**HYDROGEN ENERGY STORAGE: RESEARCH AND INNOVATIONS TOWARDS GREEN TECHNOLOGY**

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# **ABSTRACT**

# There is a need to use sustainable energy sources to generate electricity without emitting greenhouse gases. Hydrogen works well for this purpose because the mass energy produced by hydrogen is three times greater than that produced by hydrocarbon liquid fuels. This makes hydrogen-based technology critical to future energy needs and its storage is crucial for successful commercialization of hydrogen-based energy applications. Storage techniques should be efficient to help with transportation as well, so choosing the best is important. There are many conventional and advanced promising methods used for hydrogen storage, but each has its own limitations. In this chapter, the methods used to store hydrogen, the most sustainable method of hydrogen storage and the methods required in the future are discussed. Along with that, the importance of zero-emission hydrogen production, which has shown great promise for a future called green hydrogen, is also discussed.

**Keywords:** Hydrogen energy, green hydrogen, Hydrogen storage, Hydrogen production, Sustainable energy

# **INTRODUCTION**

Sources of renewable energy exist throughout the environment like the sun, wind, water, waste, and heat from the earth, and that do not cause the atmosphere to be polluted or filled with greenhouse gases (Hassan et al; 2023). Due to the enormous increase in population and the demand for energy, sustainable energy sources are becoming more prevalent (Hosseini et al; 2015). It is used in industry, power generation, driving vehicles, homes, and agriculture. Due to zero emission of CO2, high energy density, versatility, storage capacity, hydrogen will be the fuel of the future. This chapter introduces hydrogen as an energy carrier, discusses hydrogen production and its applications, and discusses various methods for hydrogen storage, including news on high-pressure and cryogenic-liquid storage, absorption storage on high-surface-area adsorbents, chemical storage on metal hydrides, and complex hydrides (Eberle et al; 2009). Green hydrogen method is an emerging solution to produce hydrogen without emission of other gases, which are used in storage system and their advancements and technologies are moving towards green and sustainable environment.

# **HYDROGEN PRODUCTION METHODS**

In molecules where it exists, hydrogen must be separated from other elements to form hydrogen. Hydrogen is primarily produced from two types of sources: fossil fuels and renewable energy sources. The most effective methods to produce hydrogen include directly converting solar energy, using solar and wind energy to electrolyze water, as well as converting fuel and biomass. A few methods, including photobiological, photoelectrochemical, electrochemical, photocatalytic, thermochemical, thermolysis, and steam gasification, have been employed to produce cleaner hydrogen and separate it from chemical contaminants. (Singla et al; 2022).

 **A. Hydrocarbon Reforming**

In a steam reforming reaction, vapour and hydrocarbons interact at high temperatures to transform the gas into hydrogen and carbon oxides. Frequently, a nickel-based catalyst is used. The gas combination undergoes reformation, a heat recovery stage, and then introduced into water. When CO reacts with steam in a gas shifter reactor, additional H2 is generated. The CO2 was eliminated by pressure swing adsorption after the combination had been filtered to 100% high purity (Steinberg; 2008).

## **B. Gasification of Hydrocarbons and Biomass**

In the absence of oxygen, hydrogen can also be produced through pyrolysis-based hydrocarbon gasification methods, which have been estimated to have similar delivery costs at greater scales. Coal, heavy residual oils, and other low-value refinery products are only a few of the hydrocarbon fuels that can be partially oxidized to produce hydrogen. At temperatures between 1200 and 1350℃, the hydrocarbon fuel undergoes this reaction with oxygen to form carbon monoxide and hydrogen. The gasification of biomass yields a variety of beneficial byproducts, such as syngas, heat, power, biofuels, fertilizers, and biochar. The resultant gas is changed into hydrogen using the water Gas shifter method (Sikarwar et al; 2016).

