangalore	Prof. S. Dasappa	s.dasappa@gmail.com
IIT Kharagpur	Prof. D. Das	ddas@bt.iitkgp.ac.in
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CSIR-IIP, Dehradun	Dr Subham Paul	spaul@iip.res.in
CSIR-IIP, Dehradun	Dr. Shailendra Tripathi	
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IACS, Kolkata	Praveen Kumar	praveen.kumar@iacs.res.in
Dr. Babasaheb Ambedkar Univ. Lonere, Maharashtra (BATU)	Dr. Yogesh S. Mahajan	ysmahajan@dbatu.ac.in
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3. Storage

The major bottleneck in the hydrogen pathway is compact, efficient, conformable, cost effective and safe storage of hydrogen. The requirements from a hydrogen store is different for stationary and vehicular applications. For transportation sector, the weight and size should be low, refueling 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, refueling time, life and cost etc. There are several challenges towards storing hydrogen and achieving the above-mentioned criterions, those are summarized in Figure 9.

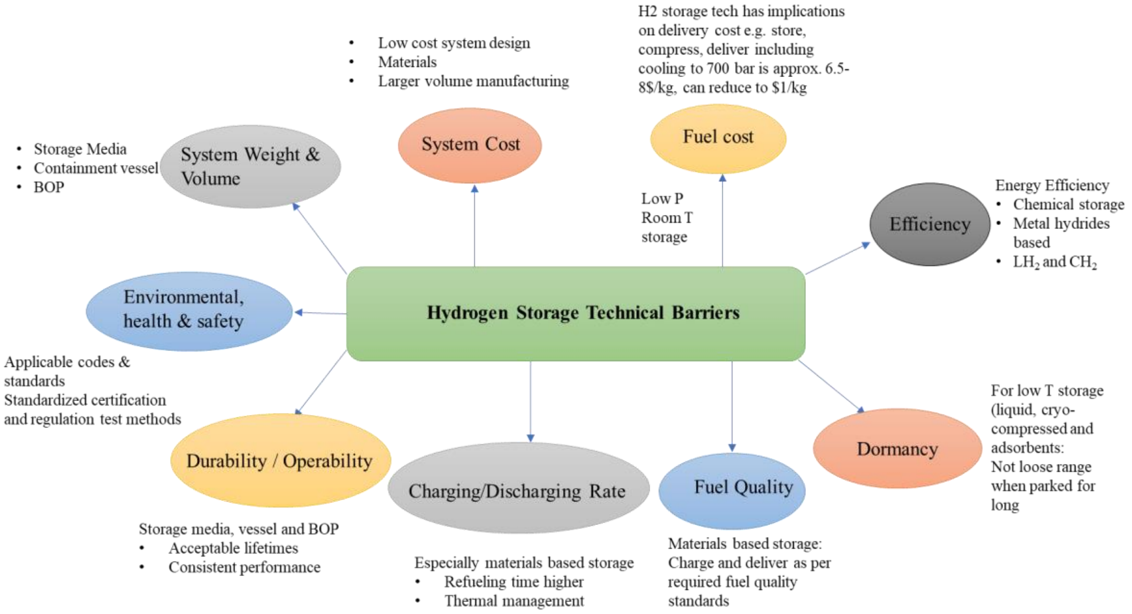


Figure 9. Technical barriers to the hydrogen storage

Hydrogen can be stored in either compressed, liquified and solid state, the various options are mentioned in figure 10. Since the density of hydrogen is very low 0.089 kg/m^3, as such storing in gaseous form requires compression to high pressures. The commercially available Type III and Type IV tank, can store hydrogen at 350 bar or 700 bar. As we go from Type I to Type IV tanks the weight of the tank reduces but the cost increases. Besides this compression of hydrogen requires around 21 MJ/kg or 0.13 kWh_{el} / kWh H_2 to compress from ambient to 700 bars through a five-stage compressor[6]. The method of hydrogen production which could supply hydrogen at a higher pressure up to 30 bar or more can save in terms of compression power. Since the compression power is logarithmic function of the pressure to which hydrogen is compressed. The energy required to compress hydrogen is equivalent to 4.1wt% to compress from 20bar to 700bar. The Type I tank which are all metal and thus high in weight, this weight penalty is reduced in the rest three types of tanks. Since hydrogen has high permeability as such an inner liner of metal is provided to ensure gas tightness, while the stability is provided by a partial (Type II) or complete (Type III) mesh of carbon fiber. In Type IV tank the inner liner is made of polymer and outer winding with carbon fiber, thus these composite containers are light in weight but high in cost. Caron fiber accounts for more than 50% of the cost of the tank and next major cost is BOP. The choice of auto industry for FCEVs is compressed hydrogen. Common fuel cell vehicles like Honda Clarity, Toyota Mirai have pressurized vessel-based storage. According to the Toyota Motor Corporation, the gravimetric density of 2017 Mirai tank is 5.7wt% at 700 bars. Mirai tank has an internal volume of 122.4 L with volumetric energy density of 4.9 MJ/L[7]. In the tank 5 kg of usable hydrogen is stored at 700 bar and the cost predictions states that is if production rate is 1000 systems per year than cost will be USD

8,171 while if the production rate is 20k/year then cost will drop down to USD 4529[8]. Such high-pressure tanks need to be fabricated indigenously, currently team at IIT Ropar is working towards the same.

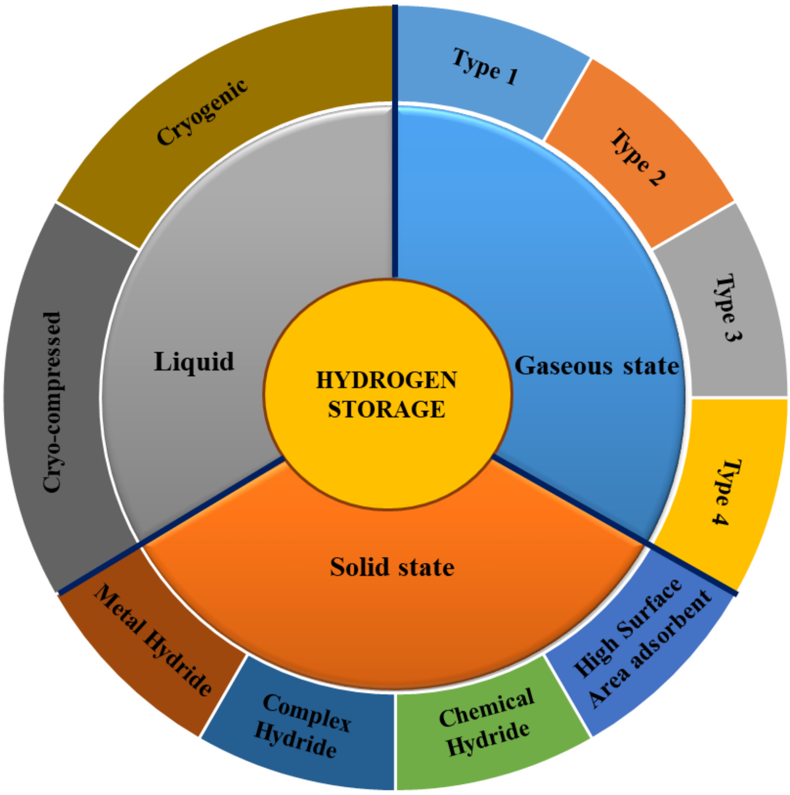


Figure 10. Different ways of hydrogen storage

The liquefaction of hydrogen is much more energy intensive than compression, roughly requires 0.33 kWh_{el}/kWh_{H2}. Liquid hydrogen temperature is 20K (density is 70.8 kg/m^3), as such the container design should involve super insulation to protect any heat inflow into the vessel, but these are not meant to bear high pressures. The liquified hydrogen storage suffer with boil-off losses, which are observed after the pressure build-up and the evaporated hydrogen is released to maintain the tank pressure, thereafter the tank system acts as an open system. The boil off losses are minimized if the tank is designed to have high volume to surface ratio. A spherical tank with 25 mm of insulation containing 5 kg of hydrogen is expected to have energy densities 6.4 MJ/L and 7.5wt%[9]. The cost associated with liquefaction is around USD 1/kg. The cost of storage varies for small and larger reservoirs for e.g. USD 167/kg for a capacity of 4300 kg for large scale storage vessel and USD 386/kg for 100L internal volume tank for vehicular applications[10,11]. Liquid state storage being a mature technology and is widely used for space and industrial applications.

There is another possibility like cryo-compressed tanks, which is a hybrid method combining both compressed and liquid state storage. Hydrogen is stored at cryogenic temperatures (typically 70 K - 200 K) and elevated pressure (typically 100 bar – 500 bar). The benefits of such tanks are that a higher effective storage density of H_2 and reduced system size could be achieved rather than spending on the energy and cost for a complete hydrogen liquefaction, thereby even achieving a longer driving range. Here the tank is designed to hold both the cryogenic liquid and also withstand the internal pressure. A prototype for BMW with boil off rate of 3-7 g/h and energy densities 5.4 wt% and 4.0 MJ/L has been reported[12].

Another method to store hydrogen is in solid state form where either the molecular hydrogen gets adsorbed on the high surface area materials or absorbed to form a hydride. This method of storage has several advantages as against the compressed and liquid state storage methods i.e. it is safe, volumetrically efficient and operating conditions involved like temperature and pressure are optimum unlike the other two methods. Hydrogen is bonded via weak Vander Waals bond in case of adsorption on to high surface area materials like Metal organic frameworks (MOF), zeolites, carbon nanostructure (CNF, GNF, AC, CNT etc.), clathrate hydrides and polymers of intrinsic micro porosity. The enthalpy of formation for such materials is low around 10 kJ/mole and thus a low temperature is required to hold the hydrogen, however this method of storage is reversible and kinetics is fast. The reported capacities in MOFs is around 4.5wt% at 78 K and 1.0wt% at room temperature and 20 bar, the volumetric energy density reaches up to 7.2 MJ/L at 100 bar and 77 K.

Hollow glass microsphere, microcapsules and micro balloons are interesting materials which are very inexpensive, safe and can store large quantities of hydrogen. The uptake and release of hydrogen is under defined set of temperature and pressure conditions.

Metal hydrides are compounds which react with hydrogen under certain temperature and pressure conditions reversibly to store hydrogen. There are wide range of metal hydrides studied in literature and these have been classified in to classes like AB (e.g. TiFe), A_2B (e.g. Mg_2Ni), AB_2 (e.g. $ZrMn_2$) and AB_5 (e.g. $LaNi_5$) etc. In these classes, A is a strong hydride forming element and B is non hydriding element. Since the metal used in formation of alloys are higher in weight, these materials suffer from poor gravimetric capacity but have high volumetric capacity. Some of the well-studied metal hydrides include FeTi, $LaNi_5$, $MmNi_5$, Ti-V-Cr alloys etc. The requirement from a metal hydride, if it is to be used for different hydrogen storage applications is that it should have equilibrium pressure of 1-10 bar and desorption temperature of room temperature to max of 100^0C. There are some metal hydrides which are unstable and have lower enthalpy of formation, while some have high enthalpy of formation and thus are very stable. The strategies followed to get the required thermodynamics i.e either stabilize/destabilize is either alloying, nanosizing, interface effects or nano-confinement.

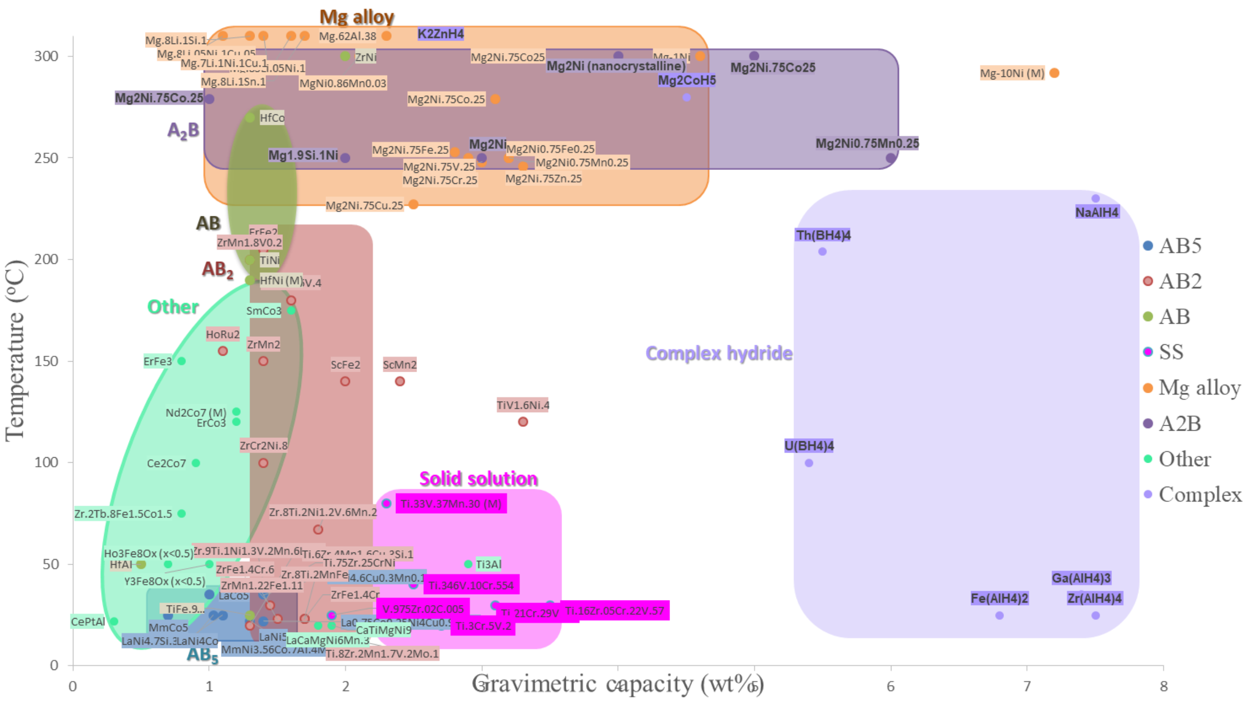


Figure 11. Gravimetric capacity versus desorption temperature plotted at 1 bar

Typical gravimetric capacity of these metal hydrides range between 1-3 wt% except for magnesium hydrides. MgH_2, which has 7.6 wt% capacity but very high desorption temperature of greater than 300^0C. This desorption temperature can be lowered through either milling, nanosizing, alloying, making composites, doping or addition of catalysts, but still the temperatures are very high for being used for PEMFC based applications. A plot of gravimetric capacity versus the desorption temperature for various hydrides is shown in figure 11.

