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RESEARCH ADVANCEMENTS & CHALLENGES FOR SUSTAINABLE HYDROGEN ENERGY

A comprehensive review on unleashing the power of hydrogen: revolutionizing energy systems for a sustainable future

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Abstract
Population growth and environmental degradation are major concerns for sustainable development worldwide. Hydrogen is a clean and eco-friendly alternative to fossil fuels, with a heating value almost three times higher than other fossil fuels. It also has a clean production process, which helps to reduce the emission of hazardous pollutants and save the environment. Among the various production methodologies described in this review, biochemical production of hydrogen is considered more suitable as it uses waste organic matter instead of fossil fuels. This technology not only produces clean energy but also helps to manage waste more efficiently. However, the production of hydrogen obtained from this method is currently more expensive due to its early stage of development. Nevertheless, various research projects are underway to develop this method on a commercial scale.

Keyword Hydrogen · Clean energy · Heating value · Greenhouse gases · Hydrogen storage · Environment · Waste management · Technical barrier

Introduction

Energy serves as the basis for national development, which, in turn, supports economic growth. Despite sustained and rapid economic growth, countries all over the world are paying close attention to the impact of the energy problem (Li and Ge 2023). The need for energy increases daily as the world's population grows and the economy progresses. However, conventional fossil fuels, such as natural gas, coal, and oil, have been used continuously for over 20 decades, resulting in excessive energy consumption, unrestricted exploitation, and significant waste production (Zhang et al. 2021a). Fossil fuels currently provide approximately 95% of the world's energy needs (Pareek et al. 2020). So, too much and careless use of fossil fuels has caused environmental problems and energy crises (Balachandar et al. 2020). Approximately 36 billion tonnes of carbon dioxide are released into the atmosphere each year to meet energy demands. More than 90% of these emissions come from fossil fuels, which are likely to be used more in the near future (Qureshi et al. 2022b). In addition to carbon dioxide (CO_2), nitrogen oxides (NO), sulfur dioxide (SO_2) (Sekar et al. 2021), ozone (O_3), carbon monoxide, lead, ash, and soot, they emit highly hazardous gases (Dincer 2011), so it is essential to utilize environment-friendly and renewable energy sources (Balachandar et al. 2020) to advance humanity sustainably.

Hydrogen burns cleanly and sustainably as an alternative to fossil fuels, producing harmless water (H_2O) instead of greenhouse gases after combustion (Lanjekar et al. 2023). In addition, they are highly energy dense (142 MJ/kg) (Balachandar et al. 2020), which is 2.75 times more powerful than energy derived from hydrocarbons (Dahiya et al. 2020), and can be utilized directly to generate electricity via fuel cells (Venetsaneas et al. 2009). Moreover, it can be made from sustainable raw materials, including organic residues and waste streams (Antonopoulou et al. 2008b), contributing

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to efficient trash disposal. As well as the hydrogenation of coal, vegetable oils, and petroleum is a prerequisite for producing ammonia, aldehydes, and alcohols (Fan et al. 2006). Because of the steadily growing population, there is a more pressing need for food and energy. Therefore, fossil fuels must be replaced by a reliable, affordable, and environmentally friendly alternative (Maroušek et al. 2023). Hydrogen is currently more efficient than gasoline but is also more expensive. It does not emit any pollutants, and in the future, hydrogen-dependent economies will also generate thousands of stable industrial jobs globally (Medisetty et al. 2020).

Green hydrogen has gained the utmost importance as a sustainable alternative to conventional fuels due to its lower carbon footprint and potential application in balancing energy production and demand (Bosu and Rajamohan 2023). The coal reserves in the world are large, and the biomass potential is excellent, both of which could contribute to increased production. Fuel cell technologies are being marketed around the world rapidly. Besides public acceptance, the country faces challenges such as establishing rules, norms, and laws. If these problems can be resolved, the country will soon be able to meet its energy needs cleanly and sustainably. The fuel efficiency of cars with hydrogen fuel cells is three times better than those with standard internal combustion engines (Guo et al. 2022). In addition to discussing how hydrogen is made, stored, and used, this review looks at its current status and technical challenges (Medisetty et al. 2020). The purpose of this review article is to provide current information on hydrogen production, distribution, transportation, economic analysis, challenges, limitations, and safety concerns during the production and use of hydrogen and the challenges of energy storage.

Hydrogen and its properties

Hydrogen is the first element of the periodic table and can be produced by a variety of methods, including water (H_2O), hydrogen sulfide (H_2S) (Sharma et al. 2022), methane (CH_4), fossil fuels, and biomass (Boretti 2021). Compared with gasoline, hydrogen has a significantly greater energy content (gasoline's heating value is 44 MJ/kg), a higher calorific value of 141.8 MJ/kg at 298 K, and a lower calorific value of 120 MJ/kg at that same temperature (Vincent and Bessarabov 2018). However, liquefied hydrogen has an energy density by volume of around a factor of 4 lower than hydrocarbon fuels like gasoline (density of 8 MJ/L against 32 MJ/L) (Brandon and Kurban 2017). Therefore, compared to hydrocarbons, hydrogen gas has a better energy density by weight but a worse one by volume, so it needs a larger storage tank (Dawood et al. 2019).

Because H_2 is a non-toxic, combustible gas having a lower ignition temperature, a significant percentage of the risk involved with using it is due to this (Rivkin et al. 2015). Because it is a small molecule and can break things (hydrogen embrittlement), it can also pass through materials (Hosseini 2022a), which can cause mechanical failure and leaks. As a result of its lightweight nature, it dissipates rapidly when released. This makes it significantly safer than most other spilled fuels because the fuel will dissipate relatively quickly in case of a leak (Møller et al. 2017). There is a safety issue in that if a leak is left unnoticed and the gas builds up in a small area; it could eventually catch fire and explode (Dawood et al. 2019).

Using hydrogen (H_2) as a fuel carries some risks, as does using any fuel. The safe use of any fuel, including hydrogen, is determined by avoiding conditions in which the three combustion components are present—ignition, fuel, and oxidant (Dawood et al. 2019). Despite this, specific characteristics of hydrogen, such as a wide range of airborne flammable concentrations (4–75%), necessitate extensive engineering controls to ensure its safe use (Dicks and Rand 2018). Materials for H_2 storage equipment must also consider metal hydrogen's brittleness and the possibility of damaging materials near the leak location (Dicks and Rand 2018). A thorough understanding of hydrogen properties, the design of security features in hydrogen (H_2) systems, and appropriate training in safe and secure hydrogen handling and storing procedures is essential for ensuring the safe use of hydrogen (Dicks and Rand 2018). According to the US Department of Energy, "when more hydrogen fuel demonstration gets going, hydrogen's safety records can expand and increase the willingness that H_2 can be as stable and reliable as the fuels in broad use today" (Dawood et al. 2019).

Some basic fundamental properties of hydrogen element are given in Table 1.

Hydrogen could make us less dependent on oil fuels, but we must make more technological advances before a hydrogen (H_2) economy can be built (Thompson 2008). Hydrogen will supply most energy requirements in a hydrogen economy, with electricity providing the remaining portion. However, the minimal amount of free hydrogen in nature is a significant barrier to developing a hydrogen economy. Hydrogen-containing molecules like methane, water, and others are required to produce hydrogen (Boretti 2021). To create a hydrogen economy that is entirely sustainable and renewable, it could also be a potential storage solution for intermittent renewable energy (Chakraborty et al. 2022).

Hydrogen's market has grown remarkably fast since it can be produced from any primary source of energy (i.e., biomass, coal, oil, and natural gas). Despite high pressurization (70 MPa) and unique materials, storing enormous amounts of hydrogen for extended periods is possible. In this way, hydrogen can be used for various end-use activities in centralized and distributed systems. By the IEA (International Energy Agency), hydrogen can be converted back into

Table 1 Principle properties of hydrogen fuel

S. no	Property	Value
1	Physical appearance	Colorless
2	Odor	Odorless
3	Nature	Non-toxic and flammable
4	Molecular formula	H_2
5	Molecular weight (g/mol)	2.016
6	Melting point (°C)	−259.18
7	Boiling point (°C)	−252.74
8	Specific gravity	0.091
9	Flash point (°C)	−253
10	CO_2 emissions (%)	0
11	Density (kg/m^3)	0.0838
12	Higher heating value (MJ/kg)	141.90
13	Lower heating value (MJ/kg)	119.9
14	Flame color	Pale blue
15	Auto-ignition temperature (°C)	585
16	Flammability limits in air (vol. %)	4–75
17	Mass diffusivity in air (cm^2/s)	0.61
18	Maximum flame temperature	1526.85°C

(i) electricity used to power companies as well as residential buildings (power to power); it can be transformed into (ii) artificial methane or incorporated with the natural gas infrastructure (power to gas); (iii) or even marketed to the transportation industry like fuel for (FCEV) fuel cell electric vehicles (power to fuel) (Toledo-alarc et al. 2018).

Different processes are used to produce pure hydrogen. Hydrogen can also be made from biomass, microorganisms, concentrated solar power, semiconductors, other sources, water, the sun, wind, and geothermal energy (Pareek et al. 2020). However, more research must be done before onboard applications that use hydrogen gas as a fuel can be made (Chakraborty et al. 2022).

Types of hydrogen

Hydrogen can be divided into the following categories according to its manufacturing method, with lighter shades in a hydrogen color palette denoting more environment-friendly options.

Gray hydrogen

Gray hydrogen is the form of hydrogen derived from hydrocarbons (such as natural gas and fossil fuels). Today, this method of producing hydrogen is the most frequently utilized. This method produced carbon dioxide as a waste product (8 kg CO_2/kg H_2) (Boretti 2020).

Blue hydrogen

It utilized the same production method as gray hydrogen and carbon capture and storage (CCS) practices, emitting no direct carbon dioxide. The expense of capturing and storing carbon dioxide is increased in this method (Boretti 2021). Existing CCS technology can hold and capture only 80 to 95% of carbon dioxide (Qureshi et al. 2022b). When it is produced from coal with 90% capture rate CCS techniques, it emits 2.4 kg CO_2/kg H_2, while using natural gas emits only 1 kg CO_2/kg H_2. There are some obstacles to the emergence of blue hydrogen as a transitional solution: the CCS technique is still in its infancy, is expensive, and has low carbon dioxide capture efficiency (Yu et al. 2020).

Black/brown hydrogen

This hydrogen is obtained from the transformation of coal into hydrogen gas and is the oldest hydrogen production method. When lignite coal is utilized for hydrogen production, it is known as brown hydrogen. When bituminous coal is utilized, produced hydrogen is known as black hydrogen. Due to the release of CO and carbon dioxide (20 kg of CO_2/kg of H_2) into the environment, it is a very polluting method (Yu et al. 2020).

Green hydrogen

When renewable energy sources such as wind, solar, biomass, agricultural crop residues, etc., are utilized to produce hydrogen, the hydrogen produced is known as green hydrogen. It has no emission of carbon dioxide gas (Boretti 2021). The 4.4 kg CO_2/kg H_2 is the threshold emission for green hydrogen-producing processes (Dawood et al. 2019).

White hydrogen

Electrolysis, in which water molecules split into hydrogen and oxygen in the presence of electricity, produces this hydrogen.

Aquamarine hydrogen

This hydrogen is made when natural gas splits into H_2 and solid carbon at high temperatures (De Blasio et al. 2021) during solar thermal methane pyrolysis, with stable carbon as a promoter or catalyst. Carbon black is obtained from this method as waste or by-product. Solar thermochemical pyrolysis inside a fluidized carbon bed at 1000°C makes aquamarine hydrogen that works better (Boretti 2021). This hydrogen is still in its early stages of development (De Blasio et al. 2021).

However, purple is the preferred color for hydrogen produced by thermolysis or electrolysis powered by nuclear energy. Yellow is recommended for hydrogen produced by electrolysis propelled by solar energy (De Blasio et al. 2021).

A comprehensive table (Table 2) has prepared to know about the different types of hydrogen, their production methodology, and their impact on the environment, which is given below.

Production of hydrogen

It is necessary to know hydrogen's sources to recognize it as a clean energy source. Despite this, a variety of energy sources, including conventional fuels and renewable sources, are available, as shown in Fig. 1a, and can be used to generate it by utilizing various substances, methods, and technologies, as illustrated in Fig. 1b (Khan et al. 2020). Furthermore, hydrogen production from renewable energy sources is important today since H_2 is an emerging energy vector that will decarbonize the world's energy and industrial/commercial sectors (Hosseini 2022b). Nevertheless, its long-term viability depends on the efficiency of the energy used and the purity of the hydrogen used (Megía et al. 2021).

Currently, the world produces 45–65 Mt of hydrogen annually, a precursor for the petrochemical and chemical sectors (Mari et al. 2022), and more than 96% of the world's hydrogen is derived from conventional fossil fuels (da Silva Veras et al. 2017), with coal gasification accounting for 18%, steam reformation of natural gas contributing about half, 48%, partial oxidation of petroleum products for 30% (Staffell et al. 2019), water electrolysis for 3.9%, as well as some other resources for 0.1% (Dincer 2011), as shown in Fig. 2. Figure 3 illustrates different methods of H_2 production. Still, most natural gas is used to make hydrogen through steam reforming, which releases many greenhouse gas emissions (Dincer 2011). Hydrogen can only be considered safe and sustainable when produced in an environmentally friendly and carbon-natural manner since it is made from fossil fuels only in Europe, which emit between 70 and 100 million tonnes of carbon dioxide yearly (Dahiya et al. 2020). Combining carbon capture technology with petroleum-based hydrogen generation is a viable approach that might reduce emissions by up to 90% and increase levelized costs by 25–50% (Greene et al. 2020).

The adoption of renewable sources of energy and operating biological hydrogen generation systems at atmospheric temperatures and pressure are the two primary factors increasing their importance in the current situation (Cardoso et al. 2014). These technologies have much potential for advancement from a long-term development standpoint, even though they are not yet sufficiently developed to replace the current industrial hydrogen generation systems. Therefore, future investigations should concentrate on developing safe, accessible, cost-effective, and environmentally friendly hydrogen production systems (Khan et al. 2020).

Thermochemical methods

Most hydrogen is currently made commercially by thermochemical processes like gasification (Paul and Panwar 2021) and steam reforming, among others. In these methodologies, chemical reactions are carried out at very high temperatures to obtain hydrogen fuel, which requires higher processing costs and expensive infrastructures. Some thermochemical methods are described in detail below.

Table 2 A glance at different color coding of hydrogen, their production methods, and environmental assessment (Qureshi et al. 2022b)

Types of hydrogen	Methodology	Feedstock	Technology readiness level (TRL)	CO_2 emission	Environmental impact	Cleaniness level of H_2
Gray hydrogen	Steam reforming	Fossil fuels (Natural gas)	Commercial (TRL 9)	High	High	Medium
Blue hydrogen	Steam reforming/gasification + CCS	Fossil fuels (natural gas)	Industrial scale (TRL 8–9)	Medium	Medium	Medium
Black/brown hydrogen	Gasification/steam reforming	Coal	Commercial (TRL 9)	High	High	Medium
Green hydrogen	Gasification, fermentation/electrolysis	Renewable sources (biomass)/electricity from solar or wind energy	Commercial (TRL 9)	Low	Low	High
White hydrogen	Electrolysis/thermolysis	Water	Industrial scale (TRL 8–9)	Low	Low	High
Aquamarine hydrogen	Pyrolysis	Natural gas	Research and development (TRL 3–4)	Low	Medium	Medium

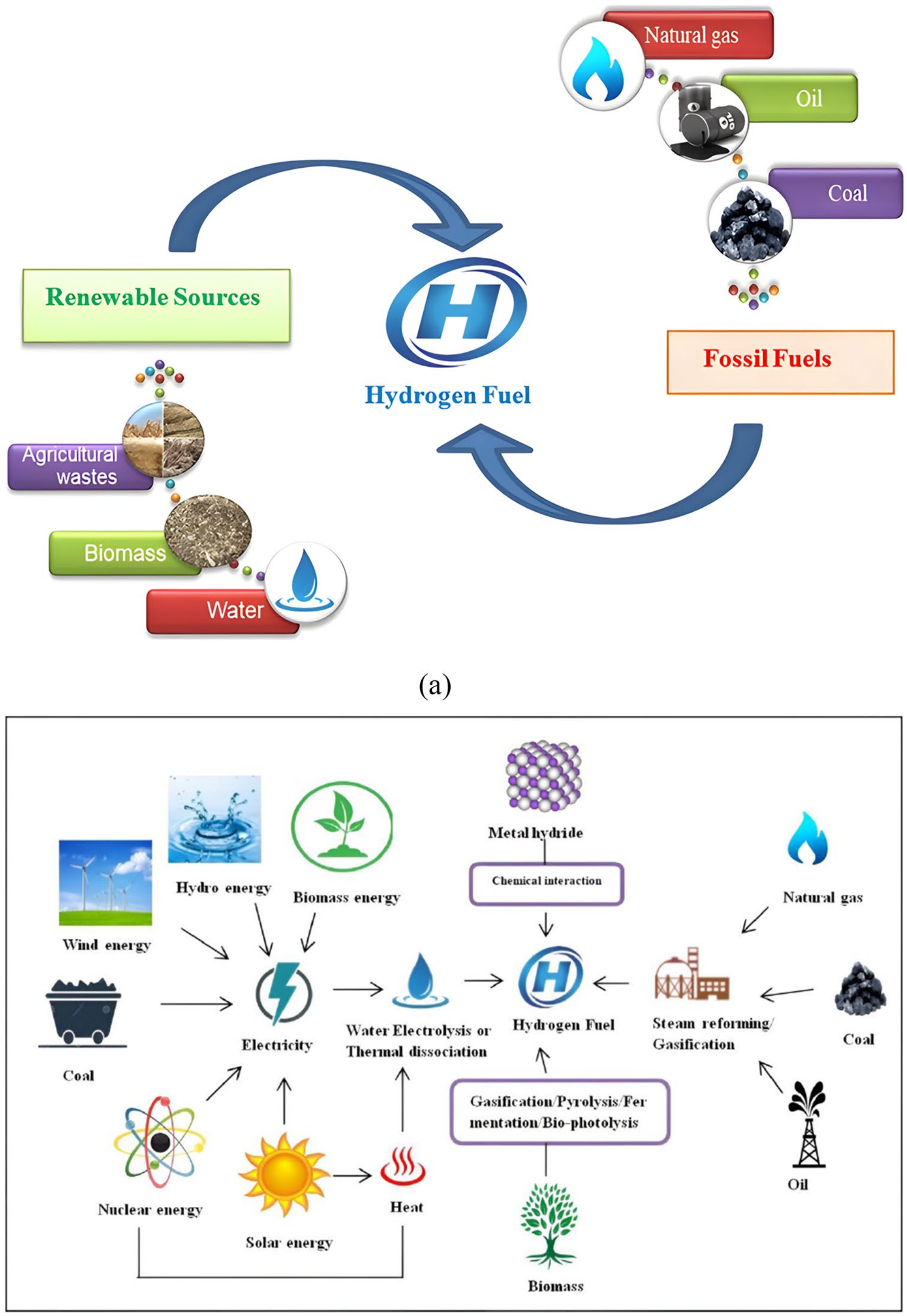


Fig. 1 **a** Types of feedstock for hydrogen production. **b** A schematic diagram of different technologies using various feedstock for hydrogen production

Steam reforming

Steam reformation is the most effective and affordable method for industrial-scale hydrogen synthesis. It accounts for 48% of the hydrogen produced globally (Medisetty et al. 2020). Numerous studies have been conducted on steam-reforming methane, propane, acetic acid, gasoline, toluene, ethanol, glycerol, and methanol (Basu and Pradhan 2019). Since the previous three decades, ethanol and methanol have been steam reformed to produce hydrogen. Steam reformation of methane makes most of the hydrogen production (Singh et al. 2018). Steam methane reformation (SMR) is a well-established route for producing hydrogen and is not a new invention. Its primary energy source is already existing natural gas, which is retrieved from the planet's crust. This technology

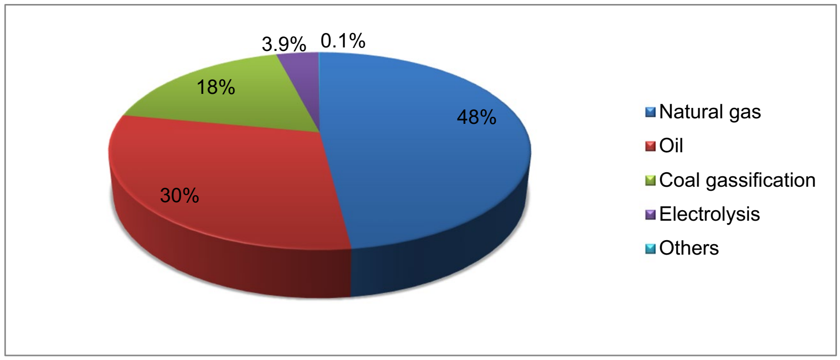


Fig. 2 Share of different sources for global hydrogen production

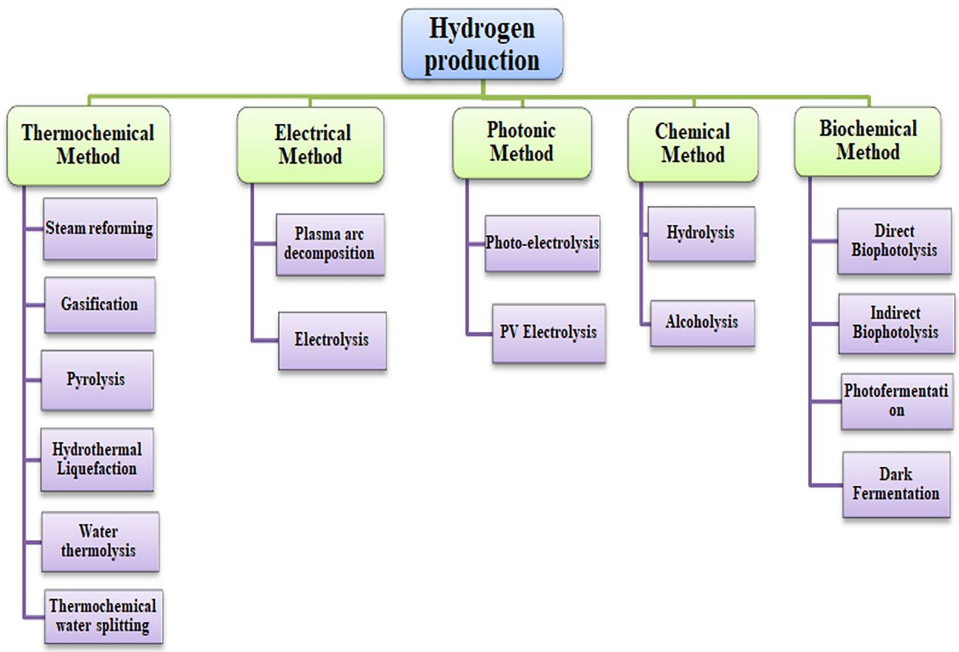


Fig. 3 Classification of hydrogen production method

underpins about 96% of hydrogen production in the USA. Methane is a component of natural gas, and when mixed with steam, it can be converted to hydrogen through thermal processes via partial oxidation and steam methane reformation. In this method, methane (CH_4) interacts with steam at high pressure (0.3–2.5 MPa), high temperature (700–1000°C), and a catalyst to generate a mixture of hydrogen, carbon monoxide, and carbon dioxide. Over a catalyst, additional carbon monoxide (CO) and steam interact to produce carbon dioxide and more hydrogen gas. A process that further extracts carbon dioxide and some other contaminants from the produced gas mixture to achieve pure hydrogen is referred to as pressure swing adsorption. Some catalysts reliant on nickel (Ni) are primarily required to conduct such processes. The process of steam reforming involves the following chemical reactions (Pareek et al. 2020):

Reforming reactions (Pareek et al. 2020):

$$CH_4 + H_2O \rightarrow CO + 3H_2 \Delta H = +206 \text{kJ/mol} \quad (1)$$

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

Methanol conversion also produces hydrogen through steam reformation and methanol decomposition. It entails dehydrating methyl alcohol to yield methyl formate, hydrogen, and formic acid at low temperatures. The intermediates, formic acid, and methyl format break down at high temperatures to produce carbon monoxide and hydrogen (Cai et al. 2020).

The primary source of hydrogen production in the commercial sector is the SMR approach. This method is highly favored since it guarantees that industrial hydrogen generation will economically meet all the needs. Compared to approaches that depend on gasoline, emissions of GHG are also significantly lower. This method's primary drawback is that it depends on diminishing fossil fuel reserves (Pareek et al. 2020), and the requirement of higher-temperature steam for its operation could be more economical.

Gasification

A further significant method of producing hydrogen is gasification (Pareek et al. 2020). In this process, syngas is created by partially oxidizing a carbon-rich feedstock with steam or a small amount of oxygen at a temperature between 900 and 1200°C. Syngas are a combination of gases, primarily carbon dioxide, methane, carbon monoxide, and hydrogen (Swetha et al. 2021). The gaseous mixture engages in the shift reaction with steam following cooling, cleaning, and desulfurization. After that, a significant portion of the CO gas is transformed into carbon dioxide and hydrogen gases. Ultimately, pressure swing adsorption is used to obtain pure hydrogen (Zhang et al. 2021a). The following equations can be used to describe the reactions that took place throughout this process:

$$2C + O_2 + H_2 \rightarrow H_2 + 2CO \tag{3}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{4}$$

Biomass gasification has long been regarded as one of the most important methods for producing hydrogen because of its immense potential aspects and myriad cutting-edge prospective applications. Along with other wastes like rice husk, wheat stalks, and wood chips, wood is the most prevalent feedstock. Technological advances for the gasification processing of biomass materials such as sugarcane bagasse, paper waste, food scraps, wood chips, branches of palm oil trees, and wastewater sludge have emerged due to various research initiatives (Medisetty et al. 2020). However, the biomass gasification operating circumstances, such as flowing steam temperature and the kind of biomass feedstock, all significantly impact the hydrogen output, which is a serious issue (Martino et al. 2021).

Biomass gasification is more complex than coal gasification and produces additional undesired hydrocarbon molecules as a by-product, which presents the biggest obstacle to this technique. Hence, other processes are needed to use a catalyst to convert these hydrocarbons into pure syngas (Pareek et al. 2020). Currently, catalysts are frequently used to gasify biomass, lowering the temperature, and speeding up the middle stages of gasification. Hydrogen is produced from biomass materials primarily through gasification, which involves mainly three steps: biomass gasification, catalytic reforming of syngas, and hydrogen extraction and purification (Singh Siwal et al. 2020).

The inability to use biomass material with a high percentage of moisture is one of the primary issues with conventional gasification (Martino et al. 2021). The supercritical water gasification (SCWG) method for producing hydrogen was first suggested in the middle of the 1970s. A series of complicated thermochemical processes, including hydrolysis, pyrolysis, condensation, as well as dehydrogenation, transform biomass under supercritical water into carbon monoxide, carbon dioxide, hydrogen, methane, and some other gases; this method also does not involve drying and can use less energy (Wang et al. 2019). Since the chemical reaction occurs in the water phase, supercritical water gasification allows for directly utilizing biomass without drying. The gasification efficiency approaches 99% at 700°C temperature, 15 min of reaction time, and 3% of biomass concentration, according to an experimental investigation on maize stalk supercritical water gasification that was conducted in the temperature ranges of 500–800°C, 1–15 min of reaction time, and 1–9% feedstock concentration (Wang et al. 2020). Increasing the temperature in hydrothermal gasification promotes hydrogen production since the water–gas shift and steam-reforming reactions are accelerated (Zeng and Shimizu 2021).

Pyrolysis

Another interesting method for producing hydrogen is pyrolysis or co-pyrolysis (Qureshi et al. 2023). It is characterized as a thermal degrading process that produces solid char, liquid oil, and gaseous mixture from a solid feedstock like coal or biomass without using an oxidizing factor (Jaffar et al. 2020). It is recognized as one of the cleaner techniques that help reduce landfill usage, reduce carbon emissions, and improve enterprise waste handling (Chai et al. 2021). However, compared to fossil fuels, pyrolysis biofuels can cut carbon emissions by 95% (Mardoyan and Braun 2015). Dioxin development can be eliminated because the process occurs without air or oxygen. There would not be any carbon dioxide (CO_2) or carbon monoxide (CO) generation in the lack of air or water, eliminating the need for secondary reactors.

Consequently, this method of producing hydrogen reduces emissions. However, there will be considerable COx emission when air or moisture is present (i.e., when the feedstocks are not dry). Nevertheless, this method has several advantages, including fuel versatility, clean carbon by-products, decreased COx pollutants, and comparative flexibility and compactness. Equation (5) describes the chemical reaction for this method (Agyekum et al. 2022):

$$C_nH_m + Heat \rightarrow nC + 0.5mH_2 \tag{5}$$

One of the vital methods frequently employed for coal transformation is pyrolysis. To thermally disintegrate the materials, this irreversible process is carried out at high temperatures with inert pressures (Medisetty et al. 2020). The three main categories of pyrolysis are traditional or slow, flash, and fast. Each category differs in terms of heating rate, operating temperature, and retention time, which impacts the range of products produced (Chai et al. 2021). In addition to volatile matters, moisture, and char, the pyrolysis of biomass output produced a combination of gaseous components, including hydrogen, carbon monoxide, and carbon dioxide (Bakhtyari et al. 2017). The potentially more significant syngas output can be made through the flash pyrolysis process at elevated temperatures. In contrast, slow pyrolysis can only produce bio-gas at a rate of approximately 10–35%. To favor an approximated 80% production efficacy of the gaseous yield, flash pyrolysis is often carried out at temperatures greater than 650°C with contact periods of less than 1 s (Tursi 2019). One of the difficulties with this technology is the potential for clogging from the generated carbon, but its supporters believe it can be addressed with the right design. Furthermore, given its capacity to lower carbon monoxide and carbon dioxide emissions and its potential to be used in a manner that recovers a substantial amount of solid carbon, pyrolysis could serve an important role in creating hydrogen (Agyekum et al. 2022).

Hydrothermal liquefaction

Hydrothermal liquefaction is another technique for converting biomass into valuable products, including hydrogen. Because hydrothermal liquefaction may be carried out in either supercritical or subcritical water media, the process avoids the need for dry feedstock. It is ideal for numerous biomass feedstock with large amounts of moisture (Kumar et al. 2018). Good gasification efficacy and H_2 selectivity are displayed by hydrothermal liquefaction, which speeds up the generation of cleaner gaseous fuels and reduces the development of chars and tars (Kipçak and Akgün 2015). The critical pressures (P_c) and temperatures (T_c) for water gasification are 22.1 MPa and 374 °C, respectively, and they function identically to high-temperature gasification systems and catalytic gasification processes. Outside the critical point, changes in temperature and pressure encourage the transformation of supercritical water's liquid-like density into its gas-like density without affecting the phase (Susanti et al. 2014). Water-soluble components in biomass are dispersed into the water at a temperature of 100 °C to begin the hydrothermal liquefaction, which hydrolyzes at a temperature of at least 150 °C. Once the temperature hits 200 °C with 1 MPa, biomass's hemicellulosic and cellulosic constituents break into their monomeric chains to generate a slurry (Chai et al. 2021). Due to the increased proportions of hydroxide (OH^-) and hydronium (H_3O^+) ions in subcritical and near-critical zones, water can operate as an acid or base catalyst. Since the solvation capacity in the supercritical zone is poorer than in the subcritical zone, these ions can potentially cause serious corrosion at large concentrations (Susanti et al. 2014). Water assists in the hydrolysis reaction that can be understood via the following reactions:

$$A - B(Reactant) + H - OH(water) \rightarrow A - H + B - OH \tag{6}$$

The hydrothermal liquefaction process generally consists of three stages: biomass depolymerization, breakdown of biomass monomers, and re-condensation process of reactive intermediates (Miyata et al. 2018). The outcome of the hydrothermal liquefaction process is a liquid substance termed bio-crude or bio-oil. The acquired bio-oil is then reformated to extract the hydrogen created by the syngas. Compared to the direct gasification technique, bio-oil reformation has a lesser operational temperature, which reduces energy inputs. The hydrothermal liquefaction of cellulosic material usually requires bio-oil extraction and reformation, synthesis gas cleansing, and water–gas shift reactions (Kumar et al. 2019), and ultimately hydrogen purification to produce biohydrogen (Maroušek 2022).

Water thermolysis

Water thermolysis is the single-stage thermal disintegration of water, and it can be expressed as.

$$H_2O \overset{heat}{\rightarrow} H_2 + \frac{1}{2}O_2 \tag{7}$$

For the reaction to dissociate to a decent degree (for example, 3000 K for 64% disintegration at 100 kPa), an elevated temperature heat supply above 2500 K is necessary. One disadvantage of this procedure is the requirement for an efficient method to isolate hydrogen and oxygen to prevent the formation of an explosive combination. This can be accomplished by using semi-permeable membranes made of ZrO_2 and some other high-temperature compounds up to 2500 K. Separation is also possible following the quenching of the resultant gas combination to a lower temperature (Dincer 2011). However, achieving such a high temperature is neither economically viable nor eco-friendly due to using conventional fuel sources. Hence, renewable energy can be harnessed in the form of solar energy.

Employing water to produce hydrogen solar energy-based thermolysis involves employing a solar concentrator system to directly capture solar radiation to boil water to 2500 K, where it breaks down into hydrogen and oxygen gas. This method converts 90% of solar energy into elevated-temperature thermal energy (Wang et al. 2019). As a measure of the effectiveness of thermochemical water splitting, the energy flow from thermal power input to hydrogen fuel can be expressed as

$$\eta = m_{H_2} HHV_{H_2} / P_t \tag{8}$$

Approximately 45% of solar power can be converted into hydrogen fuel energy, up from a possible 50% more than 10 years ago (Boretti 2021). However, there are issues with this strategy. The main ones are effectively separating hydrogen and oxygen at high temperatures and reaching a high temperature using a solar concentrator system. To solve these issues, a researcher suggested using catalysts in water, which would enable the dissociation of water in several stages while significantly lowering the necessary heating temperature (Wang et al. 2019). In an experiment, a researcher used solar energy to study water thermolysis. The findings suggest that 1 ms is the retention time in the furnace needed to reach 90% of the stability at 2500 K. If the produced gas mixture is quickly chilled by quenching via a dramatic temperature fall of 1500–2000 K within few milliseconds, recombining of oxygen and hydrogen can be prevented. Then, for efficient hydrogen separation, palladium membranes may be employed (Dincer 2011). However, this method is more complex due to the utilization of high temperatures, which requires costly infrastructure for its operation.

Thermochemical water splitting

Only at higher temperatures (over 2000 °C) can completely disintegrate water in a single-stage process. In contrast, thermochemical cycles, which need numerous steps and operate at lower temperatures, can provide the necessary heat (Mehrpooya and Habibi 2020). Thermochemical procedures work at a temperature range of 400–900°C to produce hydrogen gas by chemical reactions. Nuclear reactors or solar concentrators could serve as the origin of the heat. Each cycle involves the recycling of chemicals, resulting in a closed-loop chemical operation that uses only water to produce hydrogen. When water is disintegrated into oxygen and hydrogen using thermochemical water splitting, chemical operations are conducted at a high temperature. By utilizing this method, hydrogen may be produced effectively and affordably. However, it can still not enter the commercial market (Pareek et al. 2020). The sulfur/iodine cycle involves the following chemical reactions, which can easily be understood by the given Fig. 4.

$$H_2SO_4(850°C) \rightarrow SO_2 + H_2O + \frac{1}{2}O_2 \tag{9}$$

$$I_2(120°C) + SO_2 + 2H_2O \rightarrow H_2SO_4 + 2HI \tag{10}$$

$$2HI(450°C) \rightarrow H_2 + I_2 \tag{11}$$

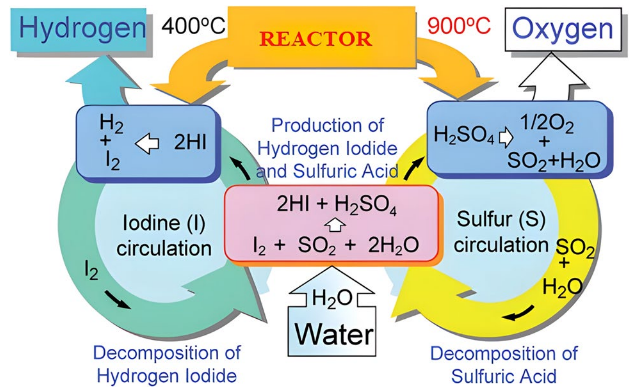


Fig. 4 A schematic of a thermochemical water-splitting cycle using iodine and sulfur (Onuki et al. 2009)

This technology is appropriate for centralized, large-scale hydrogen production. Utilizing the approach, as mentioned above, has the benefit of producing clean, pure hydrogen gas with no greenhouse gas emissions. This technology must improve nuclear reactor expertise to make heat at low temperatures while lowering the price of solar concentrator systems and heat conduction media (Pareek et al. 2020).

Electrical method

In this methodology, electrical energy is utilized to dissociate hydrogen-containing substances. Electrical power can be obtained from fossil fuels (coal, oil, etc.) or non-conventional sources (wind, solar, biomass, water, etc.). However, electricity generation from non-conventional sources is a bit costlier than traditional sources in recent times, but it is environmentally friendly and free from harmful emissions. Some technologies that utilize electrical energy are described below.

Plasma arc decomposition

Plasma is an ionized material of excited electrons and other atomic species. Plasma is a suitable carrier for high-voltage electrical power discharge because it contains particles with electrical charges. Using thermal plasma can cause the decomposition of natural gas, primarily methane gas. Ionized molecules and electrons in thermal plasma have the characteristic of existing within a similar thermodynamic temperature. Methane splits into hydrogen and ash/carbon black when it passes over a plasma arc. Unlike hydrogen, which remains in the gaseous form, carbon black could be gathered at the bottom as soot (Dincer 2011).

The following Eq. (12) describes how natural gas (CH_4) breaks down into carbon and hydrogen atoms:

$$CH_4 \rightarrow C + 2H_2(g)\Delta H = 74.6 MJ/kmol \quad (12)$$

Researchers used a reactor with three electrodes attached to a three-phase voltage to conduct a reaction under a high-temperature thermal plasma. Plasma gas was injected into two of the electrodes, and methane was supplied into the reactor from the above. As a result, the reactor's bottom has formed carbon black while releasing no carbon dioxide, and hydrogen fuel production has been 100%. In actuality, plasma disintegration is a pyrolysis mechanism at high temperatures. According to the analysis, compared to large-scale hydrogen production using steam reforming of methane with carbon dioxide extraction, the price of hydrogen produced via plasma cracking is lowered by at least 5% (Dincer 2011). Wu et al. (2023) investigated plasma-bubbled hydrogen production through methanol and found a 63.21% hydrogen and 26.38% carbon monoxide content. Furthermore, this plasma technique was suitable for hydrogen production using concentrated methanol (Wu et al. 2023). Although the hydrogen yield in a microwave plasma reactor depends on the flow rate and feed concentration, it can reach up to 50% in a gliding arc plasma reactor that uses a methane and ethanol–water mixture pathway with optimal oxygen/carbon ratio values and residence time. Consequently, all reactors can potentially produce hydrogen with less energy input (Budhraja et al. 2023).

Electrolysis

The most well-established commercially available method for hydrogen gas from water is electrolysis. The method of separating water into its parts, hydrogen, and oxygen, using an electric current is known as water electrolysis (Chakraborty et al. 2022). An aqueous solution comprising a KOH electrolyte is often utilized with two electrodes (anode and cathode). This equipment is termed an electrolyzer (Yuvaraj and Santhanaraj 2014). Electric current causes positive ions (H^+) to be pulled to the cathode while negatively charged ions (OH^-) are drawn to the anode (Chi and Yu 2018).

An electrolyzer may be small or massive depending on how much hydrogen is produced on a small or large scale (Kovacova and Lăzăroiu 2021). Therefore, distributed hydrogen generation is appropriate for this technique (Durana et al. 2021). Depending on the resource employed to make electricity to separate the water molecules, the electrolysis mechanism can produce hydrogen with absolutely no greenhouse gas emissions. Electrolysis requires almost 40.4 kW of energy to produce 1 kg of hydrogen (Hodges et al. 2022). As a result, scientists are focusing on nuclear or wind energy as potential energy replacements for electrolyzers. Using such an energy source is anticipated to lower the cost of transmitting electrical power. The following equations can be used to describe the reaction that occurs during electrolysis (Yuvaraj and Santhanaraj 2014):

$$Electrolyte : 4H_2O \rightarrow 4H^+ + 4OH^- \quad (13)$$

$$Cathode : 4H^+4e^- \rightarrow 2H_2 \quad (14)$$

$$Anode : 4OH^- \rightarrow O_2 + 2H_2O + 4e^- \quad (15)$$

$$Overall 2H_2O \rightarrow O_2 + 2H_2 \quad (16)$$

Some water electrolysis techniques include proton exchange membrane (PEM) water electrolysis, alkaline water electrolysis (AEL), alkaline anion exchange membrane (AEM) water electrolysis, and solid oxide water electrolysis (SOE) (Chi and Yu 2018). Water electrolysis methods dominate all other technologies because of the downward cost tendency, high purity, and lack of undesired impurities, including sulfate and carbon oxides (Dawood et al. 2019). However, the potential of electrolysis on a worldwide scale is currently constrained. The practical application of electrolysis requires much energy (Liu et al. 2020) and comes at a significant cost (da Silva Veras et al. 2017).

Photonic method

Hydrogen fuel can be generated using photon energy directly from solar radiation or a photovoltaic system that generates electricity from semiconductor material. Under UV and sunlight, the photonic band gap (PBG) of Au/TiO_2 catalyst changes into the electronic band gap (EBG), resulting in a notable increase in hydrogen production. In addition, these highly active catalysts require low process costs, are simple to use, and are stable, making them ideal candidates for direct applications (Waterhouse et al. 2013). Despite being eco-friendly, these methodologies require expensive infrastructure for their operation, affecting the economics of produced fuel, and the intermittent nature of solar energy also affects its smooth operation. There has yet to be an efficient method of converting photonic energy into electrical energy. Only 15% of solar energy is converted to electricity by photovoltaic systems. Some technologies that utilize photonic energy are described below.

Photo-electrolysis disintegration of water

In photo-electrolysis, hydrogen is produced using two of the most plentiful renewable resources: sunlight and water (Kim et al. 2019). It entails applying heterogeneous photocatalysts to a single electrode exposed to sunlight (Dincer 2011). In most cases, two electrodes are employed, one serving as an anode to produce oxygen and the other as a cathode to make hydrogen (Kim et al. 2019). In addition, the electrodes of the electrolysis cell are provided with an electrical energy supply. Photonic radiation has the effect of reducing the amount of electrical energy needed (Dincer 2011). Sunlight is absorbed by the cell's photo-anode, which causes the semiconductors at the anode to produce electrons. The cathode then has hydrogen because these electrons are delivered to it through an external current (Wang et al. 2019).

The photo-electrochemical cell, a more advanced adaptation of photo-electrolysis, consists of counter-electrodes and photosensitive semiconductors submerged in an electrolyte. The semiconductor functions similarly to a photovoltaic cell by splitting electron–hole pairs produced by photons with energies higher than the semiconductor bandgap energy using an electric field that travels through the electrolyte. One of its significant advantages is that the photo-electrochemical cell combines water electrolysis and solar power absorption into one functional system. As a result, the device is more compact because it does not need a separate electrolyzer and solar power converter (such as a PV cell). The technique is still in development, but it has a laboratory efficiency of roughly 18% (Dincer 2011). The commercial potential of this innovation is still in its infancy. Therefore, it is necessary to perform an intensive study to choose the best semiconductor with excellent electrolyte stability and appropriate band-edge positioning. Reactor design is another crucial element that requires scientists' and engineers' focused attention to address several issues with the fabrication and application of an optimum configuration (Pareek et al. 2020). Since water erodes the electrodes, PEC (photoelectrochemical cell) experiments conducted up to this point have demonstrated that their lifespan is short. Numerous types of photosensitive semiconductor-based electrodes have been studied, with titanium dioxide (TiO_2) being considered one of the most viable among others. Among the various types are strontium titanate, tantalum oxynitride, sodium hydroxide, carbonate oxides, cadmium sulfide, and other titanates and niobates (Dincer 2011).

PV electrolysis

A PV electrolysis system only differs from an electrolysis unit in that it generates its electric current using solar panels. It consists of accumulator batteries, an electrolyzer, hydrogen storage cylinders, a DC bus bar, an AC grid, and PV modules. As a result, this technology can deliver consistent and dependable electricity within a specific range, making up for the low reliability brought on by frequent inconsistency of solar power production (Wang et al. 2019).

Approximately 15% of the sun's energy captured is used to generate power using solar photovoltaic technology. The electrolyzer's efficiency, or the ratio of the flow of hydrogen fuel energy to the input of electric power,

$$\eta = m_{H_2} HHV_{H_2} / P_e \quad (17)$$

is substantially below 80%. Ultimately, less than 12% of the total solar energy captured is converted into hydrogen energy. Furthermore, it is unreasonable to convert solar energy into electricity, hydrogen, then back into electric energy in fuel cells, all while incurring additional costs for each conversion (fuel cell efficiency for converting extra hydrogen energy to electric power is less than 60%). It is plagued by the underlying sustainability issues brought on by excessive energy conversions (Boretti 2021).

Water can be electrolyzed using a variety of methods, including alkaline water electrolysis technique, solid oxide electrolysis, alkaline anion exchange membrane (AEM) electrolysis, and proton exchange membrane (PEM) electrolysis (Chi and Yu 2018), as discussed earlier. The Chinese Academy of Sciences and Dalian Institute of Chemical Physics have successfully established alkaline water electrolysis as part of a pilot demonstration project, with a maximum energy efficiency of 88%. Electrolyzing coal slurry to make hydrogen is better than electrolyzing water, regarding how much energy is used and how well it works. This technology deserves expansion and development since it can simultaneously purify the ore throughout the electrolysis process. It is also thought that using AEM water electrolysis will make it possible to use transition metals instead of expensive noble metal electro-catalysts like platinum, iridium, ruthenium, and palladium. The AEM electrolysis method has drawn particular interest despite being a recent technology (Vincent and Bessarabov 2018) due to its excellent energy efficiency (Yao et al. 2022), membrane consistency, strength, simplicity of handling, and reduced hydrogen generation technique (Vincent and Bessarabov 2018). In addition to expensive metal electrodes, another obstacle to producing hydrogen gas from water electrolysis is the significant energy consumption due to the rise in electrolysis voltage brought on by the bubbles produced during the electrolysis of water (Hu et al. 2019). Energy consumption can be decreased by adding hydrocarbons to water electrolysis. Future electrodes will likely be made of affordable metals or non-metallic composite elements like Ni. Moreover, future research should concentrate on the technique for expelling gas bubbles (Zhang et al. 2021a).

Chemical method

There is a chemical interaction between various chemical compounds (e.g., metals and their hydrides and borohydride) and a solvent (for example, water, ethanol, methanol, propanol, and butanol). In chemical reactions, significant amounts of hydrogen gas are released. Since this method does not require heat or energy, it is better for use outdoors. It can be classified as two main processes depending on the solvent, as follows.

Hydrolysis

Hydrolysis is an effective process for producing hydrogen on demand due to its excellent conversion effectiveness (Ma et al. 2020), high purity hydrogen, environmentally friendly by-products, and precisely regulated hydrogen discharge (Chen et al. 2019). In this technology, hydrogen can be produced through hydrolysis of light metal-based compounds, such as borohydrides ($LiBH_4$, $NaBH_4$, etc.), magnesium (Mg)-based, and aluminum (Al)-based materials. Regrettably, most of these hydrolysable resources exhibit slow kinetics and little hydrogen production. Several approaches, including as alloying, solution modification, ball milling, and catalysis, have been developed to address these issues. The significant expenses associated with hydrolysis/alcoholysis systems in "one-pass" have finally made these approaches virtually unusable for large-scale, practical applications (Ouyang et al. 2021). Lithium borohydride ($LiBH_4$) (Chen et al. 2022) and sodium borohydride ($NaBH_4$) are considered outstanding hydrogen (H_2)-producing materials (Zhu et al. 2020). However, it is irreversible hydrolysis and expensive regeneration costs prevent their widespread use (Ouyang et al. 2017). Therefore, it is crucial to create inexpensive material systems that utilize plentiful resources and efficient spent fuel recycling technologies to manufacture, store, and transport hydrogen effectively (Ouyang et al. 2021).

In recent years, metals that are readily available and affordable (such as magnesium, aluminum, and their hydrides) have attracted increased interest as hydrolysable substances for hydrogen production (Ma et al. 2020). Because there is a plentiful supply in the earth's crust and the industry has developed a sophisticated recycling mechanism, hydrogen supply from light-metal elements is economical and sustainable compared to expensive borohydrides (Ouyang et al. 2021). Metal or metal hydride hydrolysis is a strongly exothermic procedure that produces 1.5 mol of hydrogen and 437 kJ of heat for every mol of aluminum (Al) hydrolyzed. Similarly, 1 mol of Mg hydrolyzed produces 1 mol of hydrogen and 354 kJ of heat (Ouyang et al. 2021). Due to their low cost, wide industrial availability, great theoretical hydrogen yield (Mg 8.3 wt% and MgH_2 15.2 wt%), and capacity to produce harmless by-products throughout hydrolysis, magnesium and magnesium hydride are appealing possibilities for hydrogen generation via hydrolysis. Unfortunately, due to the quick interruption of the hydrolysis of magnesium into magnesium hydroxide and the production of a passive magnesium hydroxide ($Mg(OH)_2$) layer that is built on the surface of substrate materials, which inhibits water from diffusing to the interior particles, the hydrolysis of magnesium into magnesium hydroxide has poor kinetics (Tan et al. 2018). Recently, a number of efficient techniques have been developed to enhance the hydrolysis capabilities of Mg-based materials, including ball milling, altering the composition of the aqueous solution, alloying, and catalyst loading. The hydrolysis kinetics of Mg/MgH_2 have been effectively accelerated by customizing the composition of solutions, such as the addition of organic/inorganic acids or saline solutions. However, the addition of salt or acid may be detrimental to the environment and damage equipment (Ma et al. 2020).

Alcoholysis

Since hydrolysis makes it possible to extract hydrogen from liquid water, the reaction's performance depends on the operating temperature. In low-temperature environments, the rate of hydrogen production will be significantly reduced; in icy environments, the hydrolysis process may even directly freeze (Ouyang et al. 2021). Compared to hydrolysis in water media, the hydrogen supply from alcoholysis exhibits its outstanding potential for outside applications because it eliminates the bottleneck of temperature in which hydrolysis happens over 0°C and bypasses the creation of passivation layers laid down on particle surfaces (Ma et al. 2020). These favorable characteristics make it desirable to deliver hydrogen with immediate effect (Chen et al. 2022).

Using methanol as an alternate solvent in alcoholysis to deliver hydrogen, a general reaction allows for the synthesis of hydrogen at extremely low temperatures (Ma et al. 2020). Since methanol has an extremely low freezing temperature (− 97 °C), methanolysis is thought to produce hydrogen most efficiently in places with low temperatures or below zero (Ouyang et al. 2021). A research group demonstrated the hydrogen-producing potential of magnesium and their hydride (Mg/MgH_2) at room temperature, in ethanol, methanol, and isopropanol. According to their findings, Mg alloy can release hydrogen into a methanol solution, although methanolysis of MgH_2 virtually never produces hydrogen. At room temperature, the conversion rate of magnesium after 0.5 h of ball milling can reach 47% in 40 min. The objective of producing hydrogen with a great energy effectiveness at lower temperatures (< 0°C) was not met. However, the hydrolysis kinetics of Mg/MgH_2 can be considerably improved by doping Ca or CaH_2 (Ma et al. 2020). According to a study, even at temperatures as low as − − 10 to 20°C, hydrogen extraction from $NaBH_4$ material in ethylene glycol/water solutions with the addition of a $CoCl_2$ catalyst may be promptly launched, completing 100% of the conversion of fuel in just a few minutes (Ouyang et al. 2021).

Biochemical method

Due to their low-energy requirement (lower operating temperature) and negligible gaseous pollutants, NOx and SOx emission (Cheng et al. 2020), biological processes provide a more promising and sustainable hydrogen generation method from organic waste than thermochemical, electrical, photonic, and chemical methods (Foong et al. 2020). This procedure combines the disposal of carbohydrate-rich human-derived trash with the metabolic reaction of microbes that release hydrogen (Kothari et al. 2012). Nitrogenase and hydrogenase are two essential enzymes bacteria use as catalysts in biochemical processes that transform organic matter and water molecules into hydrogen (Krishnan et al. 2023). However, there are a number of insurmountable challenges to using microorganisms as biocatalysts throughout the biochemical hydrogen generation, including a slow bioprocess, strict growth conditions, concurrent by-product generation, and low hydrogen output. Although biochemical hydrogen production obtained tremendous scientific interest around 4 decades ago, it has not yet been successfully commercialized (Chai et al. 2021). It is classified into the following four main types.

Direct bio-photolysis

Direct bio-photolysis is a photochemical reaction in which a biological system is exposed to photons, and a water molecule splits (Zhang et al. 2021b), as shown in reaction (18) given below. Green algae are especially effective at turning water into hydrogen gas because of their photosynthetic process and hydrogenase. The hydrogen ion generated as a consequence is employed to generate hydrogen gas. The main difficulty with this approach is the oxygen-induced breakdown of the enzyme hydrogenase. Enzyme degradation can be reduced using a two-stage separation technique (Dhanya et al. 2020).

$$2H_2O + 'lightenergy' \rightarrow 2H_2 + O_2 \quad (18)$$

Algae perform the photosynthetic pathway to break water molecules into hydrogen ions (H^+) and oxygen. The "hydrogenase enzyme" transforms the produced hydrogen ion into H_2 gas. One of the widespread algae that produce hydrogen is *Chlamydomonas reinhardtii*. Numerous green algae, including *Scenedesmus obliquus*, *Chlorella fusca*, *Platymonas subcordiformis*, and *Chlorococcum littorale*, have also been found to have hydrogenase activity. Using water (H_2O) molecules as a cheap and plentiful reactant is a benefit of the current approach. Numerous studies have been conducted employing microalgae to increase the efficiency of biohydrogen production (Fakhimi and Tavakoli 2019). By comparing the dark fermentation process to biophotolysis of water using algae, the latter is one of the more environmentally and economically viable approaches (De Bhowmick et al. 2019).

Three problems generally prevent green algae from producing enough hydrogen through direct photolysis: (i) the photosynthetic reactor's efficiency to convert solar energy; (ii) hydrogen production strategies (i.e., the requirement to distinguish between procedures involving water oxidation and procedures involving hydrogen production) (Pareek et al. 2020); and (iii) configurations of bioreactors and their cost (Stávková and Maroušek 2021). Nevertheless, there are several ways to increase hydrogen generation from green algae. Some of them are genetic engineering of the light-capturing antennae, optimization of input light into photo-bioreactor systems, and advancement of the two-phase hydrogen generation systems employed with green algae. Direct bio-photolysis has been reported to produce hydrogen at rates of 0.07 mmol/h L in the literature (Pareek et al. 2020).

Indirect bio-photolysis

Since the formed hydrogen is segregated from the oxygen in this form of photolysis, the hydrogenase enzyme's activity does not need to be inhibited (Dhanya et al. 2020). The sensitivity issue with the hydrogen growing process may be resolved by spatially and temporally splitting oxygen evolution from hydrogen evolution. As a result, indirect bio-photolysis procedures entail stage-by-stage isolation of the hydrogen and oxygen evolution operations and coupling them via carbon dioxide fixation/evolution (Pareek et al. 2020). The most favored resource for indirect biophotolysis systems is cyanobacteria and blue-green algae (Dhanya et al. 2020). The distinctive properties of cyanobacteria include their use of sunlight as a source of energy and carbon dioxide in the atmospheric air as a source of carbon. The cells absorb carbon dioxide to create cellular components, which are then used to create hydrogen. The following reactions can be used to illustrate the general mechanism of hydrogen synthesis in cyanobacteria (Pareek et al. 2020):

$$H_2O + 6CO_2 + 'lightenergy' \rightarrow C_6H_{12}O_6 + 6O_2 \quad (19)$$

$$C_6H_{12}O_6 + 12H_2O + 'lightenergy' \rightarrow 12H_2 + 6CO_2 \quad (20)$$

Hydrogenase and nitrogenase, two essential enzymes that carry out metabolic processes and aid in hydrogen production, are found in cyanobacteria. Due to their greater hydrogen generation rates, Anabaena genera and variants have been the topic of significant research. For example, the mutant variant of *A. variabilis* has achieved hydrogen production rates of around 0.355 mmol/h L through the indirect bio-photolysis mechanism (Pareek et al. 2020).

Photo-fermentation

Due to the availability of nitrogenase (Nováková et al. 2022) and the consumption of sunlight and reduced chemicals (organic acids) (Rowland et al. 2021), purple non-sulfur microorganisms can produce hydrogen in nitrogen-shortage environments (Pareek et al. 2020). This mechanism can be expressed by the following reaction (Martino et al. 2021):

$$CH_3COOH + 2H_2O + ' lightenergy' \rightarrow 4H_2 + 2CO_2 \Delta GO = +104\text{kJ/mol} \quad (21)$$

The ability of photosynthetic bacteria to produce large yields of hydrogen has long been explored. The benefit of this approach is that oxygen does not prevent the process from happening. These photoheterotrophic microbes have been discovered to convert sunlight into hydrogen gas when organic wastes are used as feedstock. They can do this in batch systems, continuous cultures, or immobilized entire cellular systems using a variety of solid substrates, including carrageenan, polyurethane foam, porous glass, and agar gel. It has been stated that this process can produce hydrogen at rates of 145–160 mmol/h L. Some Rhodospirillaceae superfamily photoheterotrophic bacteria may develop in the dark by using carbon monoxide as their only carbon source to produce ATP while simultaneously releasing hydrogen and carbon dioxide. Using the water gas shift reaction, carbon monoxide is converted to carbon dioxide, and hydrogen is released, as indicated below (Pareek et al. 2020):

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (22)$$

Dark fermentation

Dark fermentative hydrogen production has been regarded as a more practical and efficient approach to producing biological hydrogen (Maroušek et al. 2022). This procedure occurs at atmospheric pressures and temperatures, which use less energy and are better for the environment (Venetsaneas et al. 2009). Organic wastes (Bandgar et al. 2022), waste streams, or agricultural crop residues high in carbohydrates can be employed as substrates in this method because it is widely established that carbohydrate substances are the primary source of hydrogen (Venetsaneas et al. 2009). In the dark fermentation process, anaerobic bacteria like Enterobacter species, Thermoanaerobacterium species, Clostridium species, Ruminococcus species, or Bacillus species produce hydrogen as a by-product of both the acetogenesis and acidogenesis process (Cieciura-w et al. 2020).

For this fermentation method (Maroušek and Gavurová 2022), which typically produces butyric and acetic acids and H_2 gas, carbohydrates, particularly glucose, are the predominant carbon choice. Theoretically, the bioconversion of 1 mol of glucose has 12 mol of H_2 gas. By reaction stoichiometry, bio-decomposition of 1 mol of glucose into butyric acid produces 2 mol hydrogen/mol glucose. In contrast, 4 mol hydrogen/mol glucose is obtained when acetic acid is the final product. The stoichiometry is explained by the equations below (Pareek et al. 2020):

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (23)$$

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2CH_2COOH + 2CO_2 + 2H_2 \quad (24)$$

The most favorable feedstock for bio-hydrogen production from the dark fermentation method is reportedly carbohydrates and sucrose-rich substances (Pareek et al. 2020). *Bacillus paramycoides*, a new strain with great potential for hydrogen production, has produced 4668 ± 120 ppm cumulative hydrogen gas in 96 h of dark fermentation. The metabolic engineering capabilities of *Bacillus paramycoides* facilitate the degradation of abundant biomass wastes, the production of hydrogen energy, and the resolution of global problems associated with waste management (Chua et al. 2023).

The different methodologies mentioned above have several critical challenges, and key benefits, that are described briefly in Table 3, are given below.

Hythane—a recent treading fuel

Hythane, also known as methagen or HCNG, is a blend of methane (CH_4) and hydrogen (H_2). Eden Energy Limited registered this trademark in 2010. Hythane's estimated hydrogen concentration is typically between 10 and 25% of its volume. Hythane is regarded as one of the crucial fuels in facilitating the transformation of technical frameworks from a petroleum fuel-based community to a terminal H_2-based community since it combines the benefits of H_2 and CH_4 fuels. In India and the USA, hythane has been utilized commercially as a vehicle fuel (Liu et al. 2013).

Adding pure H_2 to natural gas is one way to produce hythane. To have hythane with the correct hydrogen-to-methane ratio, two different gas streams with quantitative control of the gas flow rates are needed. Steam methane reforming and syngas production are the primary physical/chemical processes used to manufacture hydrogen. Due to

Table 3 Some critical challenges and key benefits associated with the production methodology of hydrogen (Qureshi et al. 2022b)

Thermochemical method	Electrical method	Photonic method	Chemical method	Biochemical method
Critical challenges				
Design, long-term technology	Higher capital investment	Lower system effectiveness	Higher capital investment	Optimum microbial functionality
High capital investment	Lower system effectiveness	Efficient photo-catalytic material	slow kinetics	Effective inoculum for sustainable production
Durable and practical material, higher operation and maintenance cost, carbon capture and storage, feedstock impurities	System integration,			
complexity with system design	Long-term technology, cost-efficient reactor	Small hydrogen production	Long-term technology, selection of reactor material	
Major R&D needs				
Low-cost and efficient purification	Low-cost electricity	Low-cost materials	Reversible chemical compounds	New organisms
Feedstock pretreatment		Active, stable, and cheap supporting materials	Hydrolysis kinetics of chemical compounds	Inexpensive methods
Automated process control, efficient heat transfer	Storage system required to support intermittency	System control	System optimization	System optimization, cost of feedstock preparation
High-volume, low-cost, flexible system design	Large-scale applications	High-volume production	Small-scale applications	Low-cost and durable material
Reliability	Reliability	Reliability	Reliability	High-capacity and low-cost systems
Key benefits				
Most viable technology	Clean and sustainable	Low operation temperature	No pollution	Clean and sustainable
Lowest current cost	High quality H_2	No pollution	There is no requirement of heat, recycled chemicals	Tolerant to diverse water conditions, self-sustaining
Existing infrastructure	Existing infrastructure	Abundant available and cheap feedstock	High-quality H_2	Abundant and cheap feedstock

their substantial reliance on fossil fuel-based energy, these strategies are typically not sustainable (Liu et al. 2013).

It can be manufactured biologically utilizing biomass (Singh et al. 2022) or organic waste as the feedstock in a two-stage fermentative system. By modifying the parameters of the bacterial fermentation processes, biomethane can be created using this approach with appropriate hydrogen-to-methane ratio. As a result, the synthesis of biohythane by biomass using a two-stage biological fermentative system can be a reliable win–win situation because it produces sustainable biological hythane while also effectively using organic wastes. However, the prospective uses of biohythane have not yet gotten the attention they deserve (Liu et al. 2013).

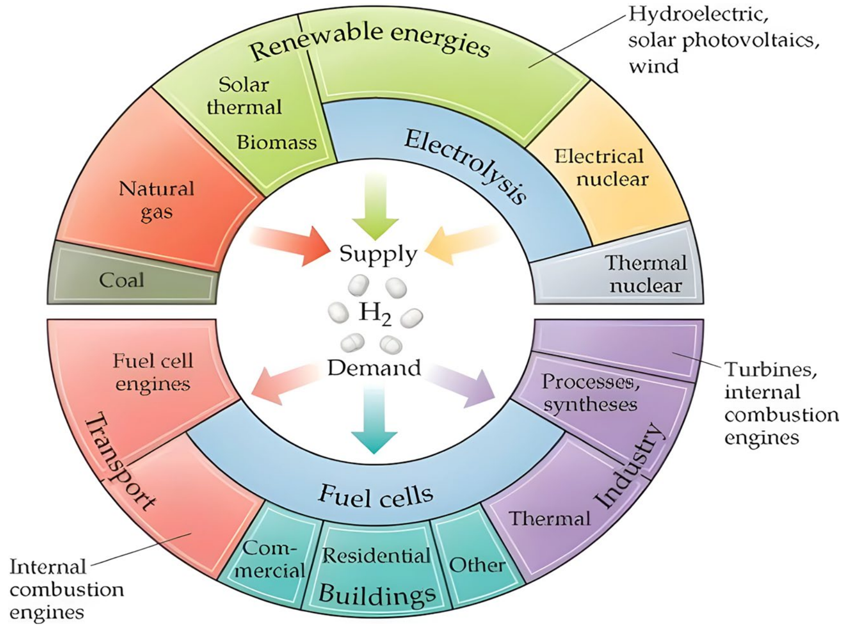
Importance of hythane

Compared to petroleum or diesel, methane (CNG) is considered a cleaner fuel for vehicle use. However, it is constrained by its slow burning rate, limited flammability range, and large ignition temperature, which have a negative impact on combustion efficiency and increase the energy needed to ignite compressed natural gas-powered automobiles. It is interesting to note that hydrogen precisely balances out methane's (CNG) shortcomings: (1) hydrogen is used to enhance the hydrogen-to-carbon ratio, which lowers greenhouse gas emissions; (2) hydrogen can be added to methane to increase its limited range of flammability, increasing fuel economy; (3) with the addition of hydrogen, the flame intensity of CH_4 can be considerably boosted, thus shortening the combustion time and increasing heat efficiency; (4) the inclusion of hydrogen can decrease the quenching length of CH_4, enabling the engine to ignite with lower energy input (Liu et al. 2013).

Applications of hydrogen

Until now, a variety of H_2-based energy infrastructure scenarios have been put out, and in every single one, hydrogen will provide energy for a variety of applications, including

Fig. 5 Different applications of hydrogen fuel (web page: https://schoolbag.info/chemistry/central/206.html)



transportation, industry, and commercial and residential operations (Toledo-alarc et al. 2018), as illustrated in Fig. 5. Instead of being used as a fuel, hydrogen is mainly employed as a chemical. The majority of its present use is as a processing reagent in oil refineries (for example, to desulfurize and improve conventional fossil fuels) and for the manufacturing of chemicals (e.g., methanol, pharmaceuticals, and ammonia) (Dincer 2011). The manufacturing of ammonia uses around 51% of the produced hydrogen, methanol uses 10%, oil refineries use about 31%, and other uses take up the remaining 8% (Qureshi et al. 2022a). Currently, it is anticipated that hydrogen-based electro-mobility will progressively displace the application of fossil fuels (Arregi et al. 2018), with a particular focus on renewable hydrogen, or "green hydrogen" (Iqbal et al. 2021).

Hydrogen is one of the most promising non-traditional fuels for use in automobiles. Defining an appropriate, cost-effective infrastructure remains the primary barrier to widespread adoption (Lahnaoui et al. 2019). To implement the hydrogen transportation plan, a system of hydrogen filling stations across the country is expected to be necessary (Sinigaglia et al. 2017).

The hydrogen-powered fuel cells were identified as the best option and the most popular approach by many researchers as the future fuel for the transportation sector. Hydrogen fuel cells are a promising option for powering the shipping industry. Unfortunately, fuel cell technology is not currently available in this sector. Latapí et al. (2023) examined hydrogen fuel cell applications in the Nordic shipping industry. They found 11 factors limiting its application: high costs, lack of infrastructure, and operational challenges. However, hydrogen could not be used in CI (compression ignition) engines due to its low auto-ignition temperature (858 K) (Medisetty et al. 2020).

Renewable or green hydrogen has the potential to be used in applications for sustainable transportation, such as the powering of fuel-cell electric vehicles (FCEVs), like cars, buses, trains, and trucks, as well as the production of synthetic or artificial fuels for use in airplanes and ships. Fuel cells use chemical reactions to transform fuels rich in H_2 into electricity. Fuel-cell electric vehicles operate almost silently and have no harmful emissions since they power their electric motors with fuel cells rather than batteries (De Blasio et al. 2021).

Hydrogen fuel is one of the best possibilities for conserving renewable energy in the power generation industry, and ammonia (NH_3) and hydrogen can be utilized in gas turbine engines to boost the flexibility of the power system. To cut emissions in coal-fired power stations, ammonia could potentially be used. Furthermore, hydrogen has the potential to replace coke and coal in the manufacturing of steel and iron in industry. One of the significant carbon emitters on the planet is the steel industry; thus, decarbonizing it with hydrogen is anticipated to have a considerable influence on climate targets (National Hydrogen Mission 2022).

Storage methods of hydrogen

Following hydrogen gas production, hydrogen storage is a crucial component that necessitates energy- and cost-efficient arrangements (Jain et al. 2023) for future transportation to maintain relatively high round-trip effectiveness and avoid compression losses. Storage will be required at hydrogen manufacturing plants, electricity generating centers, and refueling stations (Pudukudy et al. 2014). Even though there are many different ways to store hydrogen, the majority of it is kept in salt caves, cryogenic liquid storage, or pressurized gas storage (Hassan et al. 2021). Compressed air storage is the most advanced energy storage type, enabling the energy density needed for mobility operations. Based on its usage, the enhancement in tank durability must be adequately considered in the context of cost, safety, and efficiency. It is currently a significant technological flaw of the H_2 economy when compared to traditional fossil fuels (Pudukudy et al. 2014) because storage of hydrogen at a large scale is one of the minimal carbon technological options designed to counterbalance long-term power fluctuations from solar and wind energy owing to inter-seasonal changes (Spataru et al. 2014).

Hydrogen's harsh compressing, liquefaction process, and combustible and explosive characteristics make storage and transportation challenging. This limits the scope of its application (Zhang et al. 2021a). However, if the gravimetric and volumetric densities necessary for the automotive industry can be achieved, hydrogen might be a significant replacement for exhaustible energy sources. In this way, research in the domains of hydrogen storage and hydrogen economics has advanced during the past few decades. Since hydrogen is a gas, it is not easy to use in mobile applications. In general, three methods (Fig. 6)—compressed hydrogen, liquefied hydrogen, and metal hydrides—can be used to reduce hydrogen's mass to conservative and portable forms (Medisetty et al. 2020), which are discussed in detail below.

Compressed hydrogen

The most positive aspect of accumulating hydrogen, considering both capacity and refueling advancements, is its compressed nature (Medisetty et al. 2020). In specially made carbon fiber-reinforced hydrogen cylinders that can sustain extremely high pressure (35–70 MPa), hydrogen is maintained under increased pressure as well as in compressed form (Chakraborty et al. 2022). Hydrogen gas cylinders in compact form would be kept at pressures of 34.47–68.95 MPa, substantially more significant than the pressure in propane tanks (24.82 MPa) (Medisetty et al. 2020). Before implementing this technology, several issues need to be resolved, including the need for high pressure, energy for hydrogen gas compression, small volumetric density, and cylinder weight to lower the overall cost (Chakraborty et al. 2022). At 293 K temperature and 20 MPa pressure, liquid hydrogen has a roughly five times higher density than gaseous hydrogen (Medisetty et al. 2020).

For the FCX fuel cell automobile, Honda Motor Company proposed the idea of a compressed H_2 storage tank with a 3.75 kg hydrogen capacity and a 34.5 MPa interior tank pressure. The gaseous phase of H_2 changes to a liquid state under pressure of 80 MPa at a particular energy content/unit mass or volume. Hydrogen must be stored between 70 and 80 MPa. These cylinders have now shown outstanding performance as non-metal lined cylinders as a result of improved design specifications (Medisetty et al. 2020).

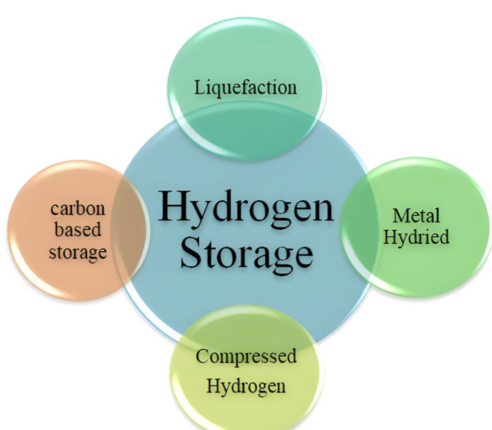


Fig. 6 Hydrogen storage methods

Liquefaction of hydrogen

Hydrogen storage at high pressure in barrels or cylinders highlighted the challenges with safety concerns. This made hydrogen liquefaction the main topic of discussion. Since hydrogen is regarded as a quantum fluid, its liquid phase has a density of roughly 70.85 kg/m^3. Hydrogen's density would not considerably rise if it were frozen. As a result, storing hydrogen in a liquid state has emerged as a viable option (Medisetty et al. 2020). However, liquefied hydrogen only possesses 8 MJ/L of calorific value, or one-fourth of the calorific value of gasoline (32 MJ/L) (Dawood et al. 2019). The backbone of the current industrial distribution and storage system is liquid hydrogen storage, which is a well-known technology (Qureshi et al. 2022a). Compared to conventional hydrogen storage technologies, liquid organic hydrogen carriers (LOHC) can overcome their limitations (Modisha and Bessarabov 2023). The unique advantage of a liquid organic hydrogen carrier (LOHC) is that it allows for safe, efficient, and high-density hydrogen storage while also being highly compatible with existing transportation infrastructures (Díaz et al. 2023).

By lowering hydrogen gas's temperature to cryogenic levels (around − 253° C), which improves its volumetric storage capability by four times, hydrogen can also be kept compressed known as cyro-compression. However, the energy needed for hydrogen compression and liquefaction makes this process energy intensive. Additional restrictions include the exceedingly volatile nature of liquid hydrogen and its ability to combine explosively with air if it evaporates. Therefore, this system needs to be created to address all security issues. The main problems with hydrogen storage are related to its weight, cost, volume, efficiency, standards, and regulations. Advanced materials, particularly polymers, need to be invented as barriers to stop the loss of hydrogen in storage vessels with high energy-to-weight ratios (Macher et al. 2021).

Metal hydrides

Nanostructured compounds used for hydrogen physisorption (Van der Waals interaction) and chemisorption (chemical interactions) can be classified as solid hydrogen storage materials. Solid hydrogen storage is made possible by metal hydrides, complex and chemical hydrides, and other hydrides under chemisorption compounds that mix with atomic or ionic hydrogen by metallic bonding, ionic bonding, or covalent bonding. Due to their reversibility and quick kinetics at an appropriate temperature and pressure, conventional metal hydrides, such as $LaNi_5H_6$, $ZrMn_2$, and $TiFeH_2$, have received much attention in the hydrogen storage sector (Ouyang et al. 2020a). Unfortunately, the restricted gravimetric density of these hydrides (< 2 wt% H_2), which is significantly below the hydrogen storage standards set by the Department of Energy (DOE), notably for automotive hydrogen energy sectors, has hampered their use. As a result, research produces novel light-metal hydride forms for use as solid-state storage materials, including Li, Na, B, Al, Mg, and N. Due to their attractive gravimetric and volumetric hydrogen densities, these light metal-based hydrides (such as complex hydrides or magnesium-based materials) have much potential for off- and on-board applications. With hydrogen capacities of 7.6 weight percentages for MgH_2 and 18.5 weight percentages for $LiBH_4$, respectively, exemplary Mg-based hydrides or complex hydrides exceed the objective set by DOE for vehicular applications. Nevertheless, most hydrides are hampered by their adverse thermodynamics and slow kinetics during the dehydrogenation and rehydrogenation processes. Recent developments have been propelled by enormous attempts to address these issues (Ouyang et al. 2020a), including alloying, doping with catalytic additives, nanostructuring, and creating nanocomposites with other hydrides (Ouyang et al. 2020b).

Sun (2018) utilized TTBNc (tetra-tert-butyl-2,3-naphthalocyanine), an efficient support compound, to stabilize Mg nanoparticles about 4 nm in size. The temperature at which H_2 is released from bulk MgH_2 (> 300°C) is much higher than at which these magnesium nanoparticles collect H_2 at 100°C and remove H_2 from 75°C. At 150°C, the Mg-TTBNc composite material also demonstrated high cycling stability with relatively quick absorption kinetics, with complete hydrogenation accomplished in 2 min. The hydrogen release rate was slower, with just 80% of the H_2 content being released in 1 h at 250°C. It was discovered that the reason for these enhanced hydrogen characteristics was a lower reaction enthalpy, namely 52.7 ± 4.9 kJ/mol H_2 as opposed to the 75 kJ/mol hydrogen reported for the bulk Mg/H_2 interaction.

Yong et al. (2021) successfully produced the magnesium-based hydrogen storage alloy (Mg–Re–Ni–Co) with three PCI platforms corresponding to the reversible dehydrogenation or rehydrogenation reactions of Mg/MgH2, Mg6Co2H11/Mg2CoH5, and Mg_2Ni/Mg_2NiH_4. Among these, the transitions from Mg_2Ni to Mg_2NiH_4 cause a "spillover" effect that encourages the breakdown of MgH_2 phases and improves the kinetics of hydrogen desorption. Meanwhile, enhancing the phase transition from $Mg_6Co_2H_{11}$ to Mg_2CoH_5 improves the hydrogen's absorption kinetics. The alloy can specifically absorb 5.5 weight percent hydrogen within 40 s at a temperature of 200°C, which is its ideal hydrogen absorption temperature.

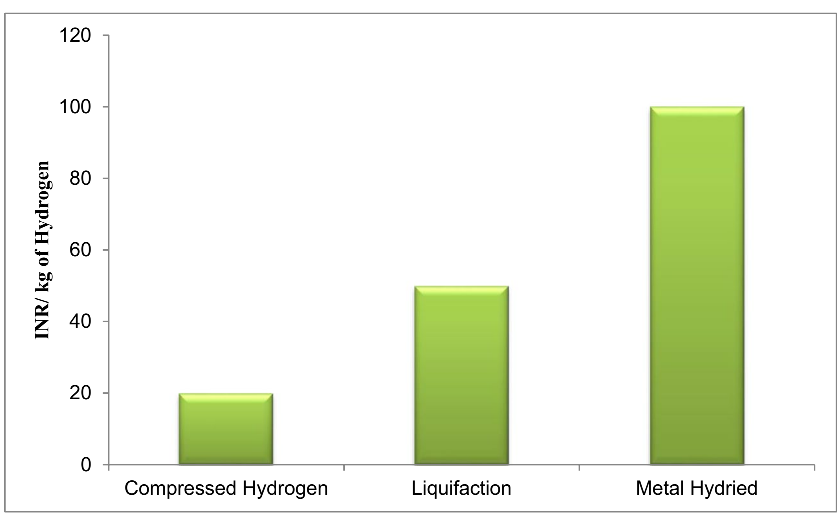


Fig. 7 Comparison of hydrogen storage method (Medisetty et al. 2020)

A comparison of the costs for hydrogen storage using the techniques mentioned above is given in Fig. 7.

Carbon-based hydrogen storage

Biochar is produced when biomass is heated in an oxygen-free environment (Maroušek and Trakal 2022). The biochar produced from agricultural crop residues has great potential as a hydrogen storage material. Biochar is ideal for energy storage and conversion applications because of its superior structural properties, such as porosity, large surface area, and diverse functional groups (Do et al. 2023). In hydrogen generation, biochar has a promising, environmentally friendly future (Bhakta et al. 2022). Activated biochar has a high surface area and pore volume, increasing hydrogen adsorption capacity by about 2.53 wt% at 0.1 MPa and about 5.32 wt% at 5 MPa (Deng et al. 2023). Biochar produced from palm kernel shell used as magnesium biochar composite for hydrogen storage reveals the hydrogen adsorption increases from 5 to 20 wt.% and conversion of Mg into MgH_2 enhanced from 83 to 93% (Yeboah et al. 2020). The porous structure of biochar has demonstrated its effectiveness in dispersing MgH_2 and providing hydrogen transfer channels for composite materials (Zhang et al. 2022). Although biochar has great potential for use in an H_2 economy, more efficient biochar-based materials for H_2 storage and production are still required (Igalavithana et al. 2022).

Current status of hydrogen

In 2021, the world's demand for hydrogen increased to 94 Mt, surpassing pre-COVID levels (91 metric tonnes in 2019), and contains energy equivalent to around 2.5% of the world's total gross energy demand. Although the need for fresh applications increased to roughly 40,000 tonnes (more than 2020 by 60%), most of the growth came from conventional uses in manufacturing and refining (International and Agency 2022).

There was no advantage for climate change mitigation since a large portion of the rise in hydrogen consumption in 2021 was satisfied by hydrogen made from fossil fuels burned unabatedly. In 2021, less than 1 Mt of low-emission H_2 was produced, virtually all deriving from fossil fuel-burning plants that also used carbon sequestration, storage, and utilization. However, the number of projects in the queue to produce low-emission H_2 is rapidly expanding (International and Agency 2022).

The world produces between 45 and 65 Mt of hydrogen annually (Mari et al. 2022). Canada produces roughly 3 million tonnes of hydrogen annually through the steam methane reforming of natural gas, making it one of the largest hydrogen manufacturers on the earth nowadays. Canada produces the fourth-most natural gas and holds the third-biggest oil reserves in the world. Since Western Canada has a significant supply of fossil fuels, it leads to Canadian hydrogen generation. The greatest hydrogen plants in Canada are found in Western Canada (Yu et al. 2020).

Public reports indicate that the total world demand for hydrogen has significantly increased, rising from 255.3 billion in 2013 to 324.8 billion m^3 in 2020, a 27.2% increment (Wang et al. 2019). Currently, more than 90% of commercial hydrogen manufacturing facilities use steam reformation of hydrocarbon, the most popular technique globally. Badische Anilin-und-Soda-Fabrik (BASF) first developed the method in 1926, and ICI (Imperial Chemical Industries) first accomplished commercialization in 1930 (Dalena et al. 2018). Natural gas, naphtha, refinery gas, liquefied gas, and different hydrocarbon-rich gases are some of the raw ingredients (Zhang et al. 2021a). In general, and especially for large plants, the cost of producing hydrogen using natural gas steam reformation is cheaper than that of producing hydrogen using water electrolysis. Water electrolysis requires less investment than SMR (natural gas steam reforming) when producing hydrogen on a modest scale. SMR has a lower conversion rate than water electrolysis for large-scale hydrogen production. Therefore, when the supply of raw materials is not constrained, and there is little demand for hydrogen, it is suitable to manufacture hydrogen using water electrolysis. On the other hand, when there is a high demand for H_2, it is preferable to manufacture hydrogen using SMR. Additionally, coal gasification outperforms SMR in terms of cost alone for producing hydrogen (Zhang et al. 2021a).

In the transportation industry, hydrogen storage systems are also being considered designers work toward creating highly effective systems. For instance, various criteria are examined, like the operating system's cost, the volumetric and gravimetric densities, and thermal stability. Advancements in the generation and storage of hydrogen for numerous automotive sectors have been created and implemented, and several of these fields are currently under development (Chakraborty et al. 2022). Additionally, compared to other alternative solutions, hydrogen vehicles have been demonstrated to have threefold reduced potential for contributing to global warming (Apostolou and Welcher 2021).

Hydrogen distribution and transportation

Both centralized and decentralized/distributed manufacturing facilities are capable of supplying hydrogen. The centralized facility has the advantage of superior economies of level to reduce the cost of production, but the requirement for distribution raises the cost of transportation (Greene et al. 2020). On the other hand, because of its smaller size, dispersed hydrogen production has more remarkable production cost despite delivering reduced transportation costs. A thorough analysis considering various criteria, including geographic dispersion, resource availability, current producing systems, and demand, will be necessary to determine the best distribution and transportation arrangement (Mari et al. 2022).

On-site production, gas storage, and compressors significantly impact hydrogen fueling station costs. Scaling up, mass-producing essential components, and better fuel utilization can all help to reduce this cost. The IEA (International Energy Agency) projects a 75% reduction in station costs when capacity is increased from 50 to 500 kg of hydrogen per day, and the American Hydrogen Council projects a 66% drop in prices between 2015 and 2030 (Greene et al. 2020).

While the essential following transit and distribution choices will comprise gas truck transport, gas pipelines, or liquefied truck transport, economies of level generally prefer centralizing hydrogen generation. Hydrogen consumption and distance are the most crucial variables for determining the least expensive alternative (Mari et al. 2022).

"Centralized" production occurs when hydrogen is generated on a big scale and delivered to clients by pipeline or truck. At the point of use, hydrogen is generated "distributed" or "on site," typically using steam methane reforming (SMR) or small-scale water electrolysis processes (Meraj et al. 2020). In addition to being transformed into other energy transporters/carriers including methane gas, electricity, or liquid fuels, H_2 can also be used as a fuel. This imposes transformation costs as well as efficiency shortfalls but enables access to current energy distribution systems without the need to build a substantial infrastructure for the distribution of hydrogen. The best hydrogen supply method must be determined about the relative costs of fundamental regional resources for H_2 production and policies. Hydrogen fuel can be transported by utilizing

1) by pipelines;
2) by railways, trucks, and vessels (Chakraborty et al. 2022).

At an average pressure of 10 MPa or less, pipeline networks may transport gaseous hydrogen effectively. Large-scale hydrogen transportation over a broad range of distances is affordable through pipelines. However, suppose the natural gas pipeline network is to be utilized for the supply of pure hydrogen under elevated pressure. In that case, the proper pipe materials for hydrogen transportation must be constructed and employed, and it must be extensively updated (Javaheri 2023).

Economic analysis of hydrogen fuel

The economic evaluation of hydrogen fuel was performed on hydrogen generated by electrolysis of water, waste biomass, natural gas, or coal and transported as cryogenic liquid hydrogen or compressed hydrogen gas. Although the price of hydrogen made from coal and natural gas is now less expensive, the expenses of carbon trading and purification of hydrogen have a significant impact on it (Chakraborty et al. 2022). The price to produce 1 kg of hydrogen using the blue, aquamarine, and green methods varies between \$1.61 and 3, \$2.73 and 5.36, and \$2.68 and 8.58. The key determining factors for any technique's commercialization will be its techno-economic viability, energy source, sustainability strategy, and carbon footprint (Qureshi et al. 2022b).

Three times more expensive than natural gas (6 \$/billion J), steam methane reformation (SMR) prices 18 \$/billion J. Producing pure hydrogen using electrolysis costs 28 \$/billion J. As a result, natural gas continues to be the preferred alternative for producing and using hydrogen in industries. Although bio-hydrogen appears to be the most significant renewable energy source, there is still a lot of work to be done to lower costs (Pareek et al. 2020).

If the grid-integrated approach is chosen, it will cost roughly \$14.11 billion to build a wind farm with tens of gigawatts (GW) capacity. However, the expense of the producing plants alone might be decreased to \$4.23 billion or lower if the hydrogen generation technique is used (Wang et al. 2019). Researchers examined a wind-driven electrolysis system with a 28% plant capacity and estimated the cost of producing 1 kg of hydrogen to be \$4.67. Moreover, Bertuccioli et al. (2014) evaluated the price of hydrogen production using an alkaline electrolyzer and a PEM electrolyzer operated by wind power to be \$7.6/kg and \$5.0/kg, respectively. Loisel et al. (2015) assessed the economy of a hybrid/dual power station comprising a hydrogen generation and storage network and an offshore wind turbine in the Pays de la Loire region of France. Depending on the type of application, the costs for the selected projects' hydrogen generation would range from \$3.5 to \$11.8/kg of hydrogen (Wang et al. 2019).

Some researchers conducted an economic analysis of a solar photovoltaic system coupled to a proton exchange membrane electrolysis setup with a potential of 1200 tons/day; they determined that the cost of producing hydrogen using their method was \$8.98/kg. Additionally, Giaconia et al. (2007) thought about adjusting the heat required for the S–I cycle that used a hybrid of solar and fossil fuel energy; they estimated the cost of producing hydrogen as \$7.53/kg with an everyday production output of 71 kg for 65% process efficiency. For a hydrogen-generation plant focused on thermochemical water (H_2O) splitting coupled with a solar central receiver, Corgnale and Summers (2011) introduced a proposed design and conducted an economic analysis; they predicted a minimum long-term cost specific to hydrogen production of $3.19/kg. According to Boudries (2016), the cost of producing hydrogen using the concentrating photovoltaic (CPV) electrolysis technology is $3.6/kg, which is much less expensive than the photovoltaic (PV) electrolysis approach, and it also provides a substantially higher rate of production. Another study was also carried out by Boudries (2018), in which hydrogen was produced utilizing a combined solar parabolic trough and gas power plant electrolysis setup. The findings of this study showed that the proposed approach could produce hydrogen for as little as $6.0/kg (Wang et al. 2019).

Summers et al. (2005) estimated the cost of producing hydrogen from a HyS system (hybrid sulfur cycle) using the modular helium reactor for a hydrogen production volume of 580 tonnes per day; the amended hydrogen manufacturing cost for a typical incorporated plant was $2.29/kg. Exergoeconomic analysis was used by Ozbilen et al. (2016) to examine the economics of producing hydrogen that used a hybrid Cu–Cl cycle combined with an SCWR (supercritical water reactor) with a per day capacity of 125 tonnes over a 15-year plant life span. They determined the cost of producing hydrogen to be $0.08 and $0.02/kWh in terms of the price of the electricity and thermal energy used, respectively, leading to an upgraded production expense of $3.60/kg. The updated Mg–Cl cycle's hydrogen price was determined to be $3.87/kg using the optimum input parameters from the previous research (Ozcan and Dincer 2017). Additionally, recent study that took into account the S–I cycle and SCWR projected the value of hydrogen to be $3.56/kg for higher capacity applications (El-Emam and Özcan 2019).

In their evaluation of a downdraft biomass-oxygen gasification method with carbon monoxide shift at ambient pressure, Lv et al. (2008) calculated the cost of hydrogen generation to be $1.69/kg. Implementing a steam gasification method in a fluidized bed reactor with in situ carbon dioxide extraction, Inayat et al. (2011) developed a heat-integrated flowchart to synthesize hydrogen gas from the empty bunches of palm oil plants. At 1150 K temperature, a sorbent/biomass ratio of 4 and an S/B ratio of 0.87 were attained, yielding 0.0179 kg/h of hydrogen for $1.91 per kg. In addition, Abuşoğlu et al. (2016) investigated the utilization of biogas for H_2 production using alkaline and PEM electrolysis, dark fermentation, hydrogen sulfide (H_2S) electrolysis, and high-temperature steam electrolysis (HTSE) technologies for small-scale plant capacities; they observed that, when considering maximum load operation and the same cost of electricity throughout the approaches, the cheapest hydrogen production cost was for hydrogen sulfide electrolysis system, while the most significant price was for the dark fermentative system. Using a catalyst filter candle, water gas shift at 200 °C and 400 °C, Moneti et al. (2016) examined 1 MWth of the indirect heating gasification system. An estimated $9.4/kg was spent on producing hydrogen (Wang et al. 2019). Based on direct bio-photolysis, indirect bio-photolysis, dark fermentation, and photo-fermentation, the costs for creating 1 kg of hydrogen were, respectively, $1342.27, $1.96, $18.70, and $370 (Jain et al. 2022). Overall, biomass-based and nuclear power-assisted hydrogen generation methods achieved the lowest costs for hydrogen production. In contrast, wind-driven and solar power-based hydrogen production techniques realized the highest prices for similar purposes. From this perspective, the later methods still do not represent a viable alternative to conventional hydrogen technologies based on fossil fuels. However, methods for producing hydrogen from biomass could be effective (Wang et al. 2019).

Zhang et al. (2021a) analyzed the costs of hydrogen production through distinctive technologies by utilizing different feedstocks, as presented in Table 4. The hydrogen economy provides a multi-sectoral perspective on affordable renewable energy and complete de-carbonization in industrial sectors (Chakraborty et al. 2022).

According to Yadav and Banerjee (2018), the cost of producing solar hydrogen using the high-temperature steam electrolysis technique can be decreased to 6–8$/kg by 2030 if component prices are brought down. As per Mehrpooya et al. (2019), water electrolysis is likely the most

Table 4 Cost of hydrogen production through different techniques (Zhang et al. 2021a)

Production method	Feedstock	Cost of hydrogen ($/kg)
Wind electrolysis	Water	5.89–6.03
Photo-electrolysis	Water	10.36
Steam methane reforming	Natural gas	2.08–2.27
Biomass gasification	Woody biomass	1.77–2.05
Coal gasification	Coal	1.34–1.63
Nuclear electrolysis	Water	4.15–7.00
Methane pyrolysis	Natural gas	1.59–1.70
Solar photovoltaic electrolysis	Water	5.78–23.27
Solar thermolysis	Water	7.89–8.40
Photo fermentation	Organic waste	2.83
Biomass pyrolysis	Woody biomass	1.25–2.20
Dark fermentation	Organic waste	2.57
Solar thermal electrolysis	Water	5.10–10.49
Direct bio-photolysis	Algae + water	2.13
Indirect bio-photolysis	Algae + Water	1.42
Nuclear thermolysis	Water	2.17–2.63
Autothermal reforming of methane	Natural gas	1.48

environmentally benign method of producing hydrogen when paired with renewable energy production. El-Emam and Özcan (2019) claim that geothermal and nuclear energy can produce hydrogen at a reasonable cost due to their reduced electricity costs. However, owing to high processing costs or poor efficiency, most hydrogen-manufacturing techniques are still in their infancy (Mohammadi and Mehrpooya 2019). New H_2 production methodologies with reasonable effectiveness, low carbon footprints, and cheap cost are required to fulfill the increasing consumption of hydrogen (Li et al. 2019). Due to this, hydrogen production may become more economical and low carbon to meet various end-user demands (Acar and Dincer 2019). Consequently, it is imperative to create inexpensive and low-carbon hydrogen in the near and long term (Di Marcoberardino et al. 2017).

Using expensive production and end-use technology makes hydrogen conversion from renewables an expensive approach (Shafiei et al. 2017), and the increased cost prevents its market acceptance (Huang and Liu 2020). Therefore, a cost-effective zero or low-carbon hydrogen (H_2) supply and a cheap and practical technique to manufacture such hydrogen energy are essential tenets of the hydrogen fuel economy (Islam et al. 2019). Green hydrogen, which is produced using renewable energy, costs roughly US$2.28–7.43/kg, more than gray ($0.67–$1.31/kg), blue ($0.99–2.05/kg), and black hydrogen (US$ 1.35/kg). For hydrogen to be cost compatible with the wholesale of diesel prices, Canada Energy Systems Analysis Research (CESAR), a non-profit energy as well as a sustainability think tank, calculated that a hydrogen cost of lower than US$2.6/kg hydrogen was required. However, green hydrogen is generally too expensive for widespread use. Some predictions state that the price of green hydrogen would not decrease until the 2030s (Yu et al. 2020).

Challenges/limitations of hydrogen

One of the significant limitations of hydrogen use is the difficulty of storing it securely, particularly in automobiles. It is, however, possible to solve this problem by using carbon nanotubes and metal hydrides that reversibly adsorb H_2 at ambient temperatures and low pressures. The techniques still face significant technical obstacles, but researchers are working to overcome them (Antonopoulou et al. 2008a). Despite this, high production and processing costs, as well as other technical difficulties like durability and dependability, remain the main obstacles to the commercialization of hydrogen fuel (Dahiya et al. 2020).

Several obstacles prevent hydrogen from being used as a fuel, including its purification, storage, and transportation. Due to current inefficient technologies, purification and storage of hydrogen still need to be solved (Kazakov et al. 2016) [158]. These are the significant issues that order must be addressed to purify and store hydrogen (Kazakov et al. 2016). Due to its rapid oxidation and corrosion, it must be stored with special precautions (Qureshi et al. 2022a). Moreover, separating bio-H_2 from complicated biological gas mixtures is challenging since carbon dioxide, H_2S, water vapor, etc., present a more significant risk than necessary. Sustainable bio-hydrogen production requires guidelines for its storage, distribution, and marketing and adequate channeling. Hydrogen storage and transport infrastructure must be well established before bio-hydrogen can be easily mixed or injected with hydrogen produced traditionally (Dahiya et al. 2020).

Although hydrogen can be produced in centralized or distributed facilities, getting it to fueling stations can be challenging. As discussed earlier, centralized systems are more expensive to transport than decentralized systems. In addition to pipes, tanks, roads, and ships, hydrogen can also be transported as liquefied gas, big molecules, or compressed gases, depending on the destination. Therefore, the production and transportation of bio-hydrogen in centralized and distributed/decentralized plants require specialized infrastructure (Dahiya et al. 2020).

In addition to membrane processing, absorption or adsorption are the main methods for storing and purifying hydrogen; their combination with organic polymeric membranes for gas extraction can yield innovative and reliable results (Dahiya et al. 2020). However, the hydrogen concentration produced by these processes, which can reach 75–80%, is unsuitable for fuel cell applications. Under the influence of toxic gases such as hydrogen sulfide or carbon monoxide, metal hydrides must have their surfaces altered or their impurities eliminated if used for this purpose (Kazakov et al. 2016).

As illustrated in Fig. 8, any nation must overcome obstacles such as transportation, storage, governing regulations, public acceptance, codes and standards, cost, and safety before adopting hydrogen technologies. The three main methods for storing hydrogen are— compressed hydrogen, metal hydrides, and hydrogen liquefaction. Transporting compressed hydrogen is dangerous and requires a constant pressure between 34.47 and 68.95 MPa (Medisetty et al. 2020). A mass density of 70.83 kg/m^3 was found in liquefied hydrogen, making it safe to transport. Despite this, gaseous hydrogen suffers a significant loss when it is liquefied since about 30% of the total energy present in hydrogen is consumed during the liquefaction process (Pudukudy et al. 2014). Additionally, it offers 8.4 MJ/L, a fairly low amount of energy (Bakuru et al. 2019). Therefore, optimizing liquefaction procedures is essential to minimize loss and enhance transportation security. Hydrogen is produced by fertilizer companies and oil refineries each year, and it is then delivered to

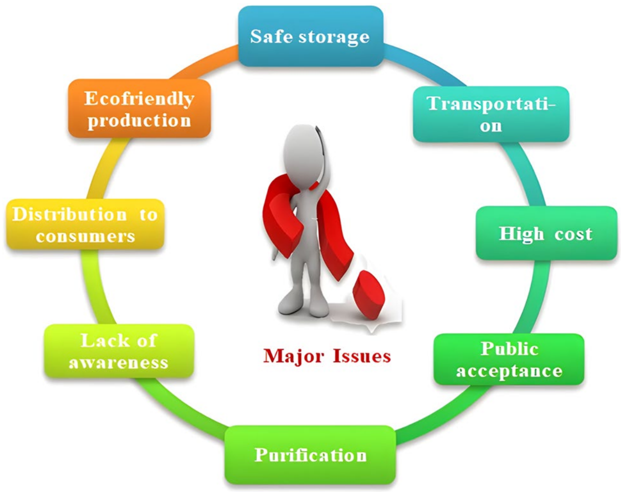


Fig. 8 Current challenges in the way of hydrogen fuel

several businesses and companies in pressurized containers (Medisetty et al. 2020).

There are also drawbacks associated with H_2 storage technologies due to the absence of appropriate protocols and regulations. To reduce transportation and distribution costs, hydrogen generation and distribution systems must be connected (Reddy et al. 2020). It is necessary to develop an entirely new infrastructure (Akbari et al. 2021) to distribute hydrogen to users (Skare et al. 2021). At present, both the delivery and storage of hydrogen involve inefficient energy use (Zheng et al. 2021). Although hydrogen has significant disadvantages, it is increasingly used as an alternative fuel in several sectors, including transportation, construction, and power generation (Reddy et al. 2020).

There are various technical or social hurdles to the adaptation of hydrogen energy as a clean alternative fuel, most of which are being solved and most of which need to be solved. Solving the single problem of hydrogen is a topic of different research that needs to be thoroughly recognized.

Some safety aspects of hydrogen fuel

Since hydrogen has a very high calorific value (142 MJ/kg), so irresponsible and impetuous handling, storage, and utilization of itcan cause serious tragedy in human health and wealth. Also, storage of hydrogen in compressed form at very high pressure (35–70 MPa), due to its very low density (0.0838 kg/m^3) (Vochozka et al. 2020a), also poses a dangerous risk. However, the high diffusion rate of hydrogen makes it safe as compared to other spilled fuels. Still, if leakage goes unrecognized and the gas builds up in a small area (Bartoš et al. 2022), it could eventually catch fire and explode (Vochozka et al. 2020b), as mentioned earlier. So, adapting open area for the operation, production, and utilization of hydrogen gas as a fuel is its most crucial priority (Vochozka et al. 2021).

The "NASA Safety Standard (Rabe et al. 2022) for Hydrogen and Hydrogen Systems" lists several potential sources of ignition, including personnel smoking, shock waves from tank rupture, electrical short circuits, lightning, flames, metal fracture, mechanical vibration, static electricity, sparks, fragments from bursting vessels, friction and galling, heating of high-velocity jets, welding, explosive charges, generation of electrical charge by equipment operations, mechanical impact, resonance ignition (repeated shock waves in a flow system), tensile rupture, and exhaust from a thermal combustion engine (Kovač et al. 2021).

Internal embrittlement produces internal cracks while environmental embrittlement results in surface cracks, ductility losses, deformations, and reductions in fracture stress in metals and alloys. When absorbed hydrogen reacts chemically with a metal component, a brittle hydride is produced as a by-product (e.g. hydrogen can react with carbon in steel and form methane) that causes hydrogen reaction embrittlement. Addition of aluminum (Al) and titanium (Ti) alloys to the primary material, the use of amorphous structured compounds, the use of plating processes like zinc (Zn) and nickel (Ni) plating, and the coating of surfaces with graphene and niobium (Nb) are some preventative measures. To prevent hydrogen from penetrating, an oxide, carbon, and nitrogen diffusion layer can also be applied (Kovač et al. 2021).

Reliable safety sensors must guarantee safe operation (Maroušek 2023) and promptly identify a leak (Pavolová et al. 2021). For interior fueling operations (Razminienė et al. 2021), the National Fire Protection Association (NFPA) mandates the installation of hydrogen detectors. A wide variety of safety sensors is available on the market and is essential for effectively implementing hydrogen technology. Integration of failure mode and effect analysis (FMEA), fault tree analysis (FTA), and hazard operability analysis (HAZOP) are highly recommended for preventing hazards. FMEA reduces the probability of flaws by identifying the most vulnerable regions to failure. FMEA minimizes the effects of failure by implementing the proper corrective measures. In contrast to FTA analysis, which assesses the likelihood of incidents occurring, HAZOP analysis aids in identifying accidents and prospective scenarios (Kovač et al. 2021). There are few studies on the risk assessment of hydrogen-related accidents at the stationary hydrogen refueling station. However, vehicle ventilation, wind direction, and hydrogen volumes all play crucial roles in the mishap at the petrol station. Li et al. (2023) reported that a mobile hydrogen refueling station is more susceptible to hydrogen leakage and diffusion when its side doors and windows are open, the surrounding wind speed is low, and the wind is blowing from the front to the back of the station. The spill area should be restricted to those who do not wear protective equipment. It is then necessary to remove all ignition sources safely. By installing atmospheric explosive devices, ignition sources can be removed from the most critical areas of a facility (Genovese et al. 2023).

Future insights for hydrogen production

Hydrogen energy is a crucial pillar for achieving net-zero and sustainable development strategy. Innovations in technology and the sensible planning of hydrogen production, storage, transportation, and consumption are necessary to establish a hydrogen society. The conventional gray and transitional blue hydrogen production methods should be replaced with sustainable green hydrogen production as renewable energy sources become more affordable. The International Energy Agency (IEA) conducted a study on global total final energy consumption and found that to achieve net-zero energy along with significantly lower consumption levels of nonrenewable fossil fuels, the share of hydrogen energy in total final energy consumption should rise to approximately 2% and 10% in 2030 and 2050, respectively (Guan et al. 2023).

Furthermore, compared to 2020, the overall final energy consumption levels of renewable should rise by approximately 0.51% and 7.41% in 2030 and 2050, respectively. From around 59 in 2000 to ~ 74 Mt in 2010 and finally to ~ 88 Mt in 2020, the world's hydrogen needs grew rapidly. Demand for hydrogen in 2030 and 2050 is expected to rise to around 2.4 (or 211 Mt) and 6.0 times (or 528 Mt) that of 2020, respectively, indicating the significance of H_2 in sustainable development.

In terms of hydrogen mainly utilization, prior to 2020, hydrogen was mainly utilized in industrial operations and refining. In the future, hydrogen will be utilized more and more in transportation, electricity, ammonia fuel, buildings, synfuels, and grid injection. By 2050, it is predicted that the hydrogen economy will generate USD ~ 3 trillion in revenue, requiring an investment of USD 7~8 trillion through the hydrogen-value chains. As a result, there is a great need for hydrogen, and society should use it extensively. Hydrogen plays crucial and essential functions in living, production, the environment, and the economy, so even though its share of the overall energy consumption system is currently tiny, it will continue to be highly required when a sustainable society is realized. The demand is propelling the development of associated technologies for transporting, storing, manufacturing, and utilizing hydrogen (Guan et al. 2023).

Global implications of national hydrogen policies

In 2017, Japan became the first country in the Asia–Pacific region to implement a national hydrogen policy, which sparked interest in the fuel. In 2019, Australia and South Korea announced their national hydrogen strategies, following Japan's example in tackling the expanding hydrogen industry. According to the aim of the Japanese Ministry of Economy, Trade, and Industry (METI), the Japanese government expects hydrogen technology to become affordable by 2030. METI has set specific targets regarding the price of the electrolyzer (USD 475/kW), cost output (USD 3.3/kg) of the green hydrogen, and efficiency (70% or 4.3 kWh/Nm^3) by 2030. The national policy was unveiled in 2019 with an estimated investment of AUD 500 million (USD 355 million) (Capurso et al. 2022).

Furthermore, the government has revealed an investment plan of AUD 70.2 billion (USD 49.8 billion) that is only meant to be used by hubs to export hydrogen. The European Union (EU) has established both immediate and long-term objectives. The amount of hydrogen in Europe's energy mix is expected to rise from the current 2–13% by 2050. Being the first European nation to implement a comprehensive hydrogen policy, Germany spearheaded the EU's hydrogen strategy through its president of the European Union Council. The German government plans to develop up to 5 GW of offshore and onshore wind farms connected to water electrolyzers by 2030 to produce up to 10 GW of hydrogen by 2035–2040. To do this, 20 TWh of renewable energy and 14 TWh of green hydrogen must be produced. Chile has been promoting the utilization of hydrogen probably more than any other nation around the world. These initiatives will become effective in 2020 as an element of the first national hydrogen plan for Latin America (Qureshi et al. 2022b). With ambitions of trading hydrogen and its derivatives for USD 2.5 billion yearly, Chile aims to attain 25 GW of electrolysis. Chile has the lowest cost of hydrogen in the world (USD 1.5/kg). Currently, 13 countries have national hydrogen policies, together with one regional integration group. Along with the European Union, the countries listed include Canada, Portugal, France, Hungary, Spain, the Netherlands, UK, and Norway. They all enacted national hydrogen policies in 2020 and 2021. This was sparked mainly by the United Nations Climate Change Conference in Glasgow (COP26), which took place between October 31 and November 12, 2021 (Buttler and Spliethoff 2018). Currently, 20 more countries are developing hydrogen strategies. Most nations now advocating for a hydrogen strategy are advanced or developing economies. In more than 30 countries, formal declarations on the hydrogen economy and early hydrogen projects are part of the ongoing political discussions (Qureshi et al. 2022b).

An overview map of the various activity levels involved in developing hydrogen strategies is shown in Fig. 9. On the one hand, the map shows that the Middle East, Central Asia, Southeast Asia, and Africa, and the remaining regions of the world are growing economically faster than the rest of the globe in hydrogen.

According to a UNEP assessment from 15 years ago, the lack of funding and skilled engineering personnel makes the developing world appear unfit to participate in the research, development, and deployment of hydrogen and related technologies, and the shift to a hydrogen economy will happen later in these developing countries. Experts from UNEP recommend that international organizations, particularly international development agencies, offer general assistance for deploying hydrogen in developing countries as a workable solution. The geographic dispersion of both supports this theory planned and implemented hydrogen methods. Without significant financial and technological assistance for the development of the prerequisites, Sub-Saharan Africa, South-East Europe, and Central Asia will not be capable of increasing their hydrogen economies. This could exacerbate malnutrition and poverty in both emerging and rich nations by increasing their income gap (Qureshi et al. 2022b).

Conclusion

Among the various fuels for the twenty-first century, hydrogen is the most promising and cleanest. As an environmentally friendly energy source, it has the potential to play a significant role in meeting the world's future energy needs. Also, it is one of the most commonly used chemical raw materials used in various industries. For the production of hydrogen, a variety of viable processes have been established. These include reforming, gasifying, and oxidation of fossil fuels, disintegrating substances containing hydrogen, microbial fermentation, and water electrolysis. Nevertheless, most of them suffer from several disadvantages, such as high impurities in the produced gas, considerable pollution, and inefficient energy conversion. The exploitation of fossil fuels for hydrogen production presents significant environmental challenges, and supplies of these fuels are in short supply. As a result, new environmentally friendly hydrogen production methods that could facilitate a successful transition to a hydrogen market have been thoroughly evaluