HYDROGEN: A SUSTAINABLE FUEL FOR FUTURE

Abstract

The increasing population and the burgeoning demand for energy supply has resulted in an active search for innovative energy sources and energy carriers. Hydrogen, as a sustainable energy vector, has assumed importance in recent years, as it can produce clean energy with zero greenhouse gas emissions. It is generally believed that there is no climate solution without clean hydrogen. Hydrogen generated employing renewable energy sources with low carbon emissions and other pollutants, is termed as green hydrogen. Since 1.8% of global carbon di-oxide present in the environment is due to the production of the element hydrogen, it is imperative to adopt alternative processes for generating, storing and delivering hydrogen as a fuel. The current chapter is an investigation of the production, storage and transportation of hydrogen. India's Green Hydrogen Mission has the basic objective of zero carbon emission by 2070. This chapter will discuss the viability of adopting green hydrogen as the energy vector embracing renewable energy sources for its production. Further, the possible outcomes of this mission by 2030 and the associated challenges will also be explored.

Keywords: green hydrogen, renewable energy, fossil fuel, climate change, global warming, hydrogen storage

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"I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together will furnish an inexhaustible source of heat and light of an intensity of which coal is not capable………water will be coal of the future"

- **Julius Verne,1876**

I. INTRODUCTION

The target of keeping the rise in global temperature below 2.0℃ by 2030 is one of the most important features of the Paris Climate agreement[1]. Since the burning of the fossil fuel contributes significantly to the increase in the emission of green-house gases which further lead to global warming, the biggest challenge today is to drastically reduce the use of these fossil fuels in industries, transportation applications and the energy sector. In recent years, hydrogen as a vector for energy storage has emerged as a clean fuel since the by-product obtained by oxidizing or burning and harvesting energy from it, is free from any carbon emissions.Thus, it has the potential to bring greater flexibility in the energy transitions and is emerging as an excellent medium for storing and transporting energy. Further, hydrogen as a fuel vector has the capacity to store energy flexibly for a few days to several months without the requirement of recharging, unlike the batteries.The energy content of hydrogen is much higher than most of the hydrocarbons, by mass. Table 1 represents the details of the abbreviated units used in the current work. Comparison of the energy density by mass and volume is represented in Table2.These properties make hydrogen particularly useful for the transport sector to be used as a fuel for trains, cars, buses, marine ships and in aviation sector. It is also a fuel for future for space shuttles. In the industrial sector, steel and iron industry can replace the coke by hydrogen. Hydrogen is also used in the manufacturing of chemicals and fertilizers.

Table 1: Details of Abbreviations of Units

S.No.	Physical Entity	Units	Abbreviated units
1.	$Mass$	$kilogram$	kg
2.	$Volume$	$(metre)^3$	m^3
3.	$Density$	$kilogram/(metre)^3$	kg/m^3
4.	$Energy$	$Joules$	J
5.	$Energy\ Density$	$Joules/(metre)^3$	J/m^3
6.	$Energy\ Density\ by\ mass$	$Joules/kilogram$	$J/\ kg$
7.	$Pressure$	$Pascal$	Pa
8.	$Temperature$	$Degrees\ Celsius$	℃
9.	$Diffusion\ Coefficient$	$metre^2/second$	m^2/s

Table 2: Comparison of Energy Density by Mass (Kilojoules/Kg) and Volume (MegaJoules/m^3)[2]

S. No.	Fuels	Energy Density (kJ/kg) by mass	Energy Density (MJ/m^3)
1.	Hydrogen gas	1,20,000	10
2.	Hydrogen Liquid	1,20,000	8,700
3.	Crude oil	42,000	37,000
4.	Coal	32,000	42,000
5.	Hydrogen, as metal hydride	2,000-9,000	5,000-15,000

A major drawback in using hydrogen as an energy vector is that it does not exist in a free state and therefore it cannot be extracted directly, unlike the metals which can be extracted from their ores. In its natural state, it is always bonded with some other elements and therefore is a part of compounds like water, metal hydrides and hydrocarbons. There are several methods to generate hydrogen from these compounds.Table3is a brief summary of the methods for producing hydrogen and its corresponding environmental impacts.

Table 3: Production of Hydrogen

Process of Hydrogen generation	Process	Carbon Emission	Name	Remarks
Steam MethaneReformation (SMR)	At temperatures 700℃ – 1000℃,steam reacts with methane in presence of metallic catalysts to produce Hydrogen and carbon monoxide(eqns,1,2)	1kg of hydrogen produced releases 10 kg of Carbon di oxide to the atmosphere	Grey Hydrogen	Globally, almost all the hydrogen used in industries is grey hydrogen. 2.2% of global carbon di oxide present in the atmosphere is due to the production of hydrogen by burning fossil fuels.
SMR	Same as above	53% of carbon is captured at source	Dark Blue Hydrogen	Captured carbon can be used in chemical industries
SMR	Same as above	89% of emitted carbon is captured at source	Light blue Hydrogen	Captured carbon can eitherbe sequestered underground or injected into oil reservoirs for enhancing oil recovery.
Electrolysis of water to obtain Hydrogen[3].	Solar or wind energy is used to generate electricity for this process	Zero carbon emission	Green Hydrogen	Only 0.1% of Hydrogen used globally is,green hydrogen.

Conventionally, hydrogen is produced by catalytic SMRtechnology which is the interaction of natural gas or gasoline, with water vapour at an average temperature of 850°C and 2.5 MPa.The general chemical equation representing the reaction is

$$C_nH_m + nH_2O \rightarrow n\,CO + (n + \frac{m}{2})H_2 \qquad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (2)$$

[Water Gas Shift Reaction]

Hydrogen can also be produced from biomass by gasification or by fermentation of the biomass. Employing the process of electrolysis, hydrogen can be produced by using an aqueous-alkaline electrolyte in which two electrodes are dipped, the anode and the cathode. By supplying a potential difference of 1.5 Volts, it is possible to generate the hydrogen and oxygen gas[4]. Another route which is currently in its nascent stage is the thermal splitting of water molecules. The temperature required for splitting is 3000 K which has the limitation of the unavailability of materials for the containers which can withstand such temperatures. Indirect routes integrating chemical processes or PV collectors can be introduced to reduce the requirement of such high temperatures. Figure 1 represents the hydrogen infographics briefly.

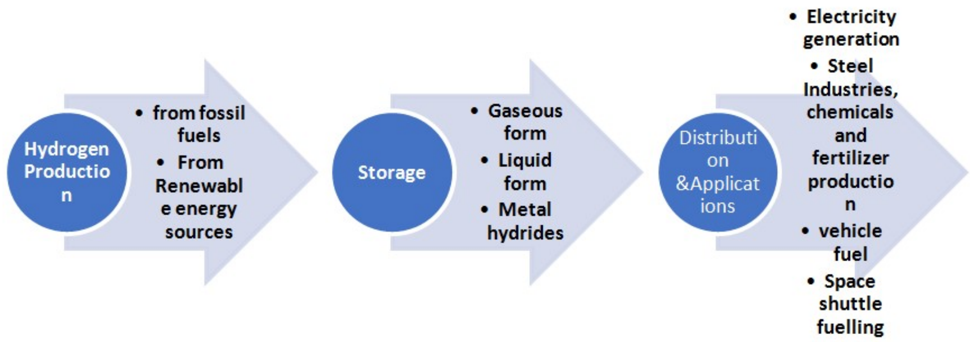

Figure 1: Hydrogen Infographics

1. **Storage of Hydrogen:** With the objective of developing a robust hydrogen economy, it is essential to develop technologies to store, transport and supply hydrogen, safely as it is highly inflammable (Table 4).

Table 4: Properties of Hydrogen, Methane and Petrol related to Safety in Storage and Transportation

Properties	Minimum Ignition Energy $(10^{-3} Joules)$	Range of inflammability in air (volume %)	Auto-ignition temperature in air(°C)	Diffusion coefficient in airat NTP$(10^{-4} m^2 s^{-1})$
Hydrogen	0.02	4-74	585	0.61
Petrol	0.24	1-7.5	230-500	0.05
Methane	0.29	5-15	540	0.16

All hydrogen storage containers must be non -corrosive, should have a resistance to hydrogen permeation and should not react with the stored hydrogen. It is important to emphasize that the methodology employed for storage of hydrogen[5] will be dependent on the type of applicationSince the density of hydrogen at NTP is $0.09\ kg/m^3$, an important first step for an economically viable application of hydrogen as an energy vector, is to increase its density.

