HYDROGEN INFRASTRUCTURE

Development and Challenges

Satisfying energy demands forms an integral part of the development of the world. Growing concerns over climate change, especially finding an alternate means of energy sources to the present fossil fuels, has increased hydrogen interest. Hydrogen is a flexible and alternative energy carrier with potential applications across all energy sectors, significantly impacting economic and social development in the low-carbon economy. Hydrogen is considered a clean energy source and a viable alternative to fossil fuels to control emissions as it can be produced from renewable sources. Hydrogen has the potential to reduce India's dependence on oil imports as several fossil fuel-based applications can be replaced by Hydrogen.

Typically, Hydrogen has the highest mass-energy density amongst other commonly used fuels and has an advantage for using it as a fuel or for energy storage. However, exploitation of Hydrogen for using it as an alternate energy option requires the development of a new hydrogen infrastructure which primarily consists of ***(a) Production (b) Storage and (c) Distribution.*** Development of such an infrastructure poses several technological challenges that must be overcome before it can be employed economically and safely in various sectors on a commercial scale. This paper briefly highlights the issues associated with hydrogen infrastructure development.

Why Hydrogen

Hydrogen has the potential to transform the energy sector by contributing to a sustainable energy future. Global climate change and emission concerns can be addressed at both ends of the value chain, i.e., hydrogen production and hydrogen user. In both ways, Hydrogen can be used as a reinforcing catalyst to connect to the energy systems. First, technological advancements to hydrogen production methods may make it economically feasible by shifting the focus of hydrogen production from fossil fuels to production using a cleaner or renewable sources. Secondly, several applications that presently use fossil fuel as sources of energy can be replaced with Hydrogen.

Hydrogen in its pure form can be possibly used

- as a fuel for transportation
- for electricity generation
- as a combustion fuel in industrial boilers and furnaces, and
- in residential sectors for heating/cooling.

Instead of using Hydrogen as a pure component, it can be further utilised in methanol production or ammonia production or synthetic natural gas production, which can be used as alternative fuels.

Hydrogen has a wide application range. It has created interest amongst stakeholders of several industry sectors such as renewable electricity, industrial gas, automobiles, oil and gas, steel, carbon capture, etc. It is not only hydrogen producers but also includes those who use or could use, Hydrogen as a feedstock for various industrial applications. Due to the renewed interest amongst different industry sectors, it has become imperative for the governments to create a roadmap to develop hydrogen infrastructure.

Hydrogen can be helpful in various ways to achieve energy security. Hydrogen can be integrated into the electricity infrastructure, by converting electrical energy (supplied by renewable sources) to produce Hydrogen and then reconvert it back to electrical energy. Further, such conversion of electrical energy to hydrogen production enables Hydrogen promotion for fuel applications and helps reduce energy imports in the form of oil and gas. Fossil fuel-based hydrogen-producing processes can be amended to employ carbon capture technologies to produce Hydrogen cleanly. A right infrastructure must be developed for exploiting the use of Hydrogen as a low carbon energy source.

Hydrogen Users and Growth Potential

Majority of the Hydrogen is presently consumed for industrial applications. Petroleum refining processes account for one-third of hydrogen consumption. Other significant users are producers of Ammonia (27%) and Methanol (11%). A small percentage (3%) of Hydrogen is utilised in steel production using direct ore reduction technology.

The Hydrogen required in the middle distillate's desulphurisation process in petroleum refineries is mostly (60%) produced from natural gas. Considering stricter emission norms for automobiles, hydrogen demand for desulphurisation is expected to increase by 7% in the next ten years. However, with the electric vehicle revolution gaining momentum, this may dampen the market in the long term. Majority of the future hydrogen demand will arise from new applications such as transportation.

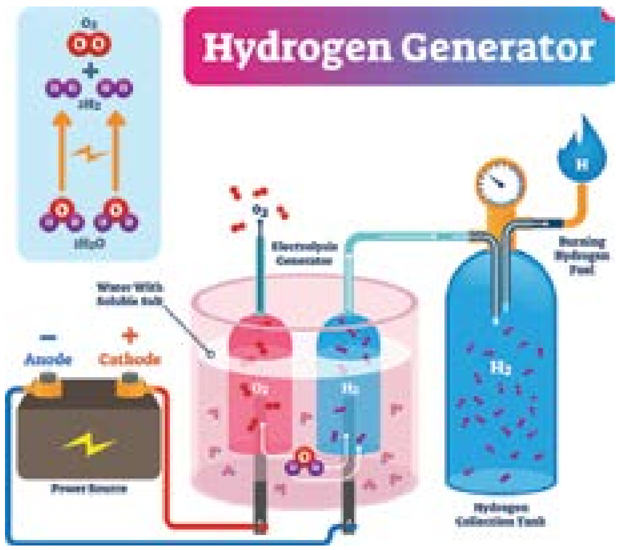
Future hydrogen demand and infrastructure development priorities mainly focus on Hydrogen's possible widespread use in the transportation sector. This suggests that research and development focus should be developing affordable hydrogen fuel cell technology to drive hydrogen growth.

Hydrogen can replace fossil fuels that are widely used for industrial combustion processes in furnaces and boilers. The hydrogen fuel cell has the potential to generate electricity on a small scale. It can be an alternative to replace diesel generators commonly used as a source for emergency power back up in industrial, commercial and residential installations.

Hydrogen Production

Currently, most of the Hydrogen (75%) produced globally uses natural gas as a feedstock. Another commonly used resource is coal, which accounts for 23% of the total Hydrogen produced. Today's total hydrogen production is about 70 Mt, and this contributes 830 Mt of carbon dioxide per year to the environment. With an increased interest in developing hydrogen-based economy, demand for Hydrogen is further expected to increase significantly. Therefore, it is evident that unless current technologies producing Hydrogen are targeted to minimise carbon dioxide emissions, the hydrogen-based economy in the future shall not help reduce carbon footprint and will not help address global climate change conditions. It is, therefore, necessary to develop options for producing Hydrogen without contributing to carbon dioxide emissions.

Another commercially available technology for hydrogen production is based on splitting of a water molecule by electrolysis. Water electrolysis methods contribute only 2% to the world hydrogen production.



Electricity is needed as an energy input to the water electrolysis process, and electricity can be economically produced using renewable sources. Therefore, water electrolysis using renewable energy sources can produce Hydrogen and reduce carbon footprint in hydrogen production. With technological advancements, electricity production costs from renewables are continuously declining, and more capacities are being added. Due to non-availability of renewable sources for 24 hours in a day, electricity produced from renewables often has energy storage requirements.

Hydrogen can be used for energy storage as well. There is significant scope for setting up dedicated renewable electricity generation facilities for environmentally clean hydrogen production and storage.

Another way of reducing carbon dioxide emissions from hydrogen production processes is carbon capture and sequestration (CCS) technologies. Natural gas-based or coal-based hydrogen production processes can amend the techniques to capture carbon dioxide.

Presently, the operating costs and CAPEX requirements for CCS technology are high due to which commercialisation of technology is yet to mature. ***Worldwide, CCS technologies are being rigorously researched, and developed economies are seriously promoting research, testing, marketing and implementation at select locations.***

Hydrogen production prices vary significantly between various regions due to the variable cost of resources used for making Hydrogen. Natural gas and coal are abundantly available at a lower price only in the select areas as its availability are not uniformly spread over the entire world. Similarly, costs for electricity generation vary widely between various regions. ***Raw material availability hence influences the cost of hydrogen production to a great extent. Hydrogen production using natural gas without carbon capture technology is presently the most economical route amongst all regions.*** Cost of hydrogen production through the electrolysis route depends on electricity production costs and overall, these methods are currently expensive compared with the natural gas-based production process without CCS. Suppose cost of electricity generation is between 10 US$ to 40 US$ and considering full load hours of 3000 – 6000 per annum. In that case, hydrogen production from water electrolysis can be cost-competitive compared to the production based on natural gas processes with CCS.