## **C. Hydrogen from Biomass**

The process which involved in the Hydrogen production from biomass is thermo-chemical and biochemical. It is possible to convert several biomass resources into energy. They are divided into four types in general are energy crops, agricultural wastes, waste from the forest, industrial and municipal wastes (Ni et al; 2006). Enzyme-based biochemical digester processes are restricted to moist, sugar-based feedstocks when using the thermo-chemical methods of gasification or pyrolysis which is heating biomass in the absence of oxygen to produce hydrogen and carbon monoxide (Holladay et al; 2009)

## **D. Electrolysis of water**

Some of the hydrogen producing methods explore different approaches to eliminate the intermediate product like syngas. One recognised method of producing hydrogen is electrolysis of water, which is regarded as an environmentally friendly method because it uses renewable energy sources including geothermal, wind and solar energy. The most common source of hydrogen is water, which can be converted into hydrogen and oxygen with an appropriate amount of energy and without any adverse effects using electricity and an electrolyser apparatus. The overall electrolysis reaction equation is shown in Eq (1) (Balat 2008). Potassium hydroxide electrolyte and PEM (Polymer membrane electrolyte) are the two prevalent electrolyser categories. These methods are considered as the green hydrogen production process.

 e- + H2O ½ O2 + H2  -----(1) With so many different applications for hydrogen production, there is still an expanding need for the production technology. Hydrogen can be generated from electrolyzing water using any electrical source, including utility grid electricity, solar power, wind power, hydropower, or even nuclear energy. (Osman et al; 2022). Of the hydrogen being produced in pure form worldwide, most comes from fossil sources (76% from natural gas to steam methane reforming and 22% from coal gasification) whereas only 2% coming from water electrolysis, which is still a major obstacle to sustainability. Such petroleum fuel-based manufacturing processes have been associated with the production of grey hydrogen (Hren et al., 2023) . Even though hydrogen is a colourless gas, it is often colour that indicates how cleanliness of hydrogen is: black, grey and brown are being considered as the less pure form of hydrogen while blue is regarded as moderately pure hydrogen due to low carbon emission, and “Green Hydrogen”, which reduces emission to net zero, an eco-friendly gas. Some of the hydrogen production techniques, their source and CO2emissions while production are shown in Table 1. (Alasadi, Tareq; 2022 & Ajanovic et al; 2022).

**Table 1: Hydrogen production techniques and CO2 emissions.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Technology for H2 production** | **Hydrogen colour** | **Source** | **Products** | **CO2 emissions** |
| Gasification | Brown hydrogen | Brown coal (Lignite), | H2 + CO2 | High |
| Gasification | Black hydrogen | Black Coal (Bituminous), refinery oil | H2 + CO2 | High |
| Reforming | Grey hydrogen | Natural gas, biomass | H2 + CO2 | Medium |
| Reforming + Carbon capture | Blue hydrogen | Natural gas | H2 + CO2 | Low |
| Electrolysis | Green Hydrogen | Water | H2 + O2 | Minimal |

# **HYDROGEN STORAGE TECHNOLOGIES**

Storage of Hydrogen is necessary to several links of chain from the production of usage. Some of the most fundamental hydrogen storage techniques are high pressure gaseous Hydrogen, cryogenic liquid, adsorbed on carbon nanotubes, absorbed to produce hydrides, and absorbed to form hydrides. The field of energy storage and transmission includes advancements in solid oxide and proton exchange membrane fuel cells, lithium-ion batteries, and solar technologies (Li et al; 2018). Achieving high pressure of up to 77Mpa using conventional piston-type mechanical compressors, high pressure gaseous hydrogen storage has become the most popular and developed approach (Nikolaidis & Poullikkas; 2017). To store hydrogen, two different technologies of physical storage and material storage have been used.

