Review Article

Journal of Environmental Nanotechnology

Hydrogen Economy and Policies Across the Globe for Environmental Sustainability: A Review

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Received: 12.03.2025 Accepted: 01.06.2025 Published: 30.06.2025
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ABSTRACT

Advancements in technology, rising population and extensive use of fossil fuels increase environmental pollution, which suggests a shift towards a sustainable form of energy. Hydrogen being present in abundance in the atmosphere makes it one of the best choices to be considered as an alternative fuel. Presently, it is being used in the manufacture of ammonia and in other chemical industries. However, it can also serve as a fuel. Hydrogen economy refers to the phase from hydrogen production to its end/commercial use, comprising three stages i.e., production phase, storage and transportation phase, and commercial or end use. Many countries are aiming towards these sustainable shifts by considering some policies and have already started their work decades back towards hydrogen economy. India is also targeting to become a carbon-neutral nation, to become a green hydrogen hub. In this review paper, the hydrogen economy and policies adopted by different countries are presented and discussed.

Keywords: Environmental sustainability; Hydrogen economy; Global hydrogen policy; Hydrogen production; Hydrogen storage.

1. INTRODUCTION

The world is in a transition phase toward sustainability, suggesting a shift from our dependency on fossil fuels to alternative energy sources. This shift is driven by two factors, namely, depletion of fossil fuel reserves and the rising levels of greenhouse emissions. With increasing population, use of vehicles is also increasing, leading to enormous emission of greenhouse gases. It is observed that most of the carbon emission is caused by the automobile sector (Jiang *et al*. 2019). Also, burning of crude oil (petroleum product) is a major reason behind this state of pollution. Apart from the depletion of fossil fuels, the dangers and fragility of nuclear power also suggest for an alternative which produces less or no carbon dioxide and that could meet India's energy demands. An alternate fuel should be safe, harmless to environment, economically and technically feasible, and easily convertible (Ngoh and Njomo, 2012).

Hydrogen is considered a viable alternative as it can completely eradicate our dependency from fossil fuel (Khanna and Pallavi, 2020). It has high calorific value (approx 140 MJ/kg) which makes it a very suitable alternative. It has a potential to be used in a fuel cell which generates only water and energy; therefore, it is considered a clean burning fuel. It is also being considered a strong alternative to achieve sustainability in automobile sector (Chakraborty *et al*. 2022). For this reason, hydrogen economy is getting much attention across the world. At present, hydrogen finds its application in synthesising ammonia and manufacturing nitrogenous fertilizers. Fig. 1 depicts the production and its use as presented by Arulmozhi (2018).

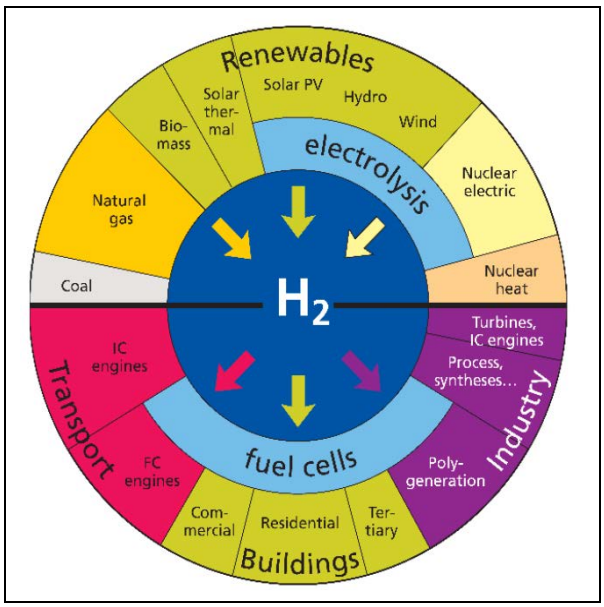


Fig. 1: Hydrogen production and its use (Arulmozhi, 2018)

1.1 Properties of Hydrogen and Its Uses

Hydrogen is the first element in the modern periodic table and a keen subject of research as it is the future of fuels. Basic properties of hydrogen are listed in

Table 1. There are three hydrogen isotopes: (i) Protium, having a mass of 1u and is the most abundant isotope, (ii) Deuterium, having a mass of 2u and (iii) Tritium having a mass of 3u, which occurs in a very small quantity in nature. Properties of the three isotopes are listed in Table 2.