In case of metal hydrides, the hydrogen interacts with metals to form the corresponding hydrides. Owing to the high molecular weight of the metal, the gravimetric capacity of stored hydrogen within the respective metal hydrides are observed to be very small (1- 3 wt%). Therefore, the hydrides of lighter elements (with lower atomic number, e.g. C-, N-, B- etc.) are more suitable for hydrogen storage due to their higher gravimetric hydrogen storage capacity. Among them most common example is the saturated hydrides of carbon, also known as alkanes. e.g. cycloalkanes including cyclo hexane, methyl cyclohexane, decaline, bicyclohexyl containing 6 - 8 wt% hydrogen and 60 - 62 g/L capacities. Conventionally, these cycloalkanes are used as solvents in various processes; however, their high hydrogen content can also be used for hydrogen storage applications. The dehydrogenation reaction of these cycloalkane compounds (C_nH_{2n+2}) follows through aromatization (C_nH_n), which introduces stability to the product species and thereby increases the feasibility of the dehydrogenation reaction. The larger enthalpy for dehydrogenation 64 - 69 kJ/mole of H_2, requires higher temperature for dehydrogenation 210 to 350 ^{0}C, which further inhibits its application. Although catalysts have been known to improve the dehydrogenation performance.

The liquid organic hydrogen carriers (LOHC) involves loading a carrier molecule with hydrogen and then extracting at the point of use. Cost associated with conversion and reconversions, also the energy equivalent requirement is between 35% - 40% of the hydrogen itself. In addition, carrier molecules in LOHC are often expensive and off board regeneration is required. Examples of LOHC include methylcyclohexane, with toluene as carrier but toluene is toxic in handling and cost is approx. USD 400-900 per tonne. Another nontoxic alternative is dibenzyltoluene and is further more expensive, other options includes methanol and formic acid but will not reduce the greenhouse gas emissions, besides there are issues related to safety and public acceptance.

The major disadvantage in Gr IV hydrides (C_nH_{2n+2}) or cycloalkanes, is their high stability in dehydrogenated state. The sp^3 hybridised C centres are charge neutral and reacts at considerably higher temperature, making their hydrogen storage application quite energy intensive. Both theoretical and experimental studies suggested that the partial substitutions of carbon atoms in the ring by nitrogen could help to substantially lower down the dehydrogenation enthalpy by reducing their aromaticity of the dehydrogenated molecules thus making heterocycles better candidates. In terms of reactivity and complete extraction of hydrogen, the Gr IIIA (Boron, B) and Gr IIIB (Nitrogen, N) based hydrides can be considered another option to their carbonaceous counterparts. Ammonia (NH_3) and borane (BH_3) are the principal hydrides of nitrogen (N) and boron (B). Ammonia can be used to produce hydrogen in presence of appropriate catalysts but then the reaction is endothermic, toxicity and corrosion are the major problems. Formation of ammonia and getting hydrogen requires 15 – 36% of hydrogen content and also in case of an uncombusted ammonia leak can lead to formation of particulate matter and acidification. Borane(BH_3) is an unstable hydride and therefore tends to dimerize at room temperature and pressure. Diborane is also considered to be high reactive, since it violently reacts in presence of water or air. Reaction of diborane with metal hydrides, especially from Gr. 1 and 2 tend to form secondary borohydrides with stable conformation via metathesis reactions. These secondary borohydrides are also known as metal borohydrides (*e.g.* $LiBH_4$, $NaBH_4$, $LiK(BH_4)_2$). This class of compounds where the complexing ion is either alanate or borohydride or amide have very high gravimetric capacity even upto 16 wt% or higher.

The stability of the tetrahedral borohydride sites and the presence of metal cations (Li^+, Na^+, Mg^{2+}) introduce ionic nature in these compounds. Therefore, these borohydrides are observed to be sensitive to moisture and oxygen. However, under inert conditions, thermal decomposition of these borohydrides occurs at higher temperature (250-400°C) which results in the formation of subsequent metal borides and hydrogen. Various methods have been reported to lower the decomposition temperature of complex borohydride, a few of them are, formation of binary metal borohydrides (*e.g.* $LiK(BH_4)_2$), increase in the cationic size, use of support material (*e.g.* activated carbon and carbon nanostructures, etc.), composite formation with another metal hydride (e.g. $LiBH_4$-MgH_2) which also results in increased regenerability. The regeneration of these complex hydrides is the major challenge. Other methods include formation of an ammoniate complex (*e.g.* $Mg(BH_4)_2$, $2NH_3$) which resulted in better dehydrogenation behaviour. Replacement of the ammonia with metal amides results into a borohydride-amide complex formation of M^1BH_4-M^2NH_2, where M^1, M^2=Li, Na, Mg and Ca. The hydrogen generated from the complex have been observed to vary within the range of 7.8-11.3wt%, however, their decomposition temperature are as high as 360-480°C depending on chemical composition.

Although the complex hydrides demonstrate high hydrogen storage capacity, the most prominent disadvantages of the metal borohydrides are their extreme susceptibility to atmospheric conditions, high decomposition temperature and irreversibility. Both of these disadvantages of metal borohydrides can be related to the ionic interaction between the metal and borohydride species. Therefore, incorporating more covalent characteristics in the borohydride material has been observed to make them prone to decompose at lower temperature. Interaction between the ammonium cation (NH_4^+) and the borohydride anion (BH_4^-) is found to result in N-B bonds, which shows partial covalent nature. Therefore, analogous to organic compounds (based on C-C skeleton) a wide variety of compounds based on the B-N based skeletal system are observed to demonstrate prominent hydrogen storage properties. These B-N based hydrogen storage compounds have been termed here as chemical hydrides. One example of such hydride is ammonia borane (NH_3BH_3) which is having gravimetric capacity of 19.6 wt% and can be handled under environmental conditions. There are several other chemical hydrides e.g. hydrazine boranes, hydrazine bis boranes etc which have been studied widely.

Department of Science and Technology activities on Hydrogen storage and fuel cells are focused on:

- New material structures for high gravimetric capacity
- Light weight high pressure hydrogen storage cylinder for vehicular applications
- Graphene and hard composite materials for hydrogen storage
- Selection, synthesis and characterization of metal hydrides
- Novel materials including metal organic framework and complex hydrides for thermal management applications
- Development of composites, graded materials, mixtures, materials and catalysts for Solid Oxide Fuel Cell (SOFC)

Some of the research work being carried at different institutions in the area of hydrogen storage is summarized below:

- A lot of work is being carried at IIT Bombay on materials for hydrogen storage. Various materials like metal, complex and chemical hydrides are being studied. The cyclability of metal hydrides and reversibility of chemical hydrides along with catalysis and support materials for achieving enhanced performance are being investigated. The synthesis of metal hydrides on large scale, synthesis from industrial grade materials and effect of impurities is being carried out. 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 has been studied. Metal hydride-based systems simulation, design, development and their performance analysis are being carried out at IIT Bombay. Studies on Mg based hydrides and their composites are being carried.

- Hydrogen Energy Centre was established at Banaras Hindu University with the funding of MNRE. A lot of pioneering work on novel materials, carbon nanotubes/nanofibres, graphene and composites, hydrogen Storage and applications in hydrogen fuelled two/three wheelers has been carried.

- Large number of metal hydride based applications have been demonstrated at IIT Guwahati. Thermal management challenges in the metal hydride-based devices has been addressed. These devices simulated, fabricated and demonstrated. Figure 12 shows some of these applications.

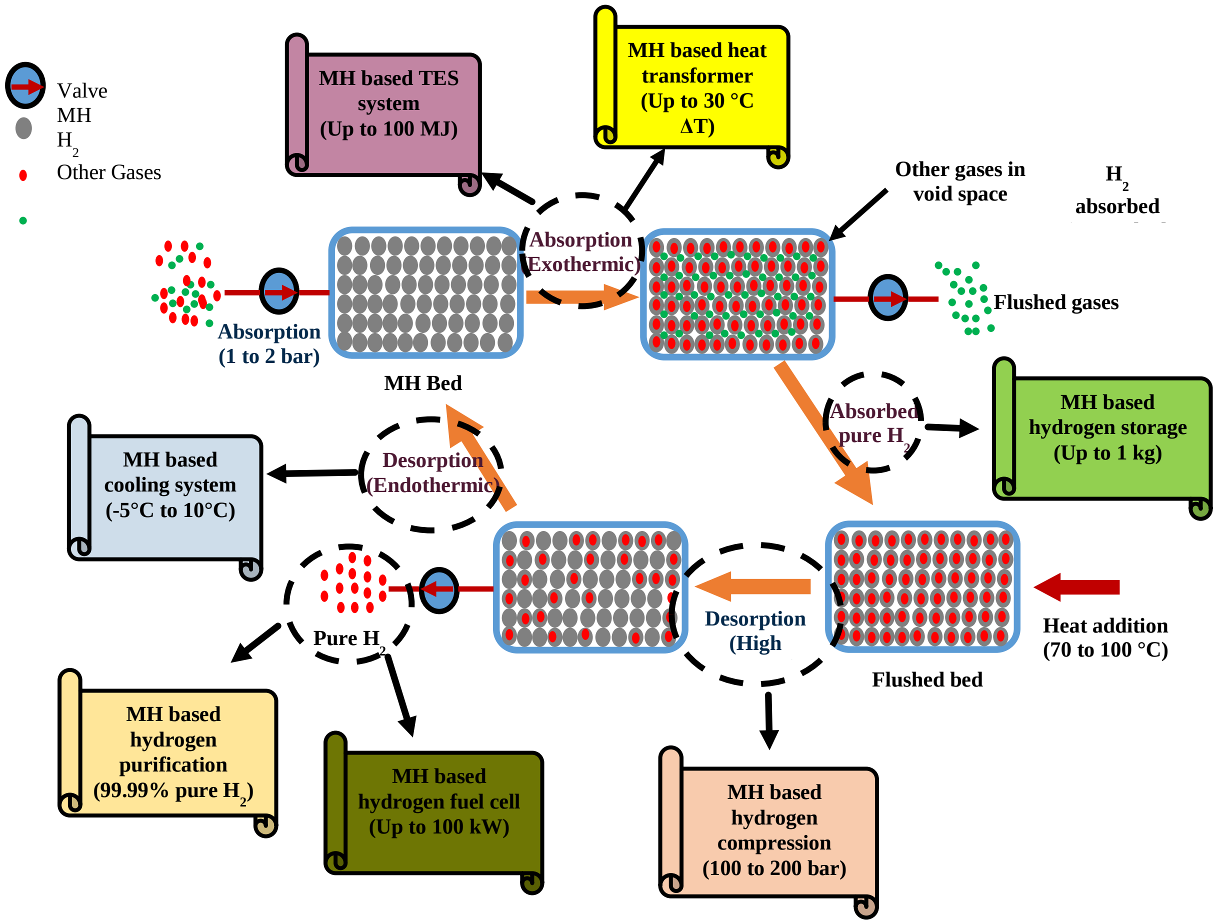


Figure 12. Metal hydride based applications

- In the metal hydrides-based storage the storage reactor design is very important. Since the exothermic and endothermic absorption and desorption processes requires efficient thermal management to ensure better performance, fast charging/discharging and achieving close to the theoretical capacities are important. A lot of system level simulation and optimisation work has been carried at IIT Madras, IIT Guwahati and IIT Tirupati.

- Two Energy Storage platforms have been established by the Department of Science and Technology. The need of innovative ideas, cutting edge research, human resource development, cost effective materials and technologies, widespread dissemination and public acceptance of the hydrogen technologies has been the major objective for establishment of these centres.

  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, industrial interactions, collaborations, manpower development and information dissemination in the field of hydrogen. The focus of the centre is towards selection, synthesis and characterization of 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 includes IIT Guwahati, IIT Kanpur, IIT Tirupati, NIT Rourkela. The centre will act as a nodal point of contact for information in the field and will provide mentorship & support to researchers in the country who are working in the area of hydrogen.

  DST- NFTDC Energy Storage Platform on Hydrogen has been established at Nonferrous Materials Technology Development Centre, Hyderabad with a core theme of hydrogen-based materials to energy devices. The focus of the centre will be specific hydrogen related systems like SOFC – integrated system and its outcomes at device level, Mg + C based hydrogen storage and La-Ni-X-Y based sorption cooling device. The network of researchers engaged in centre comprise of scientists from NFTDC, IISc Bangalore, IIT Madras, IIT Bhubaneswar, Sri Chitra Thirunal College of Engineering, Thiruvananthapuram.

A brief review of the research in the area of hydrogen storage carried at different institutions, organizations is included in the Table 5 and these are shown on country map in figure 13.