- **Gaseous Phase**: The storage of hydrogen necessitates acompression as its volume density is very low at atmospheric pressure (Reference to Table 2). An energy density of about 2000MJ/m^3can be achieved by subjecting the gas containers to high pressures in the range (20-30) M Pa. This is the most simplified process for increasing the density. In hydrogen tanks, for use in hydrogen vehicles, the pressure ranges from 35MPa-70 MPa. If the storage containers are subjected to pressures of the order of 70MPa, it is possible to increase the density to $42\frac{kg}{m^3}$. However, to withstand such high pressures, the storage must necessarily be fabricated from innovative composite materials with super high tensile strength like the Kevlar fibres for which the physical and chemical properties remain unaltered under such high pressures. To reduce the permeability, carbon fibres are used as an inner lining in the storage tanks.

- **Liquid Hydrogen Phase**: For space shuttle fuel applications, hydrogen are stored in liquid form.This necessarily means that a huge energy needsto be invested in maintaining the temperature below the boiling point of hydrogen gas. Secondly, the material properties of the pipe through which the liquid hydrogen will flow should remain unaltered at such low temperatures.As hydrogen boils at -253℃ , so the containers where the hydrogen is stored and the pipes carrying liquid hydrogen requires very heavy insulation to avoid it from converting into the gaseous form. It is important to understand that this fuel should be away from any heat sources like exhausts of engines in rockets and locations where heat can be generated in air due to friction caused by the movement of rocket through the atmosphere. The fuel can also get heated on being exposed to the solar radiation, resulting in the expansion of the liquid. To avoid explosions, vents are required. The tank containing liquid hydrogen when subjected to such low temperatures, have a tendency of becoming corrosive and brittle. Interestingly, on thespace station, it is possible to generate hydrogen in situ and recycle it, solving the problem of remote supplies from the earth. Technologically, this is a huge advancement in rocket science.However,in this form of storage though the density of hydrogen is high but about 40% of the hydrogen energy content will be required for maintaining this temperature. It is interesting to note that the fuel that is being used in Chandrayan III moon mission of India has solid fuel in the first stage, liquid in the second stage and cryogenic engine with liquid hydrogen and liquid - oxygen for the final stage.

- **Metal Hydride Storage:** Hydrogen can diffuse into metal alloys forming the metal hydrides[6], thus doubling the volume density in comparison to liquid hydrogen.The advantage of this form of storage is that atmospheric pressure 0-6 MPa is enough and the energy losses are minimal. Furthermore, purification of hydrogen happens naturally as the impurities cannot enter the metal lattices.Usually, the hydrogen storage is in the form of metal hydrides and the process is represented by equation (3).

$$\frac{1}{2}x\, H_2 + metal \leftrightarrow metalH_x \qquad (3)$$

- **Zeolite Hydrogen Storage:** Zeolites are structures in the form of frameworks which are formed in such a way that pores and cavities are created which facilitate the adsorption of hydrogen atoms. The important property of these created channels is that their sizes can be altered. The adsorbing capacity is dependent on the size of these cavities which can be tuned according to the requirement.

- **Carbon Based Materials:** Graphite fibres, carbon nanotubes and balls of big carbon structures are often employed for the storage of hydrogen as they are light weight, stable and offer a large surface area for adsorption.