**A. Physical based storage system**

The main principle of physical hydrogen storage solutions is compression. Compression of hydrogen as a gas necessitates high-pressure tanks, whereas compression of hydrogen as a liquid necessitates cryogenic temperatures. Under cryogenic and high-pressure conditions (-252.8 °C and 5000–10000 psi) hydrogen can be compressed and stored effectively (Schoenung; 2011)

### Compressed Hydrogen Storage

Compressed hydrogen storage is one of the techniques involved in compressing hydrogen with a high-pressure gas cylinder, which uses an effective pressure of about 200 bar, whereas hydrogen car tanks run at 344-690 bar. Considering the energy density increases in volume with hydrogen gas pressure is a very effective storage technology (Hren et al; 2023). It is a method in which hydrogen stored in high-pressure gas cylinders must be compressed to operating pressure of around 200 bar, while hydrogen vehicle tanks operate at 344-690 bar. Compressed hydrogen storage is a highly efficient storage methodology because the energy density increases volumetrically with the pressure of hydrogen gas (Hren et al; 2023). There are four different types of pressure vessels that can hold the compressed hydrogen: a metallic pressure for industrial uses. The vessels with high pressure can be carried using tube trailers (Eberle et al;2009). The adverse effects of these pressure vessels include linear blistering brought on by saturation and decompression as well as expensive production costs, inadequate storage capabilities, restrictions on size, and a limitation on the amount of pressure that may be used in tanks (Hren et al; 2023).

### AB. Liquified Hydrogen Storage

A common method of storing the hydrogen involves liquefied storage, which compresses the gas at high pressure at -253°C. For better efficiency, the vessel must have adequate insulation, a protective outer coat, and an inner pressure vessel. For more effective of storage, it requires lower thermal conductivity between inner vessels, therefore the vessel is covered with the sheet of aluminium film or has a pertile covering. This kind of hydrogen is utilized in the medium to large scale industries storage and transportation (rail, road, intercontinental). This approach is still being developed (Hren et al;2023)

## **Material based storage system**

The last few decades have used metals and alloys as a storage method because the metal matrix can be expanded and hydrogen atoms can be absorbed and filled (Eberle et al;2009). Absorption can be used to store hydrogen both physically and chemically. In the process of chemical sorption, hydrogen molecules are broken up into atoms and mixed with the chemical composition of the substance. The most well-known category of materials that can be used for chemical sorption is metal hydrides, such as LiAIH4. The charge-discharge rate of this approach is enhanced, which controls the generation of undesirable gases during desorption, but it also has its own drawbacks in terms of cost, weight, and operating temperature. By using these energy storage techniques, it is possible for the   effective, and safe ways to store the very promising energy carrier hydrogen in the future. (Hirscher et al; 2020).

### BA. Metal hydrides

There is a technique that doesn’t require high temperature for storage of hydrogen, and it involves the use of metal hydrides which only need moderate temperature and pressures. Metal ions that form a lattice make up its composition. Atomic hydrogen is created when hydrogen adsorbs at a metal centre, dissociates, and then enters the metal lattice (Tarasov et al., 2021). It is an exothermic reaction overall. For storing hydrogen, the metals Li, Be, Na, B, and AI have been investigated and Mg is typically the major metal hydride used for storage but others like Ti or La are also used (Preuster etal., nd) Good kinetics, reversible nature, cost-effectiveness, and a substantial storage capacity under moderate settings are important characteristics of materials used to store hydrogen in solid form (Meduri et al;2023) Many factors affect the metal hydride material selection criteria for hydrogen storage and compression applications. The processes of hydride synthesis and decomposition must first be reversible in the application-specific operating temperature and hydrogen pressure range. Second, under working circumstances, the material must have a high dynamic hydrogen storage capacity (Tarasov et al;2021).