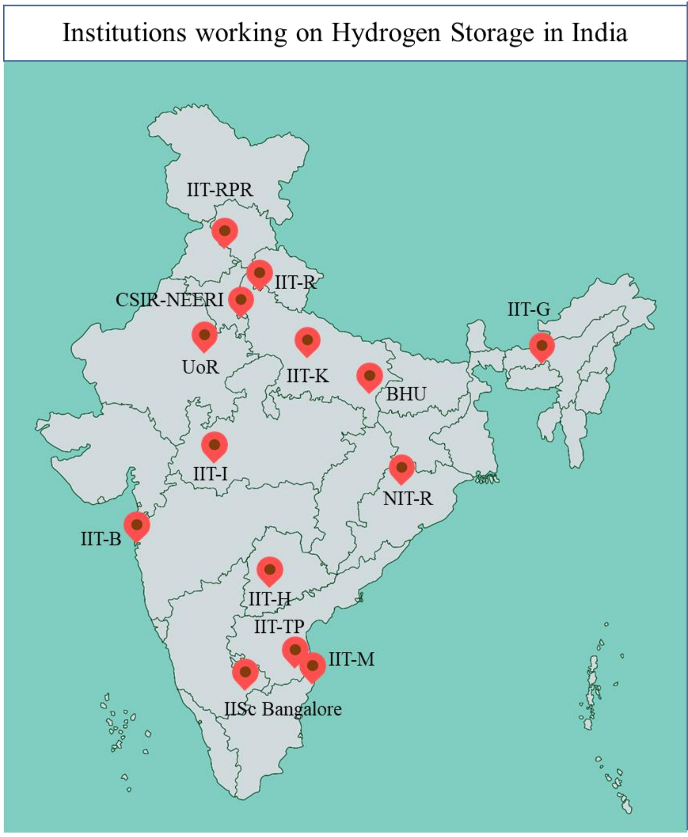
Table 5. Institutions/ organization/ companies working on hydrogen storage and nature of work being carried

S.No.	Institution	Nature of work
1	BHU	Hydrogen Energy Centre; development, synthesis and characterization of hydrogen storage materials, nanotubes/nanofibres, graphene and composites based on these, applications of hydrogen storage materials, hydrogen storage in hydrogen fuelled two/three wheelers, hydrogen combustion catalytic cooker
2	IISc Bangalore	Solid state hydrogen Storage, heat and mass transfer in hydride beds, thermodynamics of

S.No.	Institution	Nature of work
		storage, various applications of solid-state storage of hydrogen, organometallic compounds, chemical hydrides for hydrogen storage
3	IIT Bombay	Materials for hydrogen storage: metal hydrides, complex and chemical hydrides, hollow glass microspheres; hydrogen generation from complex hydrides via both hydrolysis and thermolysis; reversibility of complex and chemical hydrides; cyclability of metal hydrides, effect of impurities on metal hydrides, large scale synthesis of metal hydrides, catalysis and support materials; theoretical studies on de/adsorption on various hydrides; hydrogen storage systems simulation, modelling and development, thermal management in metal hydride beds; different applications of systems developed like thermal energy storage, backup power etc.
4	IIT Guwahati	Numerical and experimental analysis for the development of a metal hydride based hydrogen energy storage, metal hydride based thermal energy storage, metal hydride based compressor system, hydrogen purification. Design & application of carbon-based hetero atom modified nano-porous materials for hydrogen storage, development of supported noble metal catalysts using surfactant assisted electroless plating process for the dehydrogenation of light alkanes, ionic liquid assisted thermal dehydrogenation of ammonia borane
5	IIT Madras	Design, development and testing of metal hydride based devices, thermal and mechanical engineering design of the hydride beds; studies on hydrogen storage in metals, composites and carbon materials, diffusion studies of hydrogen in alloys, metal hydride devices; microporous, mesoporous and hierarchical zeolites; organic-inorganic hybrids, metal-organic frameworks; heterogeneous catalysis: eco-friendly nanostructured catalysts design for organic

S.No.	Institution	Nature of work
		transformations (petrochemicals, fine chemicals and pharmaceutical intermediates)
6	University of Rajasthan	Nano materials and nanocomposites, Mg based materials, complex hydrides, effect of nano sizing, AB_5 alloys and thin films for hydrogen storage
6	IIT Tirupati	Metal hydrides for solid state hydrogen storage, metal hydride based hydrogen compressors and other devices, metal hydride based devices
7	IIT Indore	DFT studies of borohydride, atomistic modelling of cathode electrode for PEM fuel cells, designing of Mn-based electrocatalysts for CO_2 vs. proton reduction
8	IIT Kanpur	MOFs for hydrogen storage, hydrogen solubility as a probe for Pd/oxide composites prepared by internal oxidation of Pd-rich alloys nano hybrids, novel materials and mechanisms for hydrogen storage, hydrogen embrittlement of aluminium lithium alloys and carbon alloyed iron aluminides
9	IIT Hyderabad	Amidophosphine borane as potential source for hydrogen – both experimental and computational approach
10	IIT Ropar	Membranes for hydrogen purification, chemiresistor gas sensors, hydrogen storage materials, photocatalysts for wastewater decontamination; modelling, design and development of Type IV tanks, high pressure testing,; inorganic and organometallic synthesis and catalysis, design of multifunctional metal-organic framework (MOF) materials, development of transition metal photocatalysts
11	IIT Roorkee	solid state and materials chemistry, photocatalytic energy storage, catalytic materials, nanomaterials for hydrogen storage
12	ARCI	Agricultural based activated carbon for hydrogen storage, Mg based materials and composites for hydrogen storage

S.No.	Institution	Nature of work
13	CSIR-NEERI	Liquid organic hydrides, catalysts and catalytic reactors for LOHC dehydrogenation, zeolites and MOFs for hydrogen storage
14	NIT Rourkela	Novel materials for hydrogen storage, metal hydride based hydrogen storage device
15	GIDC, Vadodara	Development of a metal hydride based hydrogen storage system for standalone portable hydrogen fuelled Gen-set
16	National institute of Technology, Tiruchirappalli	Development of nanostructure / composites and metastable magnesium based multicomponent alloys through mechanical alloying for hydrogen storage applications
17	CMRI, Durgapur	Development of design methodology for light weight high pressure hydrogen storage composite cylinder for vehicular applications



- Indian Institute of Technology-Bombay (IIT-B)
- Banaras Hindu University (BHU)
- Indian Institute of Science-Bangalore (IISc)
- Indian Institute of Technology-Madras (IIT-M)
- Indian Institute of Technology-Guwahati (IIT-G)
- Indian Institute of Technology-Tirupati (IIT-TP)
- Indian Institute of Technology-Indore (IIT-I)
- Indian Institute of Technology-Ropar (IIT-RPR)
- Indian Institute of Technology-Kanpur (IIT-K)
- Indian Institute of Technology-Hyderabad (IIT-H)
- Indian Institute of Technology-Roorkee (IIT-R)
- CSIR-National Environmental Engineering Research Institute (CSIR-NEERI)
- University of Rajasthan (UoR)
- National Institute of Technology-Rourkela (NIT-R)

Figure 13. Institutions working on hydrogen storage in India

Table 6. Scientists working on hydrogen storage at various organizations/institutes in the country

Affiliation	Name	E mail ID
BHU, Varanasi	Prof. O. N. Srivastava	ons@bhu.ac.in
IISc Bangalore	Prof. S. Srinivasa Murthy	ssmurthy@iitm.ac.in
IIT Madras	Prof. B. Viswanathan	bviswanathan@hotmail.com
IIT Madras	Prof. S. Ramaprabhu	ramp@iitm.ac.in
University of Rajasthan	Prof. I. P Jain	ipjain46@gmail.com
IIT Bombay	Prof. Pratibha Sharma	pratibha_sharma@iitb.ac.in
IIT Guwahati	Prof. P. Muthukumar	pmkumar@iitg.ac.in
NFTDC	Dr. K. Bala Subramanian	director@nftdc.res.in
IIT Kanpur	Prof. P.K. Bharadwaj	pkb@iitk.ac.in
IIT Hyderabad	Prof. T. K. Panda	tpanda@iith.ac.in
IIT Kanpur	Prof. R. Balasubramaniam	bala@iitk.ac.in
IIT Guwahati	Prof. Mahuya De	mahuya@iitg.ac.in
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ARCI	Dr. N. Rajalakshmi	rajalakshmi@arci.res.in
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IIT Madras	Prof. P. Selvam	selvam@iitm.ac.in
IIT Madras	Prof. M. P. Maiya	mpmaiya@iitm.ac.in
IIT Kanpur	Prof. Anandh Subramaniam	anandh@iitk.ac.in
IIT Tirupati	Prof. E. Anil Kumar	anil@iittp.ac.in
IISc Bangalore	Dr. P. Balachandra	p.balachandra@gmail.com
NIT Rourkela	Prof. Paresh G Kale	pareshkale@nitrkl.ac.in
CSIR-NEERI	Dr. Rajesh B. Biniwale	rb_biniwale@neeri.res.in
IIT Ropar	Prof. Dhiraj K Mahajan	dhiraj.mahajan@iitrpr.ac.in
IIT Indore	Prof. Biswarup Pathak	biswarup.pathak@gmail.com
IIT Ropar	Prof. Ravi Mohan Prasad	ravimohan.prasad@iitrpr.ac.in
IIT Kharagpur	Prof. Swati Neogi	swati@che.iitkgp.ernet.in
NIT Rourkela	Dr. Anbarasu Subramanian	anbarasus@nitrkl.ac.in

Affiliation	Name	E mail ID
IIT Ropar	Prof. Nagaraja C. Mallaiah	cmnraja@iitrpr.ac.in
IIT Roorkee	Prof. Tapas Kumar Mandal	tapasfcy@iitr.ac.in
BARC	Dr. Seemita Banerjee	seemita@barc.gov.in
IIT Kharagpur	Prof. M. Ramgopal	ramg@mech.iitkgp.ernet.in
IIT Kanpur	Prof. Jayant K singh	jayantks@iitk.ac.in
IISER, Thiruvananthapuram	Dr. M.M. Shaijumon	shaiju@iisertvm.ac.in
IIT Bombay	Prof. Sankara Sarma V Tatiparti	sankara@iitb.ac.in
Sree chitra Thirunal college of Engineering, Thiruvananthapuram	Dr. G. Mohan	mohan.g.menon@gmail.com
IIT Bhubaneshwar	Dr. Soobhankar Pati	spati@iitbbs.ac.in
Pillai HOC College of Engineering and Technology, Maharashtra	Dr. Manvendra Vashistha	manvendrav@mes.ac.in
NIT Karnataka	Dr. Airody Vasudeva Adhikari	avachem@gmail.com
IIT Jammu	Dr. Satya sekhar Bhogilla	Satya.bhogilla@iitjammu.ac.in
NPL, Delhi	Dr. Bipin Kumar Gupta	guptabgupta@nplindia.org
Electrical R & D Association GIDC, Vadodara	Dr. G. S. Grewal	
NIT Tiruchirappalli	Dr. S. Kumaran	kumara@nitt.edu
Central Mechanical Engineering Research Institute, Durgapur	Dr. Surendra Kumar	
Ahmedabad University	Dr. Sridhar Dalai	Sridhar.dalai@ahduni.edu.in
Vivekanand Global University, Jaipur	Dr. Subodh Srivastava	

4. Transport

Whether hydrogen is being produced in a centralized or decentralized manner, there is a need to transport hydrogen to the place of distribution or to take it to the point of use. In case of centralized production, the cost of hydrogen generation is lower due economies of scale but T&D costs are higher, while in decentralised production say at the refuelling station (using on site electrolyser or reformer), the T& D costs are minimized but cost of production is higher.

From the production site, there can be different ways of transporting hydrogen, like in the form of compressed gas or liquified form or in the form of high energy density molecules i.e in the form of larger molecules and transporting as liquids as indicated in figure 14. Several countries have extensive existing natural gas pipelines, either blending of hydrogen in existing natural gas grids is a possibility or a dedicated infrastructure of laying down pipelines for hydrogen is required.

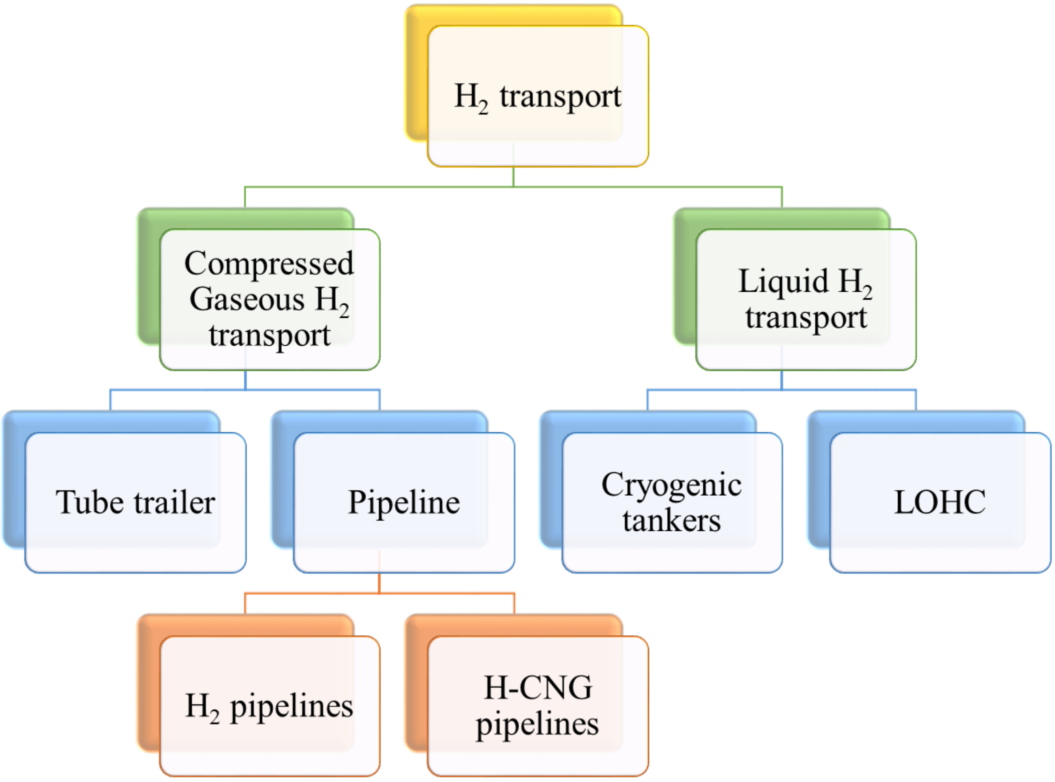

Figure 14. Different ways of transporting hydrogen

Thus, hydrogen can be transported either via road through tube trailers and trucks, through pipelines, or in the form of other molecules like methanol etc and then can be reformed at the point of usage or via shipping networks.

The choice of selection of appropriate method depends on geography, the volume to be transported, distance of transport and the end use application. Thus, long distance and large volume of hydrogen transport can be via pipelines and shipping route, while local distribution can be using either pipelines or trucks and trailers. It is known that pipelines have high CAPEX but a lower operational and maintenance cost, while the other methods including road transport may have low CAPEX but high O&M costs as the quantity of hydrogen being carried need to be compared with the energy required to transport and cost associated. Pipelines exist when hydrogen in large volumes need to be transported within refineries or over large distances (<1500km).

For further higher distances carrying in the form of high energy density materials like LOHC is a preferred choice. However, the conversion of hydrogen to LOHC and reconversion at the point of use adds up to the cost, offsetting the purpose. This will depend on the end use i.e. whether the requirement is of pure hydrogen for fuel cells or for other applications, for example hydrogen can be transported in form of ammonia for use in fertilizer industry. Thus, from economics point of view it's difficult to suggest a single solution and it depends on factors mentioned above.

However, in the absence of pipelines liquid hydrogen is transported and carried through super insulated, cryogenic tankers and trucks. However, the liquid hydrogen and gaseous hydrogen are better choice when the distances and volumes to be transported are relatively lower compared to where there is a need of pipelines or shipping network. With the density of hydrogen in liquid state being 70.8 kg/m^3, significant volumes can be carried at intermediate distances. Mostly liquid hydrogen is carried via tanker trucks where there is a consistent requirement and the savings in terms of cost of transport (as larger quantity carried than compressed via trailers) could be encouraging than the added liquefaction cost. Gaseous hydrogen can be transported through high pressure tanks making clusters of such tanks transported via tube trailers. The density of hydrogen at pressure of 200 bar is 15.6 kg/m^3 and at 500 bar it is 33kg/m^3. Pressurized tube trailers operate at pressures between 200-500 bar to carry small volumes of compressed hydrogen over short distances, with the tube trailer capacity in the range 500-1000 kg H_2. Else to carry intermediate volumes and larger distances liquid hydrogen is preferred option and can carry upto 4000 kg in liquified hydrogen truck. Over longer distance it is economical to carry liquid hydrogen than compressed hydrogen in the absence of pipelines. Challenge with carrying liquid hydrogen is boil-off. The various possible ways in which hydrogen can be transported and distributed for both the centralised and decentralised production is shown in figure 15.

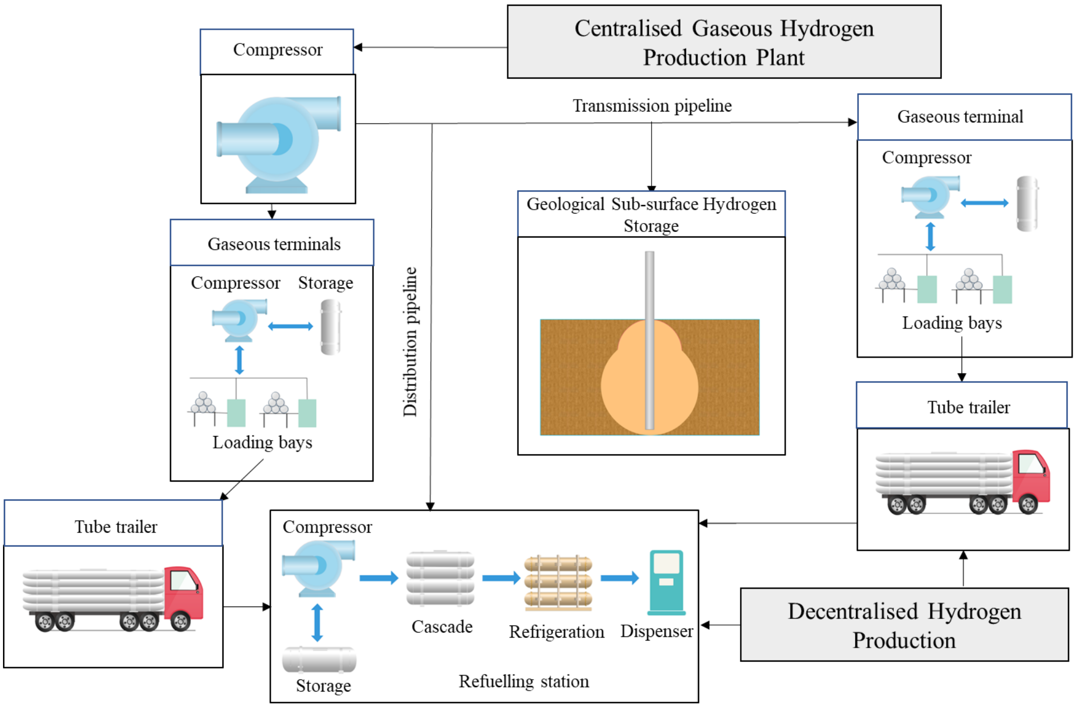

Figure 15. Possible ways for hydrogen transport, distribution and refuelling

Another method of transporting hydrogen at ambient temperature and pressure is in the form of liquid organic carriers, as being mentioned above. Hydrogen can be carried in the form of hydrocarbon carrier, which are high energy density materials having low flammability and toxicity and either can be used as such depending on end use application or can be converted to hydrogen at the point of use.

Hydrogen refuelling stations is an integral part of the hydrogen supply chain considering the vehicular applications. The small refuelling stations can refill 10-20 vehicles and have capacity of 50-100 kg/day. In future with the adoption of FCEVs and the market is mature, there will be need of larger refuelling stations of capacity 2000 kg/day.

IOCL have a pilot project for using hydrogen enriched compressed natural gas (H-CNG) in vehicles. H-CNG has been found to be more efficient than CNG in terms of reducing emissions. IOCL has developed a single-step procedure for blending hydrogen with CNG and the resultant blend is expected to lower down the emissions and will be cost effective. The Supreme Court had directed IOCL to finish this pilot project soon and H-CNG introduced in buses in 2020.

PSUs such as ONGC (Oil and Natural Gas Corporation) and Hindustan Petroleum also conduct research on Hydrogen. One of such project being conducted with the help of Industry and Government is shown in Figure 16.

Figure 16. H-CNG Dispensing Station set at Faridabad in Haryana

5. Hydrogen Utilisation - Fuel cell Technology

The most promising of all fuel cell technologies developed is Proton Exchange Membrane Fuel Cell (PEMFC), which operates at a lower temperature. The variant of PEMFC is Direct Alcohol Fuel Cell (DAFC), which is direct fed with methanol and ethanol as fuel instead of hydrogen. A majority of organizations are involved in fundamental research, for e.g. polymer membranes electrolyte, anode and cathode catalysts and membrane electrode assembly and hydrogen storage with very few involved in manufacturing and technology. Some institutions are involved in more application-oriented research such as stack and balance of plant development and fuel cell bus demonstration program. PEMFC technology has been developed to the commercialization stage in many countries like Canada, USA, Japan, Germany etc. As per Industry Review, the shipment of PEMFC units dominated in 2011 for the stationary and transport applications. In India, a large number of groups are engaged in the research, development and demonstration activities of PEMFC but it has not reached the stage of commercialization. A few organizations like CFCT-ARCI, CSIR-Network Labs, NMRL, VSSC and BHEL are engaged in complete development of PEMFC system. Engineering input and infrastructure for producing such system in large numbers for trials / demonstration are lacking. These activities rely on pressurized bottled hydrogen procured at high cost. On site hydrogen generation units (reformers) operating on commercial fuels such as LPG, methanol or natural gas are not available in the country, which again restrict the technology development process.

Department of Science and Technology activities on Hydrogen Utilisation are mainly focussed on:

- Novel materials, catalysts for durable and low-cost PEM Fuel Cells
- Nano-doped hybridized biodiesel as pilot fuel for hydrogen dual fuel operation in a CI engine and compressed hydrogen-fuel cell integrated system suitable for light duty vehicles
- Stationary power backup application for telecommunication towers and gas turbine combuster

A brief summary of the activities being carried out at various organisations in the area of fuel cells is presented in Table 7. Further organisations where research work on different components like catalysts support material is included in table 8, on membrane in table 9 and other than these components is included in table 10. Table 11 summarizes various other studies being carried in the area of fuel cell.

Table 7. Different organisations with research groups working on fuel cells and the nature of work

Organizations	Nature of work
IITM, NCCR, IITB, IITG, IITK, IITKGP, IITR, IITH, IISc, BESU, CSIR- CECRI, CSIR-NCL, CSIR-NPL, CFCT- ARCI, CIPET, CSIR-CSMCRI, BITS- Goa, TU, AIIST, PSGIAS, Anna University, UoH, DTU and many other universities, BHEL, SSF (closed), ISRO Labs & Def. labs	• Basic Science • Catalysts, membrane, bipolar Plate • Modelling • Stack and system • Application and demonstration
Tata, M&M, TVS, REVA, NMRL, Some CSIR labs, IITs, BPCL, RIL	• System integration using bought out stacks for demonstration • Demonstration of indigenously built fuel cells

Organizations	Nature of work
	• Application Simulation studies
ARCI, CSIR-NCL, CSIR-CECRI, CSIR NPL, Arora Matthey, Falcon Graphite, TCIC	• Materials (large scale)

Table 8. Different organisations with research groups working on the catalyst support materials

Organizations	Nature of work
IITM, NCCR, CFCT-ARCI, CSIR-NCL, CSIR-CECRI, BESU, ARAI-Pune, JNCASR and many other universities	• Modified CNT • Microporous CNT • Oxides • Metal Carbides, different carbons, • Ni mesh substrate • Graphene, • Nitrogen doped graphene and hybrid carbon nanostructures • Nitrogen-doped multi walled carbon nano coils • Multi walled carbon nano tubular coils • Nitrogen –doped mesoporous carbon with graphite walls • Nitrogen-doped multi walled carbon nanocoils

Table 9. Different organisations with research groups working on working on Membranes

Organization	Nature of Work
CSIR-CSMCRI, CSIR-CECRI, Anna University, CSIR-NCL, UoH, CFCT-ARCI, NMRL, CIPET, IICT, BHU, BIT, AIIST, IIT-D, ONGC and many other groups	• Nafion Based Membranes • Nafion Composites • Organic-Inorganic composite membranes (nafion with silica, MZP and MTP) • Polyelectrolyte complexes of nafion and poly (oxyethylene) bisamine • Fluorinated polymers • Fluorinated poly(arylenes ether sulfones) containing pendant • Sulfonic acid groups • Fluorinated poly(ether imide) copolymers with controlled degree of sulfonation • PVA based polymers • Inter penetrating with PSSA • Incorporation of mordenite

Organization	Nature of Work
	• Stabilized forms of phosphomolybdic acid, phosphotungstic acid and silicotungstic acid incorporated into PVA cross linked polymers • Novel mixed-matrix membranes sodium alginate (NaAlg) with PVA and certain heteropolyacids (HPAs) such as PMoA, PWA and SWA • High temp polymers-PBI, SPEEK • Cross-linked SPEEK-reactive organo clay nanocomposite • Phosphonated multiwall carbon nanotube-poybenzimidazole composites • Novel blends of PBI and poly(vinyl-1,2,4-trizole) • SPEEK/ethylene glycol/ polyhedral oligosilsesquioxane hybrid membranes SPEEK and poly(ethylene Glycol) diacrylate based semi interpenetrating network membranes • Heat treated SPEEK/diol membrane • High temp polymers-others • Anhydrous proton conducting hybrid membrane electrolytes for high temperature (>100˚C), PEM • Aprotic ionic liquid doped anhydrous proton conducting polymer electrolyte membrane • Polysulfone/ clay nanocomposite membranes • Multilayered sulphonated polysulfone/ silica composite membranes • Other type of polymers • SPSEBS/ PSU blends- bleeding SPSEBS (sulfonated poly styrene ethylene butylene polystyrene) with boron phosphate (BPO_4) • Organic-inorganic nano-composite polymer electrolyte membrane • Zwitterionic silica copolymer based cross linked organic-inorganic hybrid polymer electrolyte membranes • Carbon nanotubes rooted montmorillonite (CNT-MM) reinforced nano-composite membrane • Domain size manipulation by sulfonic Acid functionalised MWCNT's • Functionalized CNT based composite polymer electrolytes • Minimally hydrated polymers, replace water with proton mobility facilitator

Table 10. Research and development work on other Components/ Materials/Issues at various organizations

Components / Materials/ Issues	Organizations	Nature of work
Bipolar plates	CFCT-ARCI, CSIR-NPL, CSIR-NCL, SSF, NMRL, IITB, TU, IITG, IITK, VSSC, DTU	Resin impregnated, resin bonded, exfoliated graphite, metal, PCB
Carbon substrate	CSIR-NPL, CFCT-ARCI, NMRL	PAN, modified rayon, carbon composites
GDL	CFCT-ARCI, CSIR-CECRI, CSIR-NPL, IITM, Bharathiyar University	Studies on micro porous layer, method of fabrication, effect of additives, impedance analysis
Operation methods	CSIR-CECRI, CFCT-ARCI	Dead end mode operation
Fuel Impurities	CFCT-ARCI, AU with SVCE	Effect of impurities in gas feed
Durability	CFCT-ARCI, CSIR-CECRI, IITM	Single cells & stack, composite membrane GDL

Table 11. Other Studies being carried at various organizations

Study	Organizations
Flow field modelling	IITM, IITG, IITH, NMRL, CFCT-ARCI
Heat and mass transfer modelling	IITM
Cathode reactant supply modelling and design	CFCT-ARCI with IITM
Operation	IITB, CFCT-ARCI
Control system modelling	IITM, IITB, SSN College of Engg., CFCT-ARCI with Anna University
Power electronic modelling	IITB, Anna University with CFCT- ARCI, SSN, IISER Kolkata
Electrochemical modelling	IITM , IITD, IISER Pune, NIT-W, AU-Vizag, CFCT-ARCI, IITM(cyl. cathode), IITM (multiple layer), Bharathiyar University
Electrical conductivity	IITG, BARC

.

System integration modelling with wind energy etc.,	MNIT, BESU, IITB, IITK
Stack modelling	CFCT-ARCI, IITB
Stack analysis, artificial neural network	CFCT-ARCI with ISI, CSIR-NCL, CFCT-ARCI
Molecular dynamics	CSIR-NCL with IISER-Pune

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With reference to systems development Table 12 summarizes the organisations working on the development of fuel cell systems and the major achievements. Figure 17 shows the major activities in the area of hydrogen and fuel cell and the major institutions working in the area are marked on country map. Similarly, the institutions were research on membrane is being carried out in the country are marked on the map in figure 18, while on catalyst development are indicated in figure 19. Table 13 lists the major institutions and scientists working in the area of fuel cell, membrane in table 14 and on catalyst development in table 15.

Table 12. Summary of organizations involved and major fuel cell R&D work at these institutions in India

Institute/Organization	Main Focus Area(s)	Achievements/Remarks
CECRI, Chennai	PEMFC, DMFC, DBC, hydrogen generation	Developed a 1 kW PEMFC stack, Developed a 5 kW PEMWE
CFCT, Chennai	PEMFC, hydrogen generation	Developed PEMFC stacks up to 5 kW, Grid independent power systems (3 kW), Fuel cell systems for transport applications with Mahindra Rise and Reva
CGCRI, Kolkata	SOFC	Developed electrode and membrane materials for high performance SOFCs and Low Temperature SOFC. 400 W SOFC stack developed
SPIC SF, Chennai	PEMFC, DMFC, hydrogen generation	Developed 5 kW PEMFC stacks, 250 W DMFC Stack, PEM-based water and methanol electrolyzers, fuel cell based stationary applications such as UPS
IIT Bombay	PEMFC, DMFC, IT-SOFC,	PEMFC system development, catalysts for PEMFC, working on HT-PEMFC and IT-SOFC
IIT Delhi	PEMFC, DAFC, hydrogen generation, SOFC	Developed DEFC with power density of 70 mW/sq.cm, electrode-catalysts, developed direct glucose fuel cells, non-PGM ORR catalyst and micro fuel cell for MEMS, anode materials for hydrogen generation using PEM water electrolyzer, anode material for direct hydrocarbon SOFC and low temperature SOFC.