Table 1. Basic properties of hydrogen

S. No.	Properties	Values
1.	Atomic number	1
2.	Atomic Mass	1.007825 $g.mol^{-1}$
3.	Electro-negativity	2.1
4.	Melting Point	13.8K (-259.2 °C)
5.	Boiling Point	20.2K (-252.8 °C)
6.	Density	0.0899×10^{-3} $g.cm^3$ at 20 °C (~ 0.09)
7.	Van der Waals radius	0.12 nm
8.	Ionic Radius	0.208 (-1) nm
9.	Isotopes	3
10.	Electronic Shell	$1s^1$
11.	Energy of 1st ionization	1311 $kJ.mol^{-1}$

Some other properties of hydrogen are as follows:

- Hydrogen is a clean burning fuel. It can be used in fuel cells where the by-product is only water.
- It is lighter than air, so while burning it won't spread like petroleum and other fuels do.
- Hydrogen is a reducing agent at normal temperatures. It reacts with metal oxides and metal chlorides to produce free metal.
- Hydrogen gas is insoluble in water and partially soluble in organic compounds.

Table 2. Properties of isotopes of hydrogen

S. No.	Properties	Protium	Deuterium	Tritium
1.	Relative abundance	99.9	0.015	10^{-15}
2.	Melting point / K	13.96	18.73	20.62
3.	Boiling point / K	20.39	23.67	25
4.	Density gL^{-1}	0.09	0.18	0.72
5.	Atomic mass (u)	1.008	2.014	3.016

1.1.1 Uses of Hydrogen

Hydrogen is widely used in ammonia industry to synthesize ammonia. Other uses include:

- To obtain saturated fat from unsaturated vegetable oils by catalytic hydrogenation.
- Widely used in manufacturing industry of organic chemical products.
- In combination with oxygen, it serves as a rocket fuel and as a rocket propellant which is driven by nuclear energy.

1.2 Hydrogen as an Energy Carrier

Hydrogen is not a fuel, as oil and gasses are, but rather an energy carrier. Previously, hydrogen was assumed to be a means of energy storage and transportation. When hydrogen was first proposed as an energy carrier, it was intended to carry energy *via* pipeline rather than electricity via wires, because pipelines are more cost-effective. According to Bockris and Khan (1993) hydrogen transfer by pipeline, excluding infrastructure costs, would be more efficient and less expensive than electricity transmission *via* voltage lines. Hydrogen offers numerous advantages as an energy carrier. It is regarded as a clean and ideal fuel because it produces no pollutants or Green House Gases (GHGs) when used in fuel cells, whereas burning other fuels cause significant air pollution and GHG emissions (Page and Krumdieck, 2009). Hydrogen is emerging as a promising energy storage solution when combined with renewables, and its position in today's society is becoming increasingly important. Furthermore, this integrated system has the potential to replace fossil fuel combustion, hence improving energy sustainability. Another factor for hydrogen's acceptance in sustainable development is its high energy density compared to other fuels. It is regarded as an excellent medium for energy storage and utilization due to its higher mass energy density than other fuels (Dou *et al.* 2017).

1.3 Hydrogen Economy

Hydrogen is attracting much attention for its development as fuel for the future needs. A new term 'Hydrogen Economy' has been coined in the context of innovation and implementation of technological advancements in social world (Ngoh and Njomo, 2012). Hydrogen Economy refers to the phase from hydrogen production to its end/commercial use. It comprises of three stages: (i) Production phase, (ii) Storage and Transportation phase and (iii) Commercial or end use. Fig. 2 shows the diagrammatic view of hydrogen economy.

A variety of processes, employing both renewable and non-renewable resources, are capable of producing hydrogen. In order to prepare it for usage and

application, it must be stored at ideal temperature and pressure conditions after manufacture.

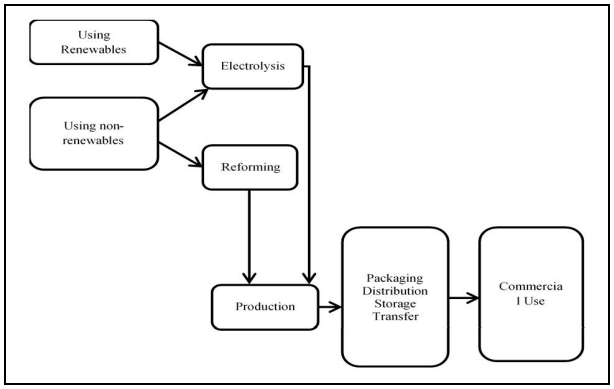


Fig. 2: Diagrammatic view of hydrogen economy

1.4 Challenges

Although hydrogen economy is getting much attention, there exist some challenges specific to each phase. In hydrogen production, although, there are various methods available to produce hydrogen, commercial production of hydrogen at cheap rate is still a big concern (Bernard and Nnabuife, 2021). Hydrogen production process involves emission of harmful gases such as CO_2, CO etc. Researchers are making effort to produce green hydrogen which does not involve production of any harmful gases. The storage of hydrogen poses its own set of challenges. Since hydrogen has a very low density of 0.0838 kg/m^3, it has to be stored at a high pressure (600-650 bar) in gaseous form. As hydrogen gas is highly flammable, storing it in high pressure in the gaseous form can cause explosion. The boiling point of hydrogen is very low and to liquefy hydrogen gas to store it in liquid form will require a lot of energy. Researches are going on to store hydrogen in solid form in few intermetallic compounds and alloys in metal hydride form (Sakintuna *et al*. 2007). Apart from these, there are other challenges with hydrogen gas, such as if it is inhaled it can cause oxygen deficiency resulting in headaches, dizziness, vomiting, blue colour of skin and eventually death too. However, this can only happen if the hydrogen gas concentration is more than a certain limit.

2. LITERATURE REVIEW

This section provides an in-depth study of hydrogen economy; hydrogen production, hydrogen storage and transportations as well as its end use. Additionally, it comprises a detailed study of hydrogen policies across the world.

2.1 Hydrogen Production

Hydrogen production is the first phase of the hydrogen economy. Despite being most abundant element on this planet, it doesn't exist in free form and needs to be extracted. There is great flexibility in producing hydrogen (Blanchette, 2008) i.e. it can be obtained from a variety of sources. These sources include fossil fuels, hydrogen containing materials, hydrogen recovery from by-products and generation by electrolysis of water through renewable energy (solar energy and wind energy).

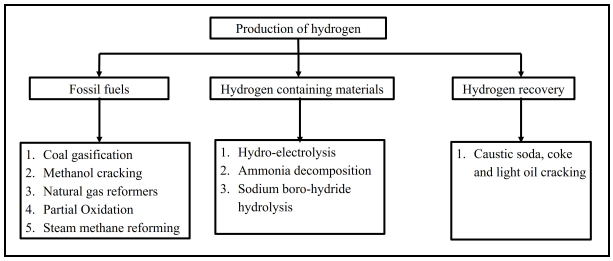


Fig. 3: Production methods of hydrogen

2.1.1 Methods to Produce Hydrogen

Hydrogen can be produced by a variety of methods. Fig. 3 shows some of the methods. The production of hydrogen from fossil fuels involves coal gasification, natural gas reformers, methanol cracking etc. On the other hand, production through hydrogen containing materials includes process like hydro-electrolysis, ammonia decomposition and sodium borohydride hydrolysis. Similarly, the method of recovery includes caustic soda, coke and light oil cracking (Shan and Wang, 2020). Some of the important methods are listed below.

a) **Electrochemical:** Hydrogen is majorly produced through electrolysis. It is a process of energy transformation. In this process, water (H_2O) gets split into hydrogen and oxygen using electricity. Electricity can be produced through different sources, but using renewables for production is a sustainable way. As presented by Bossel and Eliasson (2003) electrolysis is associated with losses. To separate hydrogen and oxygen from water, it needs high voltage leading to ohmic losses caused by current flow under operational conditions.

b) **Reforming:** Reforming is done with hydrocarbons to extract hydrogen. Theoretically, there are no losses but the practical application shows that there has been always less energy in generated hydrogen than the original hydrocarbon fuels. Moreover, the efficiency is about 90 %. Furthermore, release of CO_2 is not desirable (Bossel and Eliasson, 2003).

c) **Thermo-catalytic Decomposition:** In this process, natural gas (methane) is thermally converted into solid carbon and gaseous hydrogen. As suggested by Muradov (1993), after the process

of thermo-catalytic decomposition of methane and/or liquid hydrocarbons, the emitted carbon can be used in a number of ways. A major suggestion for its utility was to press the resulting carbon into blocks which can be stored under water and/or land for a long period of time, so as to use it when required.

Fig. 4 shows the cost comparison between different methods to produce hydrogen (Peighambardoust *et al*. 2010). It is evident that though using electrolyser for electrochemical process is a sustainable way, it is not economic. Other methods are cost-effective, but can lead to carbon emission.

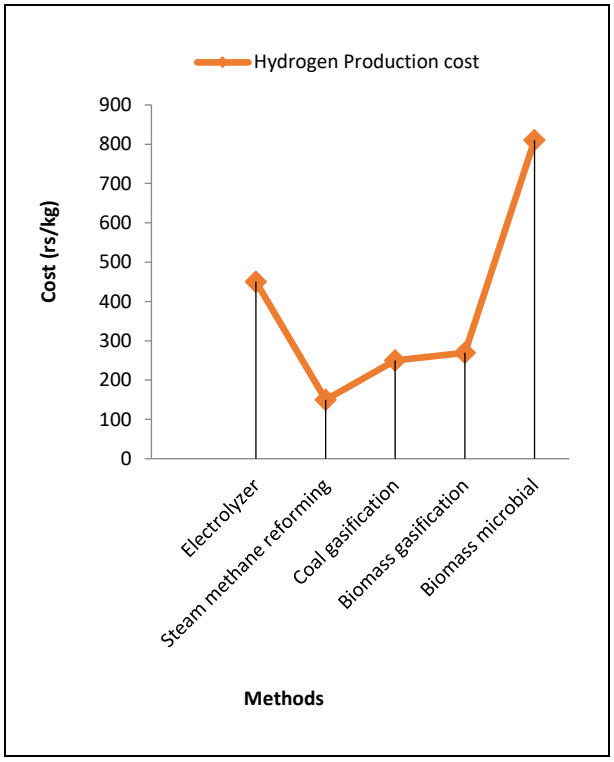


Fig. 4: Cost of hydrogen production (Peighambardoust *et al.* 2010)

2.1.2 Types of Hydrogen Produced

Hydrogen, which is produced through different processes, has been colour coded according to the procedure and the by-products of the reactions taking place. Fig: 5 depicts a colour spectrum of hydrogen. Green hydrogen is produced through electrolysis by using electricity, produced by any renewable energy resource. It does not produce any carbon dioxide. The process of producing blue hydrogen involves separating methane gas into hydrogen and carbon dioxide, which are then stored, using either Steam Methane Reforming or Auto Thermal Reforming. Grey hydrogen is the by-product of the aforementioned process when carbon dioxide is released into the atmosphere. When for hydrogen production, black coal or brown coal (lignite) is used, it produces carbon dioxide and carbon monoxide as by-products, leading to name hydrogen as black or brown hydrogen. Hydrogen produced by the methane pyrolysis is named as turquoise hydrogen. Pink hydrogen is produced through the electrolysis by using nuclear energy. Similarly, when nuclear energy is used for the process of catalytic water splitting at high temperature, hydrogen produced is called red hydrogen. White hydrogen is the naturally occurring hydrogen. A new type of hydrogen is added recently named as yellow hydrogen, in which the production takes place by using only solar power as energy source. Table 3 shows types of hydrogen produced on the basis of method of production. Currently, green hydrogen is getting a major focus as nations are targeting sustainability and a reduction in carbon footprint.

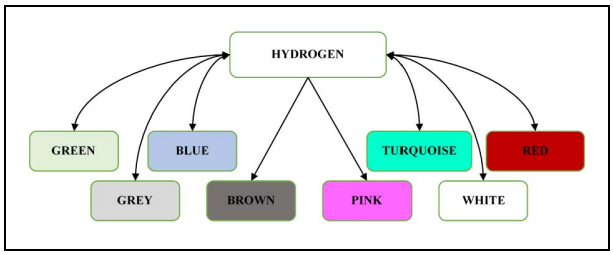


Fig: 5. Color spectrum of hydrogen

Table 3. Types of hydrogen based on color code

S. No.	Type of H_2	Production Process	By-product
1.	Green	Produced through electrolysis by using electricity from renewable energy resource	No Carbon
2.	Blue	Reforming (methane gas is split into hydrogen and carbon dioxide which is further stored)	Carbon dioxide
3.	Grey	Reforming (but carbon dioxide is left into the atmosphere)	Carbon dioxide
4.	Black / Brown	Black coal or brown coal (lignite) is used	Carbon dioxide and mono-oxide
5.	Pink	Electrolysis by using nuclear energy	-
6.	Red	Catalytic water splitting at high temperature using nuclear energy	-
7.	Turquoise	Methane pyrolysis	-
8.	White	Naturally occurring hydrogen	-

2.1.3 Green Hydrogen

Renewable hydrogen is also known as green hydrogen. Produced from renewable energy sources (such solar or wind) in a clean and sustainable manner, it is referred to as "green" (Abad and Dodds, 2020). Green hydrogen can be produced by a variety of methods; electrolysis, thermolysis, thermocatalysis, bio-photolysis

are some of them where only water or any other non-carbon substance is used. All these methods are driven by some energy such as electrical energy or thermal energy or combination of both. Table 4 lists some methods of producing green hydrogen (Dincer, 2012).

Production of green hydrogen can take place using a variety of renewable energy sources (renewables). The most common sources are solar and wind energy and sometimes a hybrid system of both the sources. In the field of hydrogen economy, green power supply systems are getting much attention in terms of producing and storing hydrogen cost effectively and environment friendly. A green and clean power supply system generally consists of PV array, wind turbine, batteries, fuel cell and hydrogen storage system.

Fig. 6 shows a typical flowchart of a hybrid energy system for efficient green hydrogen production (Marchenko and Solomin, 2017). Some of the renewable techniques for hydrogen generation are discussed below.

Table 4. Green hydrogen production methods (Dincer, 2012)

S. No.	Driving Energy	Production Method	Resources Used
1.	Electrical energy	Electrolysis	Water
2.	Thermal energy	Thermolysis	Water
		Thermocatalysis	Hydrogen sulphide (cracking)
		Thermochemical process	Water (splitting)
			Hydrogen sulphide (splitting)
3.	Photonic Energy	PV-electrolysis	Water
		Photo electro chemical method	Water
		Bio-photolysis	Water
		Photo catalysis	Water
4.	Electrical + Thermal	High temperature electrolysis	Water
		Hybrid thermochemical cycles	Water

(a) Solar Energy for Hydrogen Generation

Solar Energy is probably the most abundant energy among all the renewable energy sources. It has certain advantages such as non-polluting energy. As suggested by (Eisenstadt and Coxt, 1975) the two main problems with this energy are the low power density and its intermittent nature. To overcome this problem either the energy should be stored or the system should be hybrid.

(b) Wind Energy

The wind turbine (wind energy system) will be feasible where there is an abundance of wind, such as coastal regions. A paper on optimal sizing of wind turbine provides a study on optimal sizes of wind turbine as well as hydrogen energy system under different modes of hydrogen production, hydrogen transmission and hydrogen demand levels (Deng and Jiang, 2020).

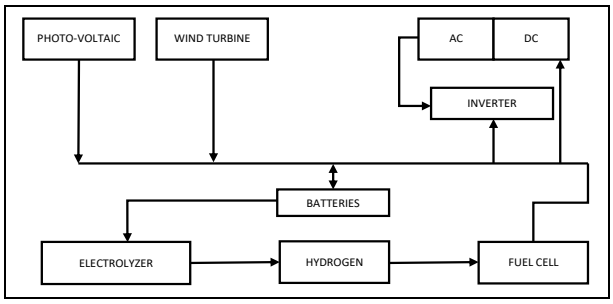


Fig. 6: Flowchart of a hybrid energy system (Marchenko and Solomin, 2017)

(c) Hybrid Energy

The conventional renewable energy hybrid system for making environment friendly hydrogen can be seen in Fig. 6. The optimization model and effective methods of producing hydrogen using hybrid systems have been the subject of extensive study (Marchenko and Solomin, 2017). Optimization mathematical model calculations suggest that using wind and solar energy together will boost the efficiency of hydrogen storage for extended periods of time at a cost-effective rate. Wang *et al.* (2021) proposed an innovative hybrid system that could produce electricity and hydrogen fuel using solar photovoltaics, wind turbines, electrolyzers, fuel cells, and Stirling engines. Fazelpour *et al.* (2016) presented their findings on the economic analysis of a hybrid energy system in Tehran (Iran). In another work, Kalinci *et al.* (2015) used a hybrid renewable energy system (PV + Wind + hydrogen) with hydrogen storage for Bozcaada Island in Turkey. Their system also had a hydrogen tank, electrolyzer, fuel cell, and converter. They found that two wind turbines produced 70% of the electricity, while a photovoltaic array accounted for 20% of the overall output. Khare *et al.* (2016) stated that the most cost-effective way to construct integrated systems is with PV-Wind-Fuel Cell-Hydrogen tank, where the wind turbine accounts for 64% of the overall production.

2.2 Storage and Transportation

Two main categories exist for hydrogen storage: (i) physical storage and (ii) material storage. The three main physical methods of hydrogen storage are liquid, cold/cryo compressed, and compressed gas. Some material-based storage methods are chemical hydrogen, interstitial hydride, complex hydride, liquid organic, and

adsorbent. Fig. 7 shows many modes of storage along with examples of each. There are three main categories into which all of these storage techniques fall when it comes to hydrogen: (i) gas, (ii) liquid, and (iii) solid.