###  Complex hydrides

# Complex metal hydrides are also employed in addition to basic metal hydrides. These are created when boron, nitrogen, or aluminium hydrides react with the hydrides of alkali metals. LiBH4, NaAIH4, and LiNH2 are some of the common examples. Many transition metals and their alloys react with hydrogen to produce hydrides. Metal hydrides, such as MgH2, TiH2, and AIH3, have demonstrated potential as solid-state hydrogen storage materials. High hydrogen capacity (up to 7.6wt%) is one of MgH2's advantageous features (Preuster et al., n.d.). It is also possible to use various types of chemical sorption, such as N-ethyl carbazole, methanol, dibenzyl toluene, and others, in which hydrogen is chemically bound to hydrogen-deficient molecules and released through a catalytic dehydrogenation. The advantage of this method is that they are not toxic and corrosive. Coming to their limitations, these have low storage capacity.

# **CHALLENGES AND LIMITATIONS OF HYDROGEN STORAGE**

Hydrogen has a low volumetric density, which makes it challenging to store for prospective needs. It is the most basic element and is also lighter than helium, which makes it quickly vanished in the environment. When it comes to effective storage, this is the main obstacle. Another difficulty is that liquid hydrogen has an extremely low boiling point (-253 °C). Due to the need for high-pressure tanks (350–700 bar/5000–10,000 psi), it is also a difficult chore to handle as a gas. Therefore, the development of safe, dependable, and affordable hydrogen storage and transportation is crucial. High density hydrogen storage is challenging to store and move, from a transportation perspective (Demirocak; 2017). Conventional methods result in releasing of Greenhouse gas (GHG). Similarly, these technologies do not produce hydrogen on the same scale, presenting one of the main limitations. (Zhang et al;2023). The important limitations of hydrogen storage methods are shown in Table 2.

**Table 2: Hydrogen storage process and its limitations**

|  |  |  |
| --- | --- | --- |
| **Hydrogen Storage processes** | **Limitations** | **References** |
| Compressed hydrogen storage | Not suitable for large scale energy storage as expensive high-pressure tanks required. | (Eberle et al., 2009) |
| Liquified hydrogen storage &cryo compressed | Difficult to store & handle.Requires expensive equipment | (Hren et al., 2023)Hren et al., 2023 |
| Material based hydrogen storage | Limited hydrogen capacity andExpensive devices are required | Molaeimanesh & Torabi., 2023 |
| Chemical Hydrogen storage | Expensive & challenging to scale up | Molaeimanesh & Torabi., 2023 |

# **ENERGY STORAGE SYSTEMS FOR FUTURE**

“Green hydrogen” created can be kept and reversed to produce electricity on demand and can be utilized directly in fuel cells as it does not emit CO2, which makes it one of the best storage techniques. Recently hydrogen storage systems and batteries are the most advantageous option for storing the energy, because batteries require lower maintenance, easy to operate, acquire higher energy capacity and have the better gravimetric and volumetric densities (Molaeimanesh & Torabi; 2023). The Hydrogen storage batteries typically store hydrogen as a hydride compound inside a solid metal alloy. When heated, these batteries release the hydrogen that has been stored, which can then be utilised to produce power in a fuel cell.

## **Conventional Battery Technology**

For many commercial uses old age battery types like Lithium-ion and lead-acid batteries are used. The mechanism present in all conventional batteries is that a redox reaction occurs in which one of the electrodes release electrons that are used for supplying load in the external circuit and then carried to the other electrode. Rechargeable Li-ion batteries are the most effective typical battery technology with a relatively long service life.

## **Molten salt batteries**

Molten salt batteries require salt ions and exhibit higher efficiency as there is no charge loss. An example is a sodium-sulphur battery that depends on sodium ion. This method is useful for applications where the temperature ranges from 270 to 350℃.

## **Redox flow batteries**

The reactants are attenuated in the electrolyte solution and stored in external tanks in the redox flow batteries. Their advantage over conventional batteries is that they are not affected by the depth of discharge. Examples of currently used redox-flow batteries include Zinc bromide, vanadium, and iron-chromium batteries used for energy storage applications (Andujar A M; 2022).