Institute/Organization	Main Focus Area(s)	Achievements/Remarks
IIT Madras	PEMFC, DMFC, SOFC	Developed a DMFC with non- noble cathode catalyst with 340 mA/sq.cm (0.6 V) at 80 ^{o}C, non-PGM catalyst for PEMFC, SOFC material research
NCL, Pune	PEMFC	Prepared thermally stable PBI membranes, demonstrated a 350 W (15 cell) PBI-based PEMFC stack
NMRL, DRDO, Mumbai	PAFC, PEMFC	Developed and demonstrated 700-1000 W capacity PAFC-based UPS/generators. 1.2 kW PAFC system integrated in an electric vehicle developed under DRDO-REVA joint project, development work on PEMFC and SOFC
BARC, Mumbai	SOFC, PEMFC	SOFC material and tubular SOFC under development
IISc, Bangalore	PAFC, DMFC, PEMFC	Developed PAFC with power density value of about 560 mW/sq.cm.
Mahindra Rise	Hydrogen IC engines	Developed hydrogen powered Alfa 3 wheeler vehicle, developing battery powered electric hybrid vehicle
TATA Motors	Fuel cell technology for transport applications	Developing a fuel cell based city bus, projects on using hydrogen blends as fuels. TATA teleservices involved in demonstration of fuel cell technology for mobile tower backup power
Indian Oil Corp. Ltd	Hydrogen infrastructure, hydrogen for transport sector	Setup hydrogen dispensing stations, HCNG usage in 3-wheeled vehicles and light duty buses
Reliance Industries Ltd.	PEMFC for stationary applications, SOFC	Joined the NMITLI project for indigenous PEMFC technology development as the industrial partner, established a fuel cell R&D lab in Mumbai
REVA (Own by Mahindra Rise)	Fuel cell based small cars	Developed a car with NMRL with 1 kW PAFC stack on board, involved in a similar project with CFCT.
BHEL	PAFC, PEMFC, SOFC	Developed a 50 kW PAFC power plant, developed 1 kW PEMFC modules and a 3 kW PEMFC power pack, partner institute in the development of a 5 kW PEMFC system under the NMITLI project
Nissan India	PEMFC technology for automobile applications	Working on membrane development for PEMFC technology, studying membrane degradation
ACME Telepower	Fuel cells for backup power	Joint venture with Ballard power systems Inc. and Ida-Tech to set up a high volume

Institute/Organization	Main Focus Area(s)	Achievements/Remarks
		low cost fuel cell systems for mobile tower backup power
Eden Energy (India) Pvt. Ltd.	Hydrogen for transport sector	Involved in production of hythane, agreement was signed with Ashok. Leyland for the supply of hythane to be used in natural gas powered buses
Gas Authority of India Limited	Hydrogen Infrastructure	Main player for supply of suitable fuels, including hydrogen, natural gas, propane, butane and methanol
Bloom Energy (India) Private Limited	SOFC	Working on testing and characterization of SOFC technology
Daimler Research Center (DMRC), Bangalore	Fuel cell for transport applications	Setup an outsourcing R&D centre in Bangalore, considering launching a commercial fuel cell vehicle in India (Final outcome of DMRC is not known to author)
Indian Space Research Organization	Application of PEMFC powering automatic weather station, PEMFC use space station and man mission	100 W PEMFC system is developed for automatic weather station

During the last 10 years, MNRE spent around Rs. 25 Crore on fuel cell research. CSIR also spent around a similar amount during this period. In addition DST and DSIR contributed around Rs.5 Crore each for the similar purpose. DRDO has so far invested around Rs.50 Crore and plan to invest another Rs. 100 Crore in near future. Exact amount spent by DAE is not available at this stage but likely to be of the order of Rs.50 Crore during the last 10 years. Government of India is likely to support the projects in three categories viz Mission Mode Projects, Research & Developmental Projects and Research Projects . Based on the application potentiality as well as available expertise in the country, the types of fuel cells identified for Indigenous development of the technology in Mission Mode(Category I) are:

i. HT-PEMFC with combined cycle (Joint Lead Institutes: CSIR-NCL, Pune and CSIR-CECRI, Karaikudi),
ii. LT- PEMFC (Lead Institutes: ARCI -CFCT, Chennai and/or CSIR-CECRI, Karaikudi/ BHEL R&D, Hyderabad),
iii. Planar SOFC (Lead Institute: CSIR-CGCRI, Kolkata)
iv. PAFC /for civilian applications only (Lead Institute NMRL, DRDO, Ambernath and/or BHEL R&D, Hyderabad).

Stake holders of Hydrogen

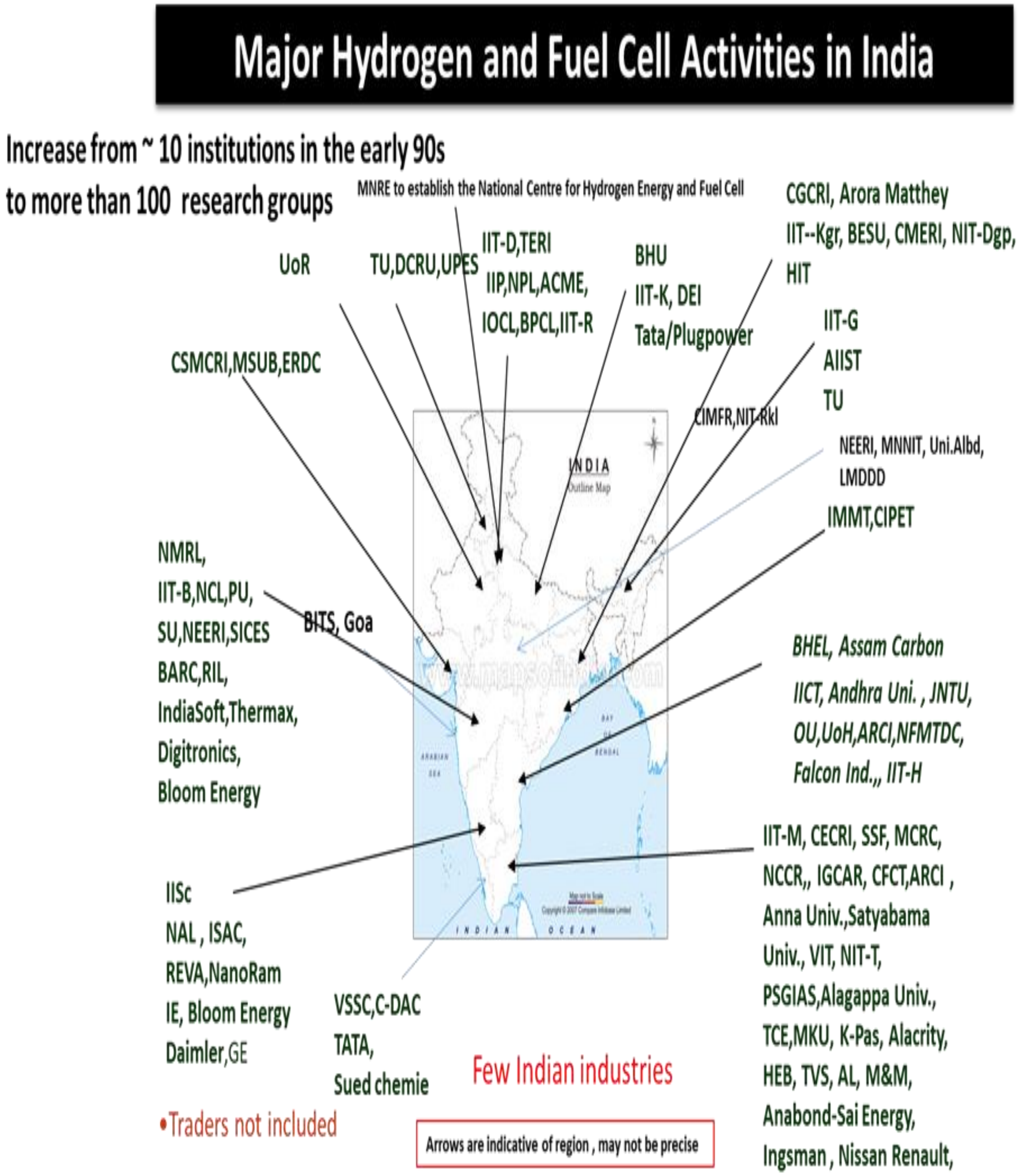


Figure 17. Map showing institutions with major fuel cell activities in India

Table 13. Scientists working in the country at various institutions/ organizations/ companies in India on fuel cells and their mail IDs

Name	Affiliation	Email details
Prof. Vivek Agarwal	IIT Bombay	agarwal@ee.iitb.ac.in
Dr. N. Rajalakshmi	ARCI	rajalakshmi@arci.res.in
Dr. Sheela Berchmans	CSIR-Central Electrochemical Research Institute, Electrodics and Electrocatalysis Division, Karaikudi	sheelaberchmans@yahoo.com, sheelab@cecri.res.in
Dr. Jayati Datta	Department of Chemistry, IIEST, Shibpur	jayati_datta@rediffmail.com
Dr. Avijit Ghosh	Center for Applied Physics, Central University, Jharkhand	avijitphy@gmail.com
Prof. P. C. Ghosh	IIT Bombay	pcghosh@iitb.ac.in
Prof. K. P. Karunakaran	IIT Bombay	karuna@me.iitb.ac.in
Prof. S.Basu	IIT Delhi	sbasu@iitd.ac.in
Prof. S. Ramaprabhu	IIT Madras	ramp@iitm.ac.in
Prof. Kothandaraman	IIT Madras	rkraman@iitm.ac.in
Prof. Sreenivas Jayanthi	IIT Madras	sjayanthi@iitm.ac.in
Prof. Raghuram Chetty	IIT Madras	raghuc@iitm.ac.in
Prof. Raghunathan	IIT Madras	raghur@iitm.ac.in
Dr. Gurpreet Kaur	Centre of Advanced Studies in Chemistry, Panjab University, Chandigarh, India	gurpreet14@pu.ac.in
Dr. Vaibhav Kulshrestha	CSIR - Central Salt & Marine Chemicals Research Institute, Bhavnagar	vaibhavk@csmcri.res.in
Dr. Jayanta Mukhopadhyay	CSIR-Central Glass & Ceramic Research Institute, Kolkata	jayanta_mu@cgcri.res.in
Dr. Vijayamohanan K Pillai	Vijayamohanan K Pillai Director, CSIR-CECRI, Karaikudi	vijay@cecri.res.in
Dr. A. K. Tyagi	BARC	aktyagi@barc.gov.in
Prof. Debabrata Pradhan	IIT Kharagpur	deb @ matsc.iitkgp.ernet.in
Prof. Shantonu Roy	IIEST Shibpur	shantonu20@gmail.com

Name	Affiliation	Email details
Dr. P N Sarma	Bioengineering and Environmental Engineering Centre, Indian Institute of Chemical Technology, Hyderabad	sarma1950@yahoo.com
Prof. R.N. Singh	Chemistry Department, Banaras Hindu University	rnsbhu@rediffmail.com
Dharmalingam S	Anna university	sangeetha@annauniv.edu, sangeetha_univ@yahoo.co.in
Janardhanan VM	Department of Chemical Engineering, IIT H	vj@ iith.ac. in
Dr. Anushree P Khandale	Indian Institute of Information Technology, Design and manufacturing, Chennai	anushri.khandal @iiitdm.ac.in
Dr. Abhijit Das Sharma	CSIR-Central Glass & Ceramic Research Institute	adassharma@cgcri.res.in
Dr. Swapan Kumar Bhattacharya	Department of Chemistry, Jadavpur University	skbhattacharya@chemistry.jdvu.ac.in
Prof. Manoj Neergat	IIT Bombay	nmanoj@iitb.ac.in
Dr. S. V. Selvaganesh	CSIR-Central Electrochemical Research Institute-Madras Unit, CSIR Madras Complex, Chennai	svsganesh.dr@gmail.com
Dr. R.B. Mathur	NPL	rbmathur@nplindia.org
Prof. S. H. Pawar	Department of Physics, Shivaji university, Kohlapur	pawar_s_h@yahoo.com
Dr. Sekhon SS	Department of Applied Physics, Guru Nanak Dev University, Amritsar	sekhon_apd@yahoo.com
Dr. L. Cindrella	NIT T	cind@nitt.edu
Dr. T. Maiyalagan	SRM	maiyalagan.t@ktr.srmuniv.ac.in
Dr. R. N. Basu	CGCRI	rnbasu@cgcri.res.in

Name	Affiliation	Email details
Dr. S. Sridhar	Indian Institute of Chemical Technology	s_sridhar@iict.res.in
Prof. Anil Verma	IIT Delhi	anilverma@iitd.ac.in, anilverma@chemical.iitd.ac.in
Prof. S. Bandyopadhyay	IIT Bombay	santanub@iitb.ac.in
Dr. S. R. Bharadwaj	BARC	shyamala@barc.gov.in
Dr. N. M. Gokhale	NMRL	
Prof. M. S. Hedge	IISc	mshegde@iisc.ac.in

Scientists working in Membrane development for PEMFC

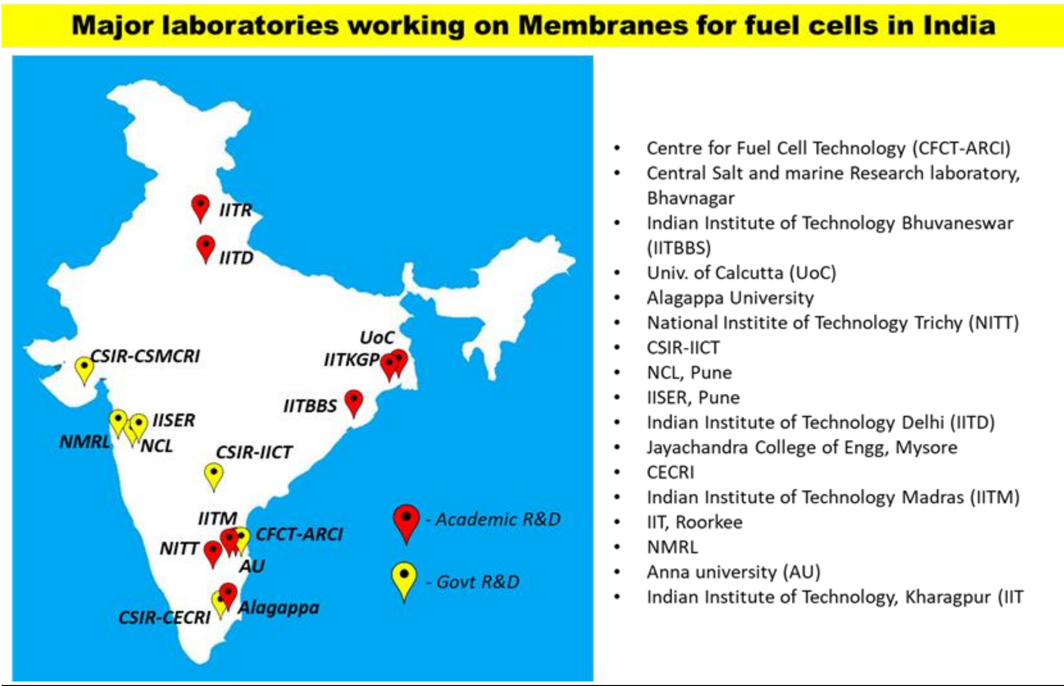


Figure 18. Institutions and organizations in the country working on membrane development