In short, CCS technologies are mandatory to produce clean Hydrogen, and renewable-based water electrolysis methods can become a financially attractive option for hydrogen production. This provides an essential direction for research efforts in future for developing hydrogen infrastructure. As Hydrogen is currently produced mainly in central processing facilities in select industrial areas, an extensive distribution network is needed for making it available across the country. Adaptation of CCS technologies will also help in the nationwide spread of hydrogen production locations and ensure Hydrogen availability.

Coal gasification process produces syngas which can be used for power generation. CCS technologies are usually integrated with coal gasification units; thus, they can produce clean electricity. Hydrogen production from syngas (obtained from coal gasification) can be enhanced using water gas shift technologies. Entire coal gasification unit can be further optimised and configured for a flexible switch between electricity generation and hydrogen production.

Biomass is another alternative source for hydrogen production. However, the limited availability of biomass and higher production costs are the significant barriers to mass-scale commercial production. Considering the difficulties in hydrogen storage and transportation due to its low molecular weight, it can also be converted into other chemicals such as synthetic natural gas, ammonia, jet fuel, etc. which can be used as fuels. This may not be an economical option at current price levels.

Hydrogen Storage

Hydrogen has high mass-energy content but is the smallest molecule (Mol Wt. 2), it has very low volumetric density and low volumetric energy. This peculiar characteristic of Hydrogen poses difficulty in its storage. Hydrogen is highly flammable material having a relatively more extensive range of explosion limits in air. Safety aspects thus form an integral part of the hydrogen storage technologies.

Hydrogen usually is available at 1 to 4 bar pressure when produced from electrolysis route and at roughly 20-30 bar when created from Steam Methane Reforming (SMR) route. Reducing Hydrogen's volume for transportation is achieved by increasing its density by compressing Hydrogen to a higher-pressure level and then storing in pressurised cylinders before transport.

An alternative method to increase the density of the fluid is to liquefy the gas. Liquified Hydrogen can be stored and transported in bulk volumes. Hydrogen can be stored in a liquid state. However, liquifying hydrogen calls for an operating temperature of (minus) −253° C. Liquefaction is an energy-intensive process and it would consume around 30% of the total energy content of Hydrogen. Another issue related to liquid hydrogen transport is loss due to heat gain and boil-off, leading to hydrogen/energy losses. Additionally, storage tanks need to be made up of expensive materials for operating at cryogenic temperature.

Both pressurised storage and cryogenic storage technologies require specialised materials of construction. Research is underway to find suitable lightweight and economical materials for storing Hydrogen under extreme pressure or temperature conditions.

Hydrogen storage in solids solution form using metal hydrides is an emerging technology. For this purpose, metals, intermetallic compounds, alloys, complex hydrides are being studied. Based on current research, it is now established that Hydrogen's absorption and release under hydrides of some metal alloys are possible. Hydrogen can be stored in solid form by using this technology. This technology requires less energy to operate. However, under these operating conditions, hydrogen density will be close to liquid Hydrogen density, making it heavier to handle. Hydrogen storage technology in solid form is at a nascent stage, and so far, it is limited to holding no more than about 1.8 % hydrogen by weight.

Comparison of various storage technologies and the associated challenges are stated in Table 1 below.

Storage Method	Advantages	Challenges
Pressurised Storage	Matured technology with high efficiency	Weight Reduction by way of using alternate materials
Cryogenic Storage	Higher liquid density and suitable for large quantities	Liquefaction costs are high. Boil-off gas management and expensive materials are required for cryogenic service
Metal Hydrides	Relatively high density, Modular operation	New technology and not commercialised. Temperature and energy requirements for desorption are high.