2. **Transportation of Hydrogen:** Transportation of hydrogen has well defined pathways. In its gaseous form, hydrogen is transported as a compressed gas by pipelines and tube trailers. Cryogenic tank trucks with heavy insulations are required for transporting liquid nitrogen for end point use. Due to no tail pipe emissions of pollutants, hydrogen run vehicles will represent a significant transition in the automobile sector. The emissions from these vehicles being only heat and water, such vehicles are likely to be adopted soon. However, transportation of hydrogen to the fuelling stations, time management of fuelling the vehicles and developing a technologically advanced infrastructure of the fuelling stations are some of the challenges particularly because hydrogen is highly inflammable(Table 4). The basic factors which need investigation for designing the transportation techniques are

- The distance from the production site to the fuelling station
- Frequency of charging (refilling) the tank.
- Average consumption

The infra structure at the point of dispensing hydrogen will require the facilities for compression, storage, metering unit and the sensors for contaminant detection. For heavyduty vehicles, dispensing hydrogen at 10kg/min will require a pressure of 350-700 bars[10]. If the distance from production to the filling station is greater than 350 km and if several refilling of the tank is required per week, the research suggests transporting hydrogen in the liquid form. Thus, the technology development for distribution networks needs immense research for deciding the form in which the hydrogen should be transported.

3. **Generation of Electricity Using Hydrogen:** The simplest process to generate electricity using hydrogen is by considering an assembly of two electrodes separated by a polymer electrolyte membrane (PEM). Hydrogen on entering the set up diffuses to the anode which has metallic catalyst coating on it. It dissociates into the proton and electron. The membrane permits the passage of protons through it. However, the electron cannot be conducted through the electrically insulated PEM and hence travels in an external circuit producing current.At the cathode, oxygenmolecule combines with the electron and the

conducted proton through PEM, to produce water. Usually, the catalyst used in both anode and cathode, is platinum.

4. Green Hydrogen: The Super Fuel

- **Green Hydrogen Production**: While hydrogen is a clean energy fuel and as discussed above finds applications in diverse industries, the irony is that the production of hydrogen generates a lot of green -house gases. With reference to Table3, it is observed that approximately 2% of the global carbon di oxide is generated due to the formation of hydrogen by burning fossil fuels. Almost all the hydrogen used in different industries is produced by burning the hydrocarbons. To make hydrogen a perfect clean fuel, alternatives to production of hydrogen without the green-house gas emissions, is the next step in developing this super fuel of the future[7,8].Referring to Table3, one of the methods of producing hydrogen is by the electrolysis of water. This process involves immersing 2 electrodes in water which needs some minerals for electrical conductivity. A potential difference across the electrodes causes an electric current to flow resulting in the production of hydrogen and oxygen. The hydrogen is produced at the cathode and the oxygen is collected at the anode.Ifthe source of energy required for electrolysis is a renewable energy source, the hydrogen so produced is termed as

- **Green Hydrogen.** Usually, the renewable energy is solar or wind energy.The special focus in this work is on using Photo Voltaic thermal cells for generating electricity from solar energy for the electrolysis of water[9]. Recently, University of Adelaide (Feb'23) has produced green hydrogen using sea water without any pre-treatments.

II. GREEN HYDROGEN MISSION FOR INDIA

In January 2023, with the objective of setting up a green hydrogen centre for the production and applications of green hydrogen, GOI has approved the Green Hydrogen Mission[11].The basic aim of the union cabinet is to make a green hydrogen hub with an outlay of Rs.19, 744 crores to beused from the current financial year to the financial year 2029-2030. One of the most important factors is to become self -sufficient and finally export green hydrogen and its derivatives to remote countries. The year2030 has been marked as the year by which India will design a transition to hydrogeneconomy. The target is the generation of 5million tonnes per annum of green hydrogen by 2030. Strategic Interventions for Green Hydrogen Transition (SIGHT) is planned as the support for facilitation of demand for domestic utilization. This mission also aims at making India an export hub of greenhydrogen. This will be an incentive for productionof green hydrogen.The major steps planned under the green hydrogen mission are the creation of infrastructure for green hydrogen hubs, developing a pool of skilled work force and spreading the awareness amongst the general public, particularly in remote and rural areas as green hydrogen production and its applications, is a sunrise industry and is still in its infancy. India has the advantage of having the primary materials namely, sea water and solar energy in abundance. In fact, India has one of the highest installed renewable energy capacities globally.

One of the important sustainable development goals (SDG) for India is using hydrogen in steel industries for producing green steel replacing coke, deploying green hydrogen for refineries,chemical and fertilizer industries. Green hydrogen for city gas distribution is another important application that India envisages with the support of public sector undertakings like Gas India limited(GAIL), Indian Oil Company(IOC), Oil India limited(OIL), National thermal power commission(NTPC) and a few private companies. The ultimate objective for India is phasing out the fossil fuels, achieving complete decarbonization and adopting the green path for climate change mitigation. The final expected economic outcome of the mission that is being planned is a reduction in fossil fuel imports by INR one lakh crores by 2030. Similarly, by 2030, the green hydrogen mission has projected amitigation of 50 metric million tonnes of carbon di-oxide emissions per annum. This will be a significant step in the war against climate change and global warming.

III. CHALLENGES OF THE GREEN HYDROGEN MISSION

1. Green- hydrogen production cost is currently projected at Rs320-Rs330 per kg while the cost of production of grey hydrogen in India is Rs.120-Rs.160per kg. The reason for this excess cost of green hydrogen is the extra cost ofrenewable energy set up,used for providing the electrical energy for water electrolysersas the energy conversion efficiency is low.
2. Green-hydrogen project will take 15-20 years to mature in India[12]hence there appears an uncertainty in investment from the private sector. High incentives and subsidies may be needed to encourage the engagement of more investors.$1.4 trillion has currently been incurred to supportfossil fuel applications by the G20 countries in 2022[13].The challenge is to transit from fossil fuels to green energy.

3. A framework of regulations defining the stipulations of safety standards is not in place. India needs to evolve stringent rules which should meet the international standards to enable the country to use and export green hydrogen and its derivatives, effectively.

IV. CONCLUSIONS

India is in the dawn of the new hydrogen era. The futuristic trend of adopting hydrogen as a sustainable energy source with zero carbon emissions and embracing renewable energy like solar energy for power generation aided with the latest innovative technologies, it will be possible to pave a greener path for the future generations.It is of utmost importance, therefore, for India to be in the top of the global race for green hydrogen.The energy transitions with zero carbon emissions will empower India to honour the commitment of net zero by 2070.

REFERENCES

[1] Global Hydrogen Review, IEA, Editor. 2021: PARIS.
[2] Sorensen B, Renewable Energy,Physics, Engineering, Environmental impacts, Economics and Planning, 4thedition, Elsevier (Academic Press),India,2011.
[3] Idriss H, Hydrogen production from water: past and present, Current Opinion Chemical Engineering, 2020, 29, 74–82.
[4] Krishna R, Titus E, Salimian M, Okhay O, Rajendran S, Rajkumar A, et.al.,Hydrogen Storage for Energy Application, edited volume:Hydrogen Storage,IntechOpen, 2012.
[5] Andersson J, Gronkvist S,Large Scale Storage of Hydrogen, International Journal of Hydrogen Energy, 44 (2019) 11901-11919.
[6] Application of hydrides in hydrogen storage and compression: achievements,outlook and perspectives. Int J Hydrogen Energy 22 March 2019;44(15).

[7] Khan M, IAl-Shankiti, A Ziani, & HIdriss, Demonstration of green hydrogen production using solar energy at 28% efficiency and evaluation of its economic viability. Sustainable Energy & Fuels, 2021. 5(4): p. 1085-1094.
[8] AlZohbi G, Green Hydrogen Generation: Recent Advances and Challenges,IOP Conf. Series: Earth and Environmental Science,1050 (2022) 012003.
[9] Calnan S, Bagacki R, Bao F, Dorbandt I,Kemppainen E, Schary C,et.al,Development of Various Photovoltaic-Driven Water Electrolysis Technologies for Green Solar Hydrogen Generation. Solar RRL, (2021) 2100479.
[10] Available from https://www.energy.gov/eere/fuelcells/hydrogen-delivery-source
[11] National Green Hydrogen Mission, Govt. of India,Jan 2023.
[12] Srivastava A,Green hydrogen options for India,Global Trade Research Initiative Report,June 2023.
[13] International Institute for sustainable development and partners report(IndianExpress)23rd August,2023.