Table 14. Scientists in India working on membrane for fuel cells

Scientist	Affiliation
Dr. V. K. Shahi	Central Salt and marine Research laboratory, Bhavnagar
Prof. P. Maiti	IIT BHU
Prof. P. P. Kundu	IIT Roorkee
Prof. Ramesh Prabhu Manimuthu	Alagappa University
Dr. G. Arthanareeswaran	NIT Trichy
Dr. A. A. Khan	IICT
Dr. U. K. Kharul	NCL, Pune
Dr. Vijaymohanan Pillai	CECRI/NCL
Dr. Sujit K Ghosh	ISER, Pune
Prof. Veena Choudhary	IIT Delhi
Dr. G. M. Shashidhara	Jayachandra College of Engg, Mysore
Dr. Santhosh Kumar Bhat	CECRI
Dr. Sahu	CECRI
Prof. Susy Varughese, Prof. A Deshpande	IIT Madras
Prof. Yuvraj Singh Negi	IIT Roorkee
Prof. Verghese Deshpande	IIT Madras
Dr. M.Patri, Dr. Swati Rao	NMRL
Dr. S. Mondal and A.K. Banthia	Department of Polymer Science, Bundelkhand University, Jhansi and Materials Science Center, Indian Institute of Technology Kharagpur

Table 15. Scientists working in catalysts development in India

Name	Affiliation
Prof. B.Viswanathan, Prof. S. Ramaprabhu, Prof. Prathap haridoss, Prof. Ranga Rao Kothandaraman, Prof. Raghuram Chetty	IIT Madras
Prof. S. Basu	IIT Delhi
Prof. Manoj Neergat, Prof. P. C Ghosh	IIT Bombay
Prof. Vijaymohanan Pillai	NCL, CECRI
Prof. Kundu	IIT Roorkee
Dr. Manoj Karthikeyan	PSGTECH, Coimbatore
Dr. Shaijumon	IISER, Trivandrum
Dr. Peter Sebastian	JNCASR, Bengaluru

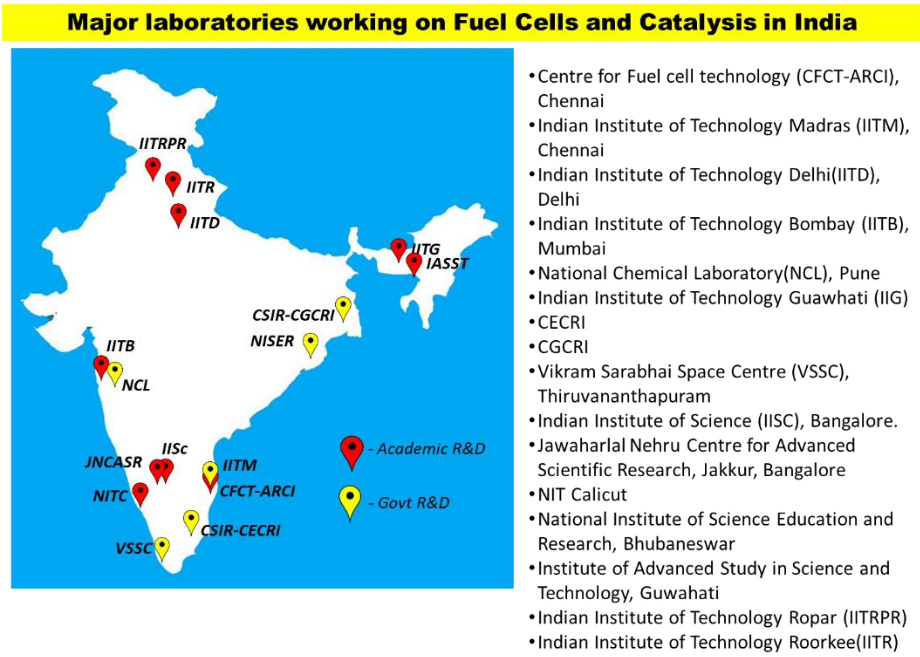


Figure 19. List of major institutes in India working on catalyst development and fuel cells

6. Utilisation – Others

Currently, there are around 11,200 hydrogen powered cars, 20,000 forklifts operating on hydrogen, 381 hydrogen refuelling stations worldwide[3].

Ministry of Non-Conventional Energy Sources have supported many demonstration projects through Indian Oil Corporation and Society of Indian Automobile Manufacturers. The first demonstration project was for setting up a dispensing station by the Indian Oil Corporation. The dispensing station at their R & D centre Faridabad, has been commissioned during 2008-09 and has an electrolyser with 5 Nm^3/hr hydrogen production capacity (about 11 kg/day). Hydrogen produced from the electrolyser is being blended with CNG for use in demonstration and test vehicles. The project is dedicated to acquire working experience in handling hydrogen for use in vehicles and also provide field performance feedback on hydrogen-CNG blends as a fuel in automobiles.

The other demonstration project is being implemented by the Society of Indian Automobile Manufacturers (SIAM) in association with five automobile manufacturers (Tata Motors, Ashok Leyland, Eicher Motors, Mahindra and Mahindra and Bajaj Auto) and Indian Oil Corporation was towards demonstrating the use of hydrogen blend with CNG in automobiles. Three buses, two cars and two three wheelers were part of the project and were used for field trials based on 18% hydrogen (by volume) blended with CNG. The project involves modifications in engine and fuel injection system. Existing hydrogen-CNG dispensing station set up by India Oil Corporation at Faridabad is being used for filling hydrogen-CNG blends in the test vehicles. The project helped in optimization of engine performance and blend ratio of hydrogen with CNG. The criteria for optimization would be the best efficiency and lowest NO_x. Hydrogen up to 20% (by volume) can be blended with compressed natural gas (CNG) for use as an automotive fuel.

Many RD&D efforts made in the area of hydrogen energy, laboratory level prototypes of hydrogen fuelled motorcycles, three wheelers, engine-generator sets, and water/methanol electrolysers for hydrogen production have been developed, their pictures are shown in Figures 20 -25. About 15 hydrogen fuelled motorcycles are being demonstrated in the campus of Banaras Hindu University, Varanasi. There are many development and demonstration activities are being taken up to develop and improve hydrogen fuelled vehicles and small generators. It is envisaged that in about a decade time, near commercial models may be available for extended demonstration of hydrogen use in automobiles. Small power generating systems are also likely to be ready by that time.

Some of the major work in the country in hydrogen utilisation which has been demonstrated is mentioned in the figures 20-25. Metal hydrides-based hydrogen storage reactors have been developed for various applications like hydrogen compression, purification, thermal energy storage, heating and cooling applications at IIT Guwahati, their pictures are included in figures 26-29. Reactors with metal hydride-based hydrogen storage for back up power applications of capacity 1.5 kWh and 10 k Wh have been developed at IIT Bombay, different exchanger designs have been simulated, optimized and used for such reactor fabrications, shown in figure 30. Demonstration of PEMFC systems of 3kW and 5 kW has been done at ARCITECH, GAIL, ESCI and Neyveli lignite corporation by ARCI-CFCT, pictures of the same are shown in figures 31 and 32. Integration and demonstration of fuel cell and battery-based vehicles for two, three and four wheelers have been carried out by ARCI, pictures of those is shown in figure 33.

Figure 20. Hydrogen fuelled 3-wheeler developed jointly by IIT Delhi and Mahindra & Mahindra in New Delhi

Figure 21. Total hydrogen S.I. engine genset using electronic fuel injection system

Figure 22. Hydrogen fuelled diesel Engine developed at IIT Delhi

Figure 23. Hydrogen fuelled three wheelers in Auto Expo 2012

Figure 24. Five Hydrogen Fuelled two Wheelers developed at Physics Dept., BHU

Figure 25. Hydrogen fuelled three wheeler developed at Physics Dept., BHU

Figure 26. Metal hydride based hydrogen storage system with 4000 liters of hydrogen storage (at STP) capacity developed at IIT Guwahati

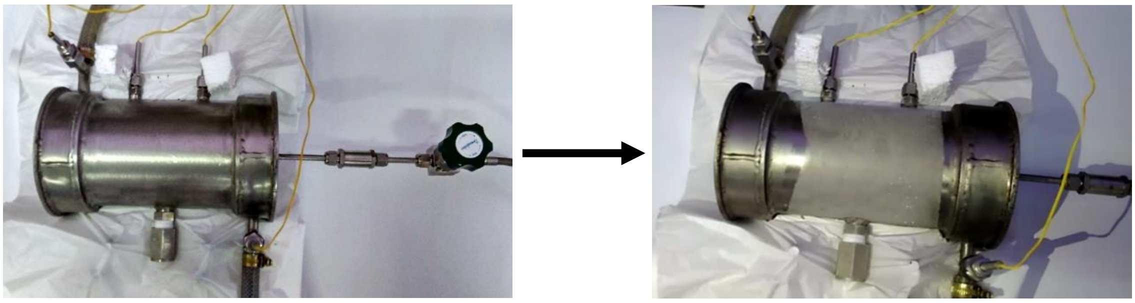
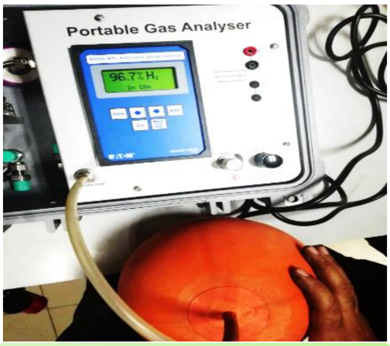


Figure 27. Prototype reactor with 55 embedded cooling tubes filled with 4 kg $MmNi_{4.7}Fe_{0.3}$ alloy capable of an average 1.5 kW cooling capacity developed at IIT Guwahati

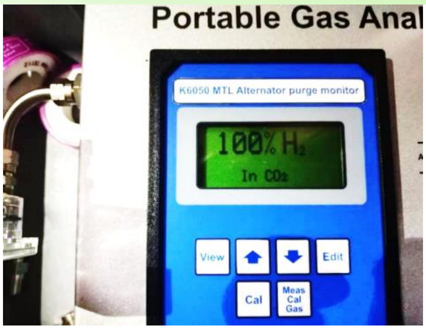
Figure 28. Metal hydride based hydrogen purification system of 1 kg H_2 (99.99% purity) developed at IIT Guwahati

Online Sample Collection



Testing of Sample Purity

Continuous Purification Test



Purification Result by Our System

Successfully Delivered **MHHPS** at NTPC with Purification Capacity of **6500 lit.** H_2 per Cycle

MHHPS at NTPC was field tested with Prototype model with capacity of **650 lit.** H_2 per Cycle

Figure 29. Metal hydride hydrogen purification system testing at NTPC (NETRA)

Figure 30. Metal hydride based reactors designed for backup power application with capacity 1.5 kWh and 10kWh resp. developed at IIT Bombay

3 kW , ARCITECH 2017, 27th Feb 2017, Hyderabad — 5 kW @ GAIL, Noida March 15th 2017 — 3 kW , ESCI, 10th March 2017, Hyderabad

Figure 31. Demonstration of PEMFC system of 3 kW and 5 kW

Figure 32. Demonstration of PEMFC system at Neyveli Lignite Corporation in year 2016

Figure 33. Fuel Cell (+ Battery) powered automobiles developed at ARCI

Table 16. Major activities in hydrogen utilisation other than for fuel cell based applications

S. No.	Project Name	Institution
1	Development and demonstration of hydrogen fuelled three wheelers, three wheelers running on hydrogen fuelled IC engine using alloy hydride / inter metallic for hydrogen storage, hydrogen based catalytic combustion cooker	BHU, Varanasi
2	Development and demonstration of diesel hydrogen dual fuel SUV	Mahindra & Mahindra, Chengalpattu
3	Mission mode project on development and demonstration of hydrogen fuelled internal combustion engine for vehicles, multi cylinder IC engine introduced into Mahindra's tourist or model mini bus, three wheelers based on hydrogen with Mahindra and Mahindra, development & demonstration of hydrogen fuelled multi-cylinder spark ignition engine generator set for stationary power generation, demonstration and field trials of hydrogen fuelled three wheelers in New Delhi	IIT Delhi
4	Performance enhancement, evaluation and analysis of an IDI diesel engine using straight (SVO) with hydrogen supplementation	UPES, Dehradun
5	Hydrogen refuelling facility for demonstration of fuel cell vehicles	R&D Centre, IOCL, Faridabad
6	Experimental investigations on combustion characteristics and emission reduction of laser fired hydrogen engine, experimental study of bluff-body stabilized LPG–H_2 jet diffusion flame with preheated reactant	IIT Kanpur
7	HCNG fuelled bus demonstration in selected city bus fleet	IOCL Faridabad
8	Design and development of hydrogen gas burner for industrial application	IIT Kanpur
11	Metal hydride based thermal energy storage systems	IIT Madras
12	Metal hydride-based devices for various applications like thermal energy storage, hydrogen purification, hydrogen compression, heating and cooling systems and heat up gradation systems.	IIT Guwahati
13	Metal hydride based systems for backup power	IIT Bombay

S. No.	Project Name	Institution
14	Prototype demonstration of wind hydrogen based stand-alone electrical generation	Electrical Research and Development Association (ERDA), Vadodara
15	Utilisation of hydrogen for lifting the weather balloons used to collect atmospheric data	Indian Meteorological Department (IMD), Thiruvananthapuram

Table 17. List of scientists in the country working on different aspects of hydrogen utilisation