Table 1: Comparison of Hydrogen Storage Methods

Hydrogen Distribution

Typically, the following options are available for transportation, ensuring availability at the user point.

- Gas tankers/trailers
- Liquified tankers/trailers
- Hydrogen pipelines
- Onsite production

Gaseous Hydrogen can be transported in medium quantities in pressurised gas containers by road tankers. The hydrogen storage capacity of road tankers depends on storage pressure and materials of construction of road tanker. Compressed Hydrogen is generally shipped in road tankers at pressures up to 200-250 bars. In India, gaseous Hydrogen is transported using road tankers having pressures up to 172 bar.

Liquefaction of hydrogen results in a significant increase in its energy density enabling transportation of large quantities using road tankers or ships. Due to the density difference in the gaseous and liquid phase, liquid hydrogen road trucks can carry approximately ten times more Hydrogen than the pressurised transport mode. For longer distance distribution, liquified hydrogen transport is usually more cost-effective as it can significantly hold more Hydrogen than a pressurised gas tank. Liquefaction requires more energy and higher capital costs compared to the pressurised mode.

Hydrogen produced at any central processing facility can be transported to user point directly through pipelines. Pipeline transport mode is a technologically sophisticated method, and it's the most efficient method of hydrogen transportation in large quantities. Selection of materials of construction for Hydrogen requires careful attention as Hydrogen tends embrittlement. Hydrogen is also prone for corrosion due to presence of an active electron of Hydrogen. The blending of Hydrogen with natural gas can be studied further. This may help in boosting hydrogen usage. Cost of hydrogen pipelines depends upon CAPEX for pipes, the compression energy costs and the available pressure limit at the source.

Transmission pipelines use mild, low carbon steels as materials of construction. Liquid hydrogen pipelines are expensive due to extremely low-temperature requirement. It may also be beneficial to consider onsite hydrogen generation using smaller-scale equipment for eliminating transport cost.

For Hydrogen as transportation fuel, it is necessary to have a countrywide distribution network. The water electrolysis method is most suitable for onsite hydrogen generation for remote areas as it is more scalable and emission-free. Electrolyser produces a sufficiently high purity (nearly 100%) Hydrogen required for hydrogen-based vehicles. It could be cheaper to produce Hydrogen locally in refuelling stations far away from central hydrogen production facilities. However, there may be space constraints in the urban area for onsite hydrogen production.

Various issues for hydrogen transportation and associated challenges are presented in Table 2 below.

Transportation Mode	Issues	Challenges
Pressurised Container or Cylinders	Low capacity	Manufacturing of indigenous onboard cylinders, reduction in material weight
Cryogenic Road Tankers	Liquefaction costs	Development of indigenous cryogenic road tankers and boil-off gas management
Pipelines	Safety such as leak detection	Reduction in costs associated with materials of construction
Onsite Production	Economical technology	Reduction in the costs of electricity and electrolyser cells

Table 2: Issues with Hydrogen Transportation Methods

For large-scale consumer adoption of hydrogen-based transport vehicles, deployment of hydrogen refuelling stations (HRS) in primary markets is essential. Hydrogen refuelling station consists of hydrogen storage tanks, compressors with aftercoolers, and dispensers for delivering fuel. It is easy and fast to set up refuelling stations. By standardising the components, refuelling station costs can be reduced. Hydrogen refuelling stations shall be conceptualised and designed considering the risk of fire and explosion.

This must be by the regulations, standards and codes of practice of each country. The European Union has adopted two directives on safety and health, known as ATEX (Atmospheric Explosion) 94/9/EC and ATEX 99/92/E.

Other Challenges

Energy security and global climate change are the main drivers for the future growth of hydrogen infrastructure. It has created a favourable environment for investing and developing hydrogen infrastructure. However, several significant challenges must be addressed to obtain benefits of hydrogen-based clean energy systems.