## **Hydrogen fuel cells**

This method utilizes renewable sources such as wind, sun, wave to combine hydrogen and oxygen resulting in electricity and water. This method is called green hydrogen as it only produces water as a by-product along with heat. HFC supports zero emission in terms of carbon, yet it is more efficient and powerful (Pellow et al; 2015)

## **Regenerative Hydrogen fuel cells**

Can hydrogen fuel cells be used for large scale; the answer is no which is where RHFC’s are used as they are more eligible for it. Stationary fuel cells and internal combustion engines can utilize H2 as an energy storage medium. RHFC comprises of an alkaline water electrolyser and a PEM fuel cell. This technology has the highest ESOI ratio amid the battery types used nowadays for storage (Pellow et al;2015).

# **GREEN HYDROGEN**

Major countries across the world have set a goal for the year 2050, that by that time the carbon footprints, which have seen a sharp rise in its levels, must be reduced. This is how we can cure the world of global warming and harm caused by climate change. This can be achieved by using “green hydrogen” as it has a zero-emission policy hoping to replace current gas-emitting technologies. This might facilitate in reduction of fossil fuel consumption and carbon footprint (Zwickl-Bernhard & Auer; 2022). Green hydrogen is becoming a promising fuel alternative for future sustainable development and energy transition due to fact that it can be produced from water and renewable energy sources through electrolysis process, and there is no GHG emissions as well as it addresses the issues of climate changes.

# **A FUEL FOR FUTURE**

Soon Hydrogen will be the significant fuel due to its high efficiency, fair performance of hydrogen as an energy storage medium, relevance toward sustainable development, energy transition and green economy- building, potential mitigation of greenhouse emissions, higher energy density of hydrogen storage than fossil fuels. Green hydrogen is 100% sustainable, easily storable, and versatile. There is no emission of GHG either during the combustion or production of green energy and at the same time it is easy to store for the later purposes. And predicted by the world Hydrogen council, if the hydrogen production costs reduce by 50% in 2023, undoubtedly it will be looking for the fuel for future. To minimize the environmental impact of hydrogen production we should reduce the CO2 emission, and renewable energy sources should be used (Hren et al; 2023) Hydrogen vehicles: Due to its zero-pollutant discharge abilities, hydrogen vehicles are being promoted as the preferable future transportation platform. The range of application of HFC is enormous as it can potentially replace light weight vehicles like cars, huge cargo ships and trains.

# **TRENDS IN HYDROGEN STORAGE**

For the direct production of hydrogen from renewable electrolysis, metal hydride storage technology is ideal which has been produced through fuel cells. With the demand for hydrogen being expected to increase by about 8-folds in 2050 (Rasol M G et al; 2022). However, the high cost of manufacturing and the high need for storage remain challenges to the growth of hydrogen energy. An important hurdle is the production of new materials for storage of hydrogen along with technologies like water splitting wherein H2 is produced using photoelectrochemical materials (Liu et al; n.d.)

# **CONCLUSION**

If humanity needs to utilize hydrogen as an energy carrier as it doesn’t have emissions while production, there is a key problem that needs to be sorted, which is the storage of hydrogen. Although various hydrogen storage techniques have been developed, each one has advantages and limitations of its own. The efficacy, adaptability, and cost-effectiveness of hydrogen storage methods must be increased to address the difficulties associated with hydrogen storage. Some of the methods like metal hydrides, electrolysis and photocatalytic are promising. However, photocatalytic water splitting's solar-to-hydrogen (STH) efficiency has remained incredibly low. Here, we present a method for achieving a high STH efficiency by combining focused solar light, pure water, and an indium gallium nitride photocatalyst. There needs to be innovativeness when designing storage methods that provides a more cost-effective and is safe. This is where new age technologies that uses metal hydrides, liquid, and solid storage, high pressure gas storage come in and promises to take this research to new directions and aid in replacing fossil fuel utilization thereby preventing global warming due to climate changes.

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