Affiliation	Name	Email ID
BHU, Varanasi	Prof. O. N. Srivastava	ons@bhu.ac.in
Mahindra & Mahindra, Chengalpattu	Dr. Abraham Matthew	
IIT Delhi	Prof. L. M. Das	lmdas@ces.iitd.ac.in
IIT Kanpur	Dr. D. E. Mishra	mishra@iitk.ac.in
Electrical Research and Development Association (ERDA), Vadodara	Dr. V. Shrinet	shrinet@erda.org
IIT Delhi	Dr. Divesh Bhatia	dbhatia@chemical.iitd.ac.in
NISE, Gurugram	Dr. S. K. Singh	sk.singh.mnre@nic.in
IIT Hyderabad	Dr. Ch. Subrahmanyam	csubbu@iith.ac.in
Institute of Minerals & Materials Technology Bhubaneswar	Dr. Bikas Kumar Jena	bikash@immt.res.in
IIT Madras	Dr. Raghuram Chetty	raghuc@iitm.ac.in
IIT Bombay	Prof. Pratibha Sharma	pratibha_sharma@iitb.ac.in
IIT Guwahati	Prof. P. Muthukumar	pmkumar@iitg.ac.in
IIT Delhi	Dr. K.A. Subramanian	subra@ces.iitd.ac.in
VSSC	Dr. M. Shaneeth	m_shaneeth@vssc.gov.in
IIT Delhi	Prof. S. Basu	sbasu@iitd.ac.in
NPL, CSIR	Dr. Sundeep Kumar Dhawan	skdhawan@nplindia.org
IIT Madras (ARCI)	Dr. N. Rajalakshmi	rajalakshmi@arci.res.in
IIT Bombay	Dr. Prakash C. Ghosh	pcghosh@iitb.ac.in
IISER, Tirupati	Dr. Vijayamohanan K Pillai	vijay@cecri.res.in
BHEL, Hyderabad	Dr. Vasu Gollangi	vasugollangi@bhel.in
CSIR-CERI- Madras	Dr. Santoshkumar D Bhat	sdbhat@cecri.res.in
CSIR-CGCRI, Kolkata	Dr. Rajendra Nath Basu	rnbasu@cgcri.res.in

Affiliation	Name	Email ID
C-MET	Dr. Girish J. Phatak	gjp@cmet.gov.in
IIT Madras	Dr. Sreenivas Jayanti	sjayanti@iitm.ac.in
ICT Mumbai	Dr. Neetu Jha	nr.jha@ictmumbai.edu.in
UPES, Dehradun	Dr. Venkateswarlu Chintala	vchintala@ddn.upes.ac.in
UPES, Dehradun	Narayan Khatri	
IIT Kanpur	Prof. Avinash K Agarwal	akag@iitk.ac.in

The biggest challenge towards commercialization of the hydrogen-based technologies is the requirement of code and standards to get a sort of consistency and encourage deployment. With such standards in place the process of deployment will drastically increase and technologies which are at laboratory demonstration level could come to marketplace faster. ISO and IEC standards once finalized will help in dealing with hydrogen vehicles in particular and help in progress of hydrogen economy in a smoother way.

In order to increase the use hydrogen technology for even industrial sector there is requirement of certain standards which is fixed by specific agencies. The Technical Committee of International Organization for Standards (ISO) is ISO TC 197 which deals with the standards of hydrogen such as its use, measurement, storage, transport and production. India is its member and the committee has published 16 standards. To ensure the security and safety of the public and property from explosion and fire, the Petroleum Explosives Safety organization (PESCO) has been administering Explosives Act, 1884, 2008, Gas cylinder Rules, 2004, Static and Mobile Pressures Vessels (Unfired) rules 1981 and other concerned acts.

India's nodal policy making think-tank, NITI Aayog has also recommended the use of H-CNG by utilisation of the existing piped-gas infrastructure in Delhi. The further recommendations include the use of H-CNG be notified as an automotive fuel, standards for its use can be issued by the Bureau of Indian Standards (BIS), and clearance for H-CNG storage cylinders on vehicles be issued by the Petroleum and Explosives Safety Organisation (PESO)[13].

As per the recommendations of the Steering Committee on Hydrogen Energy and Fuel Cells constituted by the Ministry of New and Renewable Energy**,** the Central Motor Vehicle Rules, 1989, will have to be amended to include hydrogen as an automotive fuel. The Gas Cylinder Rules, 2004, will also require amendments to incorporate standards and regulations pertaining to hydrogen storage cylinders. It is also essential that certification guidelines and regulations are issued by PESO with regard to hydrogen storage equipment and refuelling systems in order to ensure safety. The BIS will also be required to issue standards for quality of hydrogen as per standards notified by International Organization of Standards. Further, as India is developing fuel cell buses, the Ministry of Road, Transport, and Highways will also be required to devise a licensing and permit framework for such buses[3].

India is participating in various committees of international standard making bodies such as ISO, UN-ECE. These committees are developing global standards for hydrogen which could be adapted in the future by India. In Parallel, the BIS committee on hydrogen standards is working towards developing the Indian Standards by adapting the International Standards with modifications for India specific conditions. There are several lead companies in hydrogen production, storage, distribution and utilisation a summary of those is included in Table 18. A brief review of year wise achievements and major milestones reached is included in figure 34.

Table 18. List of companies involved in hydrogen production or storage or delivery in the country

S. No.	Companies and description
1	Praxair is one of the leading producer and supplier of the different industrial, medical, and specialty gases. They supply compressed and liquid hydrogen at the desired purities and concentrations. The company has maintained sophisticated hydrogen pipelines in various geographical locations across the globe. The company have plants of sizes ranging from 10 Nm^3H_2 to 150,000 Nm^3H_2. The Praxair India is known for its ability to deliver safe, reliable, efficient gas supplies and services to meet the local industrial demand. https://www.praxair.com/gases/buy-compressed-hydrogen-gas-or-liquid-hydrogen
2	Linde India Limited, which was formerly known as BOC India Limited, is a member of The Linde Group and the leading industrial gases company in India. Linde Hydrogen FuelTech provides highly efficient fueling concepts according to the requirement. Linde has provided more than 160 refuelling stations globally. Linde provides on-site generation solution and both the options including gaseous and liquid hydrogen. They also provide compressors for pressurization through ionic compressors and cryo-pumps. Linde's operates the India's largest air separation plant and run more than 20 production facilities and filling stations across the country. The company supplies more than 20,000 gases and mixtures as well as provide a range of related services including the construction and installation of plants, equipment, pipelines and associated engineering services catering to the needs of a wide variety of industries. Linde India has the largest sales and distribution network. https://www.linde-engineering.com/en/process-plants/hydrogen_and_synthesis_gas_plants/ gas_products/hydrogen/
3	Inox Air Products provides industrial gas solutions. The company provides gaseous hydrogen being stored in "bumpstop", which are large number of high pressure cylinders manifolded (connected) together. They also provide on site generation systems including membranes, packaged plants, air separation units, syngas and hydrogen plants and industrial gas pipelines http://www.inoxairproducts.com/prism/

S. No.	Companies and description
4	Bhoruka is into hydrogen production mostly via electrolysis bhurukagases.com
5	Air Liquide is contributing to the widespread adoption of hydrogen in the transportation sector by supporting the deployment of charging stations that are required worldwide. Presence of Air Liquide in India is since the year 1992. Today, Air Liquide has steady increased its footprint in the country, relying on 600 employees to serve over 550 industrial and 2,500 hospital customers. https://www.airliquide.com/india
6	Aditya Birla Chemicals represents a flagship sector of the Aditya Birla Group that spans across chemicals, agri-business, insulators and fashion yarns. It is a leading global supplier of caustic, epoxy, phosphates, sulphites, peroxides and viscose filament yarns. It is also India's leading producer of fluorides, fertilisers, soil and crop nutrition and protection products and the largest in Chlor-alkali and Insulators in India. Today, the Aditya Birla Chemicals is spread across India, Thailand and Germany with 20 manufacturing locations, reaching to customers from more than 80 countries. ABCIL supplies high purity compressed hydrogen at 150 to 200 bar pressure in manifolds and loose hydrogen cylinders to customers. It finds use in a wide range of industries including food, petroleum products, chemical processing and home and personal care. https://www.adityabirlachemicals.com/about-us.php
7	Gujarat Alkalies and Chemicals Limited are the manufactures of chlor-alkalies and other chemicals. The Company's products include caustic soda, hydrochloric acid, phosphoric acid, potassium carbonate, hydrogen peroxide, chlorine gas and hydrogen gas. Gujarat

S. No.	Companies and description
	Alkalies and Chemicals also manufactures chloromethanes, caustic flakes, sodium cyanide and sodium ferrocyanide. They are into the production of hydrogen in the process of making these chemicals https://www.gacl.com/upload_files/hydrogen_gas.pdf
8	DCW Limited DCW Limited (DCW) is an India-based chemical company, which is engaged in the manufacture of caustic soda, soda ash and polyvinyl chloride (PVC) resin. The Company's segments include PVC, caustic, Synthetic Iron Oxide Pigment (SIOP), Soda Ash and Others. Its products include caustic soda, liquid chlorine, hydrochloric acid, beneficiated ilmenite, trichloroethylene, yellow iron oxide, ferric chloride, utox, PVC, soda ash, sodium bicarbonate and ammonium bicarbonate. Through its SIOP division, DCW also operates in the specialty chemical segment. The Company produces calcium chloride at its SIOP Plant. It also runs a 36-megawatts (MW) furnace oil based captive power plant and a 58.3MW coal based Cogeneration Plant. https://www.icis.com/explore/resources/news/2007/12/24/9088886/india-s-dcw-restarts-expanded-chlor-alkali-plant/
9	GHCL (formerly known as Gujarat Heavy Chemicals Ltd) is a Dalmia group company, and one of the leading soda ash manufacturers in India. The company is engaged in manufacturing of industrial chemicals, textiles and Edible salt. In addition to domestic sales, GHCL exports to Saudi Arabia, Iran, UAE, Jordan, Bangladesh, Sri-Lanka, Indonesia, Malaysia, Thailand, Taiwan and Australia. https://www.dsij.in/productattachment/BrokerRecommendation/GHCL_BUY_HDFC_08.03.16.pdf
10	Air Science Technologies is into designing and building the biogas upgrading systems and equipment for bio-digesters and landfill gas applications. Biogas purification and upgrading biogas, a combination of methane (CH_4), carbon dioxide (CO_2) and impurities is a gaseous fuel but also a green-house gas (GHG). As a gaseous fuel, biogas must be

S. No.	Companies and description
	purified before being valorised through the production of electricity or of compressed natural gas (CNG). It is then referred to as Renewable Natural Gas (RNG) or Bio-methane and the biogas purification process referred to as biogas upgrading.
11	For more than 90 years, SAGIM is specialized in the manufacturing of hydrogen production units and has become the leadership in the hydrogen production for meteorological uses. SAGIM is actually present in more than 90 countries all over the world and has already supplied more than 500 upper air stations https://www.hmei.org/company-details/?company_id=1519
12	Air Products (NYSE:APD) is a world-leading industrial fases company in operation for nearly 80 years. The Company provides industrial gases and related equipment to dozens of industries, including refining, chemical, metals, electronics, manufacturing, and food and beverage. https://www.gasworld.com/air-products-opens-indias-first-hydrogen-station/2007574
13	Fuel Cell Energy delivers efficient, affordable and clean solutions for the supply, recovery and storage of energy. The company design, manufacture, undertake project development, install, operate and maintain megawatt-scale fuel cell systems, serving utilities, industrial and large municipal power users with solutions that include both utility-scale and on-site power generation, carbon capture, local hydrogen production for transportation and industry, and long duration energy storage https://www.glassdoor.co.in/Overview/Working-at-FuelCell-Energy-EI_IE4825.11,26.html
14	The company develops hydrogen sensing tools. The products like HY-OPTIMA process hydrogen analyzers and HY-ALERTA hydrogen leak detectors standalone product lines have been used in over 50 countries helping utilities, nuclear power plants, petroleum, fuel cells, industrial hydrogen and petrochemical companies, and other

S. No.	Companies and description
	industrial organizations meet safety, regulatory, and process control requirements when doing critical hydrogen monitoring - often in diverse and challenging environments. The developed industry-leading hydrogen analyzers and leak detectors are based on the company's patented, solid-state core hydrogen sensor technology exclusively licensed from the U.S. Department of Energy and supported by 15 years of R&D and field verification work. Idroenergy designs, realizes and installs plants and systems for the hydrogen and nitrogen on-site production of ultra-high purity gas. The company is into realization of turn key plants through all the steps of design, purchasing, production, installation, test, start-up, operators training and after-sale service.
15	ITM POWER ITM Power manufactures integrated hydrogen energy solutions to enhance the utilisation of renewable energy that would otherwise be wasted. ITM Power Plc designs and manufactures products which generate hydrogen gas, based on Proton Exchange Membrane (PEM) technology. This technology only uses electricity (renewable) and tap water to generate hydrogen gas on-site and has a product offering capable of being scaled to 100MW+ in size. The company has capability to (i) to provide a fully integrated system, (ii) ability of the system to respond rapidly to varying power profiles, and (iii) to generate hydrogen at a pressure, flow rate and purity appropriate to its application.
16	Heliocentris Heliocentris Academia International GmbH are into developing educational products for teaching hydrogen and fuel cells. The company has capability to develop full portfolio of products, covering solutions for schools, colleges, universities and professional industrial training centers. Since February 2017 Heliocentris Academia became a part of Horizon Educational Group and is nowadays leveraging on a worldwide network of partners specialized in advisory of education and technical training solutions.
17	SUKAN ENGINEERING PRIVATE LIMITED The company has been working with the thermal, nuclear and gas power plant Companies for their requirement of aftersales and service of hydrogen gas generation plant and spare parts used for various applications in their plant.

- **-** • Five Hydrogen Fuelled two Wheelers and 3 wheeler developed at Physics Dept, BHU

- **2003** • National Hydrogen Energy Board was formed
- **2005** • India's first Hydrogen refuelling station was setup at IOC, Faridabad

- **2006** • National Hydrogen Energy Roadmap was introduced
- **2009** • Clean Energy Research Initiative was setup by DST
- **2012** • Hydrogen powered 3 wheeler 'HyAlfa' was developed by Mahindra and Mahindra with the help of International Centre for Hydrogen Technologies and IIT Delhi

- **2014** • Make in India was introduced by Government of India
- **2015** • Global Initiative called Mission Innovation was setup to accelerate clean energy innovation
- **2015** • National Renewable Energy Act was introduced
- **2016** • Draft report on Hydrogen Storage & Application was submitted under the chairmanship of Dr.K.Kasturirangan
- **2018** • India's first Hydrogen fuel cell bus was introduced by IOC and Tata Motors

- **2018** • DST call for oriented Research & Technology Development proposal on 'H2 and Fuel Cell (HFC)'
- **2018** • DST-IIT Bombay Energy Storage Platform on Hydrogen (ESPHy) and DST-NFTDC Centre for Materials and Energy Storage Platforms on Hydrogen was formed

Figure 34. A short summary of achievements and major milestones achieved

7. Way Forward…….

Hydrogen has very clear-cut advantages as against the conventional fuels and a potential for decarbonisation of several sectors. Both hydrogen as fuel and hydrogen-based technologies are receiving unpresidential attention globally and thus the coming decade will be very important. The next decade will see scaling up of several high TRL level technologies to meet the required potentials and enhanced deployment. Government has a key role to play in this stage of development. The progress seen in the country like in the case of solar PV deployment with public private partnerships and policy support will be required for hydrogen as well.