Any new infrastructure development requires regulatory framework and policies to ensure risk-free investments by the users in hydrogen energy sectors. ***The government has a critical role in promoting technology innovations and its successful deployment in new infrastructure. Innovation and competition can help with cost reductions. It is necessary that all stakeholders (Producers, Users and Investors) work together to achieve long-term stability.***

Currently, hydrogen production systems are primarily based on fossil fuel availability, and a shift to the renewable source is needed. Presently, the efficiencies of hydrogen making technologies from renewable sources are low. Also, they are not available for implementation on a small scale. Most of the hydrogen production currently is achieved in central facilities due to the size of operations.

To expand and promote the use of Hydrogen as an alternative fuel to various applications, production technologies must be selected and developed suitably so that Hydrogen can be produced at near to user locations in economical and sustained manner. Small scale reforming technology, coal gasification, renewables, etc., need further research efforts.

Hydrogen storage requires special attention due to its low volumetric density. Essential criteria for hydrogen storage systems require considerations to energy requirements, methods to obtain high gravimetric and volumetric energy density, minimise emissions, safety in operation, long lifetime, etc.

Currently, compressed gas is the most favoured option in transportation solutions for onboard storage of Hydrogen.

However, the gas compression process would consume 6 to 15% of Hydrogen's total energy content.

Compressed gas storage is favoured as it is a simple, reliable and proven technique. Hydrogen storage in solid form using metal hydrides is a promising alternative to pressurised or cryogenic storage method. A significant challenge in hydrogen storage system design is selecting alternate lightweight materials to withstand high storage pressures or low temperatures. Efforts are required to increase the energy efficiency of storage systems.

Research programs can reduce the energy associated with compression/liquefaction processes related to liquid hydrogen technologies. When Hydrogen is to be used for transportation, a challenge lies in minimising refuelling hydrogen cylinders' time similar to liquid fuel tank filling.

Transportation and distribution costs are the most critical factors that affect the Hydrogen economy. Pipeline transport mode is a technologically sophisticated and efficient method for supplying large hydrogen quantities. However, the selection of construction materials, optimum pressure level selections, leak detection, and safety issues need to be standardised.

Developing a full nationwide distribution network (similar to the natural gas grid) may require much time. To start with, regional networks can be considered for faster development. Availability of relevant codes and standards to address safety issues for infrastructure development plays a critical role. Standard policy for using existing natural gas pipelines for hydrogen service can be framed if spare capacity is available in existing natural gas pipelines.

The overall hydrogen infrastructure development program should address developing alternate technologies for production at both small and large scale, economical storage methods to enhance energy density, cheaper pipeline materials, and standard practices for leak detection and other safety issues.

Continuous research, industrial interest and investment, and the country's policy can overcome the above-listed challenges. The fully developed hydrogen value chain will be more complex and requires cross-sectoral investments, especially for new network infrastructure.

Concluding Remarks

Transition to a hydrogen-based economy faces several challenges. Availability of suitable and sustainable infrastructure plays a critical role in promoting Hydrogen for several industrial sectors

Hydrogen infrastructure development and the associated production, storage, distribution technologies must be further researched to achieve energy security and economic development objectives.

To summarise, challenges are:

- Available technologies for hydrogen production, storage and distribution need further development.
- The existing fossil fuel-based processes need to adapt to CCS methods to make them financially attractive.
- In the transportation sector, the costs of fuel cells need to be reduced further.
- Lightweight materials and alternate technologies for hydrogen storage need development.
- Countrywide pipeline networks need to be developed.
- Safety issues for hydrogen handling need to be resolved by framing appropriate codes and standards.

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References:

- International Energy Agency, The future of Hydrogen, June 2019
- Report prepared by Steering Committee on Hydrogen Energy and Fuel Cells, Ministry of New and Renewable Energy, Government of India, New Delhi Hydrogen Energy and Fuel Cells in India – A way Forward, June 2016