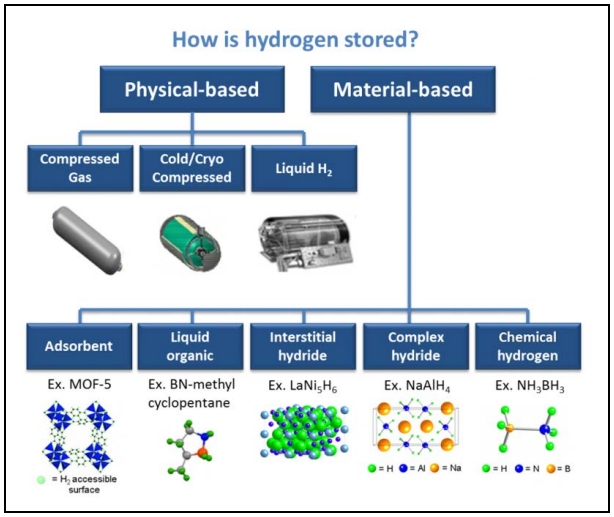


Fig. 7: Hydrogen storage technologies and examples (WHA international Inc, 2023)

2.2.1 Gaseous Form

Although hydrogen has a high energy density, it has a very low volumetric density of approximately 0.0838 kg/m^3. In order to store it in gaseous form, a large volume is required, in which hydrogen is compressed to store under high pressure. Hydrogen can be stored by normal compressing as well as in cold compressed form. Since it is stored at high pressure, it may have safety issues. Tanks which are capable of holding pressurized gas are generally made up of expensive carbon fibre, and as the pressure increases the quantity of carbon fibre also increases, leading to the increase in initial cost of hydrogen storage (Elberry *et al*. 2021).

2.2.2 Liquid Form

To store hydrogen in liquid form, it has to be liquefied by the process of liquefaction. The process of liquefaction provides comparatively a high storage density but a high energy input is required as the boiling point of hydrogen is very low. It has an advantage over other storage forms as it has high volumetric density.

2.2.3 Solid Form

Hydrogen can be stored by adsorption in metal hydrides and organic liquids. When they are stored in metal hydrides, they get adsorbed in the interstitial voids as well as create a bond (Van der Waals attraction) between the metal and hydrogen. The main challenge associated with this form is its very poor gravimetric capacity. The storage capacity is only about 1.5 wt% and 5-6 wt % in case of simple hydride and complex hydride, respectively (Singh *et al*. 2017a; Singh *et al*. 2015; Singh *et al*. 2017b).

2.3 End or Commercial Use

Hydrogen can be used in different industries. As the data given by WHA International Inc, more than half of the hydrogen around the world (about 55%) is used in ammonia production; one fourth (25% of hydrogen) is used in refining and about 10% is used for producing methanol and other applications account for almost 10%. Fig. 8 shows the graphical representation of its applications. The Toyota Mirai and Hyundai Nexo are two hydrogen-fueled vehicles that were the first to attempt hydrogen application in the transportation sector (Wen and Aziz, 2024). Hydrogen can also be used in several other industries.

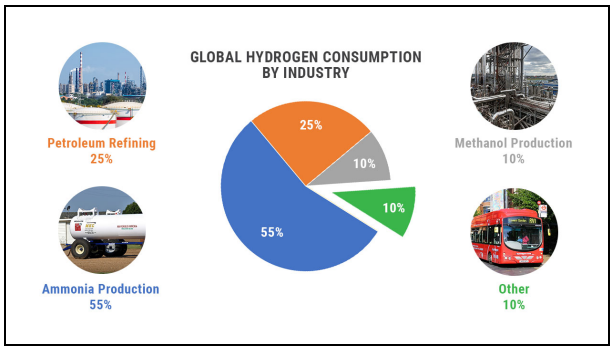


Fig. 8: Global hydrogen consumption by industry (USDOE, 2023)

2.4 Hydrogen Economy Policy Across the World

Hydrogen Economy is an economy which depends on hydrogen as the fuel used commercially and provides a considerable amount into nation's energy and services. Many countries have already finalized the phases of hydrogen economy and are paying much attention towards research in this area to allocate resources based on their respective conditions (McDowall, 2012). Some of the countries like Japan, Korea, EU, and USA lead other countries like India and China in terms of research and development.