Hydrogen has altogether separate domain of applications as against the other low carbon technologies. The need is to identify the domain of applications where hydrogen is the solution or hydrogen is the "only" possible solution. One emerging area being transportation sector, since India heavily depends on imports and transportation sector is major consumer of oil, thus hydrogen can play a crucial role. But the domain in transportation sector where hydrogen fuelled vehicles can be best suited is long haul, heavy transport and commercial fleets. Besides these long-haul vehicles require higher quantity of storage as these are driven over long distances and continuously for long times and these should be refuelled quickly. Hydrogen powered vehicles have similar range as the current fossil fuel-based vehicles, can be refuelled fast, have efficient fleet optimisation and have much higher energy density. The another set of application is in materials handling e.g. forklifts where the time available for refuelling for a unit is very short and the space available for refuelling infrastructure in warehouses is small i.e. they can't afford long charging hours. In some of the industries which have higher emissions use of certain fraction of hydrogen in their value chain will substantially bring down the emissions. Further, power to X provides wide flexibility in terms of usage, storage and transport of useful energy and finds wide range of applications. Thus, hydrogen has the potential to become the backbone of low emission energy production, storage, distribution and its utilisation for transport, industrial, heating and many other sectors. With the growing deployment of renewables this can be effective storage medium with mid to long-term and small to large-scale storage without much of losses and easily scalable. The technologies or systems or operations where hydrogen is used shows better performance and efficiencies.

An interesting route and use of hydrogen is combining hydrogen with the captured CO_2 from sequestration plants to produce a variety of hydrocarbons like methane, methanol, synthetic petro-chemicals or transport fuel. Energy can be exported from countries where rich renewable based generation is prevalent to the energy deficit countries, with hydrogen as the carrier. Another important use could be to substitute natural gas in process heat application providing higher energy density and no emissions. However, for this retrofitting of the industrial boilers and components for combustion will be required, several such projects are being discussed one of such big project is H21 project in UK, where the entire Northern Gas Network is planned convert on to hydrogen. In the short term, hydrogen can be introduced in various sectors and technologies deployed, this can be irrespective of whether it is blue or green or grey hydrogen. In the intermediate term blending of gas with hydrogen could be a possible method to reduce emissions and at the same time making hydrogen a part of large-scale distribution network, increased usage of green hydrogen should be introduced. In long term the entire hydrogen value chain should be completely emission free.

Thus, hydrogen has a potential to contribute towards decarbonised, sustainable, secure energy future. The need is to introduce it into both existing proven set of applications with more diverse set of energy sources of its production and then move on to green hydrogen or introduce it to the new set of applications. The transition pathways which make use of exiting infrastructure and skills will be both economically feasible and easier to adapt e.g. use of blended natural gas with hydrogen, use of CCUS for hydrogen production, use of certain percentage of hydrogen without much of retrofitting where there is need to reduce emissions. The immediate need here is to identify the key long-term goals and the step to achieve those goals.

The current status is that the clean hydrogen technologies are available, costs are coming down, efficiency and performance are improving. The requirement is to demonstrate the scaled version at a faster rate, this will build a confidence in investors and will receive public acceptance. Further the building up of policies, infrastructure and skills will help in wider acceptance, reducing perceived risks, enhancing confidence, increased investments, lowering costs.

Government can play a very crucial role with policy support by creating infrastructure, risk reduction, creating hydrogen market and providing benefits over use of low carbon energy chain. Once the take-off is achieved, the rest cost reduction and increased proliferation could be achieved by economies of scale. There can be clear cut targets for e.g. emission reduction norms and regulations for various sectors which will further create demand. Although taking a technology neutral approach and leaving to the market could be the most tempting choice but that may not allow for the sustainable interest seen in hydrogen, a strong public-private support with policies in place will be required. Thus, the major challenges we need to finally meet is scaling up, cost reduction, increased adoption and sustainable growth of hydrogen-based technologies. The role that Government can play is towards creating a long term policy framework which could build up confidence in private investment, create market demand with policy interventions, develop standards and regulations which should not hurdle the growth, provide enhanced R & D support.

Some key points, which need consideration are listed below:

- Currently most of the hydrogen being produced is from fossil fuels. In short to medium term CCS to be employed to reduce emissions at production site. In long term green hydrogen production will be the solution. Besides biomass-based hydrogen production have the potential and need to be explored towards making it economically feasible and sustainable.
- After the implementation of Euro VI, cost of diesel engines is increasing, this provides a window for the penetration of alternative technologies such as FCEVs in the market. Implementation of FCEVs in public transport has proven to be successful in many places such as Vancouver, California, and Japan. However, the need of the hour is to introduce hybrid systems as a first step in order to create a demand for FC accessories. Eventually, as the technology matures, the FC based systems will phase out the hybrids. Introducing FCs in railways and trucks could also be an economically feasible solution as the implementation of hydrogen-based mobility is economically more viable as compared to electrification of railways. Also, subsidies should be introduced from the consumer side to generate interest in the consumption of hydrogen-based energy solutions instead of providing subsidies to the manufacturers.
- The shipping and aviation sectors have very limited low carbon fuel options, these are the sectors where hydrogen has the major opportunity to venture in. Hydrogen in pure form may not be the best possible solution. Hydrogen or ammonia could be possible solution for shipping while biofuels and other synthetic fuels i.e. power to liquid option of hydrogen could be the choice. These areas should be thought of as the next generation of applications.
- Economies of scale whether for electrolysers, fuel cells, components of refuelling stations, storage tanks will definitely bring down cost and thus mass manufacturing will be required. Other than the economies of scale R & D could help in both cost reduction and enhanced performance.

- The long-term goals and the barriers towards achieving those need to be identified. A concrete step by step path towards achieving those goals need to be figured out.
- A complete system for information dissemination, availability of the data whether related to hydrogen production, storage, transport or utilisation should be made available in public domain.
- The need of the time is policy support, help in demand creation, reduction in associated risk of the investors, standards and regulations in place, R & D support, creating public awareness and projection of all the data to create a confidence in hydrogen and hydrogen-based technologies.

Some of the recommendations for the Department of Science and Technology and other funding agencies are as follows:

- Major R&D programmes should be introduced linking with applications which may have market acceptance. For this, large number of demonstrative projects should be supported by DST in production, storage and application areas in addition to usual development projects.
- Demonstration projects for evaluation of long-term performance, safety aspects, identifying functional losses and finding diagnostic of fuel cell stacks should be taken up. This will help in confidence building in industry as well as end users
- Sufficient centralized facilities should be made available for long term performance evaluation of fuel cell stacks which could be open to both R&D and industry.
- Fast pace research is required in various fields and converting the know- how into pilot scale.
- Demonstration of hydrogen for grid integration can be pivotal in getting visibility and acceptance. At the same time the adoption should be considering all the standards and protocols with safety being of prime importance.
- DST may organize funding support for projects as part of a well-drawn Hydrogen Business Road Map. This will involve a definite target of an end application such as vehicle /steel industry / thermal management. Project related to production/ storage/transport to achieve the specific road map should be supported on a time bound basis. This should involve multi agencies from R&D and Industry.
- Steel industry is trying to reduce CO_2emission by partial introduction of hydrogen as fuel, however currently faces gaps in the process due to lack of consistent R&D support (e.g. Tata Steel). Non-availability of required quantity of hydrogen of right specifications is one of the road blocks. Absence of continuous R&D support related to stepwise implementation of the process of reduction of CO_2 from blast furnace is another block. Projects of such nature involving technology demonstration should be supported so that visible output may be obtained.
- Demonstration projects for reduction of CO_2 from steel and cement industry will go a long way in popularizing the use of hydrogen and associated technologies. However, on reduced scale, it is also recommended that projects on using large vehicles like buses and trucks in selected locations in the country can be framed under R&D-industry collaboration and run as demonstration.
- R&D efforts should concentrate on ensuring development of consistent supply chain for hydrogen and appropriate storage systems for demonstration projects. Start-ups could be supported in this attempt.
- It is important to promote the currently practiced methods of production of hydrogen systems with required refinement for clean fuel. Simultaneously R&D projects need to be supported for alternate methods with clear targets and energy efficiency. Greener processes which are now considered expensive like photo electro chemical/SOEC should be supported with clear mandate for innovative approach for higher efficiency and lower cost.

- Filling stations and associated systems as well as safety are real gaps in the country. Demo projects related to filling systems with all long-term performance assurance as well as safety parameters need to be given sufficient support.
- Different storage systems are another key area which requires lot of R&D. In the development of pressure cylinders, many parts need to be indigenised. Start-ups could be supported to fill such requirements.
- Solid state systems like hydrides, porous media and liquid carrier should be further looked into, as they have advantages of safety, higher volumetric densities and optimum conditions of operation. The storage device is selected based on the requirements of the end application, and therefore various types of storage systems, performance efficiency and safety need to be as per specific standards. Such standards are required to be in place for our country.
- A general awareness drive on the advantages, possibilities and safety aspects of hydrogen usage in a variety of application areas currently covered by carbon-based fuels need to be undertaken along with demonstration projects. This could be done involving social scientists, R&D personnel, industry and NGOs.
- Periodic meetings involving experts from industry, academia and funding agencies are required. Discussions on the gap areas and increased R&D-Industry interaction is essential.
- In order to generate competitive interest among the stake holders, programmes like awards/ appreciation could be thought of for the best R&D-industry collaboration which bring out successful implementation of target oriented, total quality-controlled supply chain, from production to end use application including long term safe performance.
- The concept of H_2 production, storage, and its applications need to be done altogether. The facilities required are scattered in the country which needs to be centralized and open to all the research community. Strengthening of the existing technologies and promoting of the new materials-based research is required.
- Generation of hydrogen from renewable sources should be encouraged. Government should explore policies for subsiding hydrogen price generated from renewable.
- Investment on methanol economy is rising, thus hydrogen production from methanol should be given due consideration
- Currently the Type IV cylinders are not indigenously fabricated. However, there are groups working on the development, they should be supported. Besides, there should be a centralized test facility for high pressure testing of these developed cylinders.
- Our educational institutions and public sector should work towards developing awareness which is very essential for social acceptance by the customers.
- There should be linkages between academia and industry and the DST and MNRE can play a key role in achieving that.
- There is a sort of chicken and egg situation in the country i.e. for deployment infrastructure is required while to develop infrastructure demand is necessary. With government support this need to be resolve. Both refuelling stations and increase in FCEVs should be supported. The focus should be developing fuel cell technology and demonstrating for transport and heavy vehicles and slowly decarbonising other sectors as well.
- There is a pressing need of big projects in a business scale for e.g. Australia has launched H_2 business road map. DST should think about it in a business scale. At the same time large scale hydrogen production and cost reduction should be considered. Examples should be sought from success in this field for e.g. China converting coal to H_2, Australia investing in fuel cell for railway and heavy transport.

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Glossary of Abbreviations

DDUGJY	Deen Dayal Upadhyaya Gram Jyoti Yojana
MNRE	Ministry of New and Renewable Energy
MoP	Ministry of Power
MoPNG	Ministry of Petroleum and Natural Gas
MoC	Ministry of Coal
DAE	Department of Atomic Energy
MoST	Ministry of Science and Technology
DST	Department of Science and Technology
DBT	Department of Biotechnology
DSIR	Department of Scientific and Industrial Research
DAE	Department of Atomic Energy
MoC	Ministry of Coal
MoES	Ministry of Earth Science
MoHI	Ministry of Heavy Industries
MNRE	Ministry of New and Renewable Energy
NHERM	National Hydrogen Energy Roadmap
GIFT	Green Initiative for Future Transport
GIP	Green Initiative for Power Generation
MI	Mission Innovation
IC	Innovation Challenge
SIAM	Society of Indian Automobile
BARC	Bhabha Atomic Research Centre
ISO	International Organization for Standardization
IEC	International Electrotechnical Commission
PESO	Petroleum and Explosives Safety Organisation
IMD	Indian Meteorological Department
ONGC	Oil and Natural Gas Corporation
IOCL	Indian Oil Corporation Limited
IIT	Indian Institute of Technology
IISc	Indian Institute of Science
CSIR	Council of Scientific and Industrial Research
NEERI	National Environmental Engineering Research Institute
UPES	University of Petroleum and Energy Studies
IICT	Indian Institute of Chemical Technology
C-MET	Centre for Materials for Electronics Technology
NIT	National Institute of Technology
IMMT	Institute of Minerals and Materials Technology
CECRI	Central Electrochemical Research Institute
CFCT	Centre for Fuel Cell Technology
NMRL	Naval Materials Research Laboratory
NFTDC	NonFerrous Materials Technology Development Centre

IIP	Indian Institute of Petroleum
CIMFR	Central Institute of Mining and Fuel Research
IACS	Indian Association for the Cultivation of Science
JNTU	Jawaharlal Nehru Technological University
DEI	Dayalbagh Educational Institute
ARCI	Advanced Research Centre for Powder Metallurgy and New Materials
BHEL	Bharat Heavy Electricals Limited
DRDO	Defence Research and Development Organization

Technical abbreviations

TPES	Total primary energy supply
TPEC	Total primary energy consumption
TFC	Total final consumption
GHG	Green house gas
TOE	Tonne of oil equivalent
CCUS	Carbon capture use and sequestration
FCEV	Fuel cell electric vehicle
LOHC	Liquid organic hydrogen carrier
AWE	Alkaline Water Electrolysis
PEMFC	Proton Exchange Membrane Fuel Cell
HTSE	High Temperature Steam Electrolysis
MIEC	Mixed ion Electron conductors
Hy-S	Hybrid Sulphur cycle
HTSE	High temperature steam electrolysis
HI	Hydrogen Iodide
Cu-Cl	Copper-Chlorine
HER	Hydrogen Evolution Reaction
MOF	Metal Organic frameworks
SOFC	Solid Oxide Fuel Cell
MH	Metal Hydrides
BH3	Borane Ammonia
HT-PEMFC	High Temperature- Proton Exchange Membrane Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
DAFC	Direct alcohol fuel cell
DMFC	Direct Methanol Fuel Cell
NaAlg	Sodium Alginate
SPSEBS	Sulfonated Poly Styrene Ethylene Butylene Polystyrene
BPO_4	Boron phosphate
CNT-MM	Carbon Nanotubes rooted montmorillonite
CNG	Compressed Natural gas
H-CNG	Hydrogen- Compressed Natural Gas
kW	Kilo Watt
Mtoe	Millions of tonnes of oil equivalent
CAPEX	Capital Expenditures

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IAS dark field image of hollow glass microspheres

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