2.4.1 Hydrogen Economy in the United States

United States is paying attention towards hydrogen technology since 1970s. A comprehensive meeting between government, industries, universities, and other concerned organizations in 2001 recognized some opportunities and challenges for the hydrogen economy along with the strategy for transition into hydrogen economy. The inferred significance was to decrease dependency on petroleum and increase on hydrogen technology, thus, reducing environmental effects. In 2002, considering hydrogen as a long-term potential of energy, a roadmap was provided to R&D sector, public and private corporation. Some benefits that

aimed were: mitigating the climate changes and saving energy in transportation sector.

A study in 2008 by the USDOE (United States Department of Energy) revealed that a net of 6.75 lakh jobs could be created whereas another study by American Solar Energy Society, it was estimated to be 9 lakhs, if transition into hydrogen economy is fully completed by 2050. However, here also the key difficulty is to improve durability and reducing costs (George *et al*. 2008).

In 2011, the estimation cost of a stationery fuel cell depending on dimensions was 3000-7000 USD/kW higher than conventional power. However, for automotive fuel cells, the cost decreased over time but it was still found to be more than the internal combustion engines. Apart from these, costs related to production, storage and delivery were also high. It provided a road map for hydrogen economy. In long term, integration of social and technical sector is required to target on extensive commercialization of hydrogen technology (Dou *et al*. 2017).

2.4.2 Hydrogen Economy in Japan

In Japan, a pilot project in Fukuoka demonstrated that hydrogen could fuel an entire community with net-zero emissions (Stolten and Emonts, 2012). The government of Japan, in 1974 launched a project aiming the development of renewable energies as primary energy and hydrogen as secondary one. The scheme sums up that hydrogen will fulfil 30% of total energy consumption and the remaining 70% will be satisfied by liquid fuels (Dou *et al*. 2017). According to the article in a Summit of the year 2015 (NEDO, 2014), the crucial innovation was the technology for producing, storing and transporting hydrogen which was going to benefit both, economy and climate change.

According to an article (Kucharski *et al.* 2017), hydrogen importing from stable regions is expected to substitute the current petroleum products in Fuel Cell Vehicles (FCVs). Also, it was expected that it could reduce environmental impacts by producing it with CCS which leads a carbon dioxide free energy supply.

Japan targeted its promotion until 2030s by which it is aiming to the world's leading country in terms of hydrogen economy. They categorized it into three phases.

Phase 1 – from 2015, the use of FCVs was expanded to occupy a position in world market for hydrogen and fuel technologies.

Phase 2 – from 2025, introduction of hydrogen power generation, to build an infrastructure for the same.

Phase 3 – from 2040, establishing fully CO_2 free supply systems.

2.4.3 Hydrogen Economy in China

According to a paper on hydrogen economy (Shan and Wang, 2020), China has been the world's largest producer of hydrogen in recent years. In 2012, it has produced 16 million tons of hydrogen, which rose to 22 million ton in 2018. It implies that China has a very good base for hydrogen production to meet the potential demand of hydrogen economy in future. Since 2020, some of the hydrogen related government policies have been introduced in China, Shandong, Inner Mongolia and Sichuan, for promoting and developing green hydrogen (Huang *et al*. 2022).

2.4.4 Hydrogen Economy in Korea

According to estimates of Korean energy usage, imported energy accounts for around 97% of total energy. Furthermore, Korea ranks seventh as the world's largest petroleum user; yet, total oil demand is dependent on foreign countries such as Middle East Asia. The Republic of Korea is intensifying its efforts to create new and renewable energy (NRE) sources. Currently, conventional energy sources (such as trash and hydropower) account for more than 91% of total NRE supply. However, the overall energy supply from modern energy sources (fuel cells, solar, etc.) is still less than 2.5% of total NRE supply. In 2006, the Korean government established a "National Vision of a Hydrogen Economy and Action Plan" to transition Korea from a carbon-intensive to a hydrogen-based economy (Hwan and Cho, 2010). A roadmap supporting the hydrogen economy in many industries of South Korea was published in 2019. They have also proposed a plan to provide the initial infrastructure, investments, and foundations for the creation of hydrogen cities. By 2040, they hope to have 30% of Korea's cities running on hydrogen. (Stangarone, 2020).

2.4.5 Hydrogen Economy in European Union

According to Kakoulaki *et al*. (2021), 81% of EU and UK have excess potential for generating renewable energy resources after satisfying the electricity demand and hydrogen production. They have provided an analysis on producing hydrogen using renewables (solar, wind and hydropower) at both regional and national level.

2.5 Research in India

India records 7% of the global total CO_2 emitter, while its per capita emissions are 40% of the global average (Friedlingstein *et al*. 2020). India stands 1st in most populus countries, and with increasing population, usage of vehicles is also increasing, which is leading to enormous emission of greenhouse gases. Burning of crude oil (petroleum product) is a major reason behind this state of pollution. Only about 2% of total primary energy consumption considers renewable sources such as

solar, wind, hydroelectricity etc. In this regard, it is feasible to find an alternative which produces less or no carbon dioxide and can meet India's energy demands. Glasgow Climate Pact has emphasized on limiting global warming to a particular value. While at United Nations Climate Change Conference, India has announced that it targets a net-zero emissions till 2070, still global warming will exceed the value set by the standards. For that, India has to set its net-zero emission target to 2050 rather than 2070.

The green hydrogen mission aims to aid government to meet its climate targets and making India a green hydrogen hub, was launched on 15 August, 2021. India is highly dependent on energy imports. It buys 85% oil and 53% of gas from other countries. This mission will lead to become energy independent. Key points of this mission are;

a) To generate clean energy using hydrogen

b) Replacement of fossil fuels with hydrogen and use it in core industries to reduce greenhouse emission.

In India, cost of producing hydrogen by fossil fuel is around ₹100-₹200/kg (1.34 – 2.27 $/kg). Other different processes are hydrocarbon reforming, pyrolysis, steam reforming, and auto thermal reforming. Reforming techniques increase the production rate. These methods could be used further, but by considering environmental factors, it should be switched it to renewable sources. Globally, when compared to only renewables grid-based hydrogen production by electrolysis more effective, it falls in the range of approx. ₹900/kg (12.6$/kg), depending on supply chain. It was observed that most of the carbon emission was caused by the automobile sector. To achieve sustainability over this sector, hydrogen is considered as it is a clean fuel having high energy density and can be used with IC engines and fuel cell (Sontakke and Jaju, 2021).

3. DISCUSSION

Hydrogen has been identified as a potential alternative to fossil fuels for almost six decades. Since then, researchers worldwide have been making significant efforts to enhance its safety and affordability for widespread use. However, several challenges still need to be addressed to make hydrogen commercially viable. These challenges span the entire supply chain, from production to end-use.

Starting with the production of hydrogen gas from various sources, it has been observed that although hydrogen can be produced through different methods, the most desirable sources are renewables, and the most preferred method is electrolysis. The primary challenge in this phase is the production cost, which remains higher compared to other processes. Reducing production costs should be the main focus during this phase. Significant developments are underway to lower these costs, and it is anticipated that commercial production will become cost-effective in the near future.

In the storage and transportation phase, storing hydrogen in any of its three forms—liquid, gaseous, and solid presents significant challenges. Maintaining the cold temperatures required for liquefaction is not feasible. Storing hydrogen in its gaseous form under high pressure necessitates considerable maintenance and incurs high costs. When stored in solid form, the storage capacity is notably low. Among these options, gaseous storage is receiving the most attention. Advances are being made in developing storage containers made of composite materials that can hold gaseous hydrogen at very high pressure while maintaining low weight. Additionally, researchers are investigating new intermetallic alloys that can absorb more hydrogen with improved absorption kinetics at normal temperature and pressure.

Many countries have already initiated efforts towards establishing a hydrogen economy, and others are beginning to follow suit. India, for instance, has recently embarked on this path. A framework has been set, and policies are being formulated to realize a sustainable hydrogen economy. The National Hydrogen Mission in India has been launched, and the government is actively monitoring the progress, reflecting a strong commitment to this transformative energy source. By addressing these challenges through continuous research and development with a policy support mechanism, the goal of making hydrogen a commercially viable and sustainable alternative to fossil fuels appears increasingly attainable.

4. CONCLUSION

Hydrogen holds significant promise as a sustainable alternative to fossil fuels, having been recognized for its potential for nearly six decades. Ongoing research and development efforts are crucial in addressing the key challenges that hinder its commercial viability. From production to storage and transportation, each phase presents unique obstacles that require innovative solutions. While significant challenges remain, the progress in hydrogen research and development is encouraging. Continued innovation and international cooperation is essential in overcoming these barriers and realizing the full potential of hydrogen as a clean, safe, and affordable energy source for the future.

DISCLOSURE STATEMENT

The paper was presented in the International Conference on Advances in Renewable and Green Energy Technology (ICARGET 2023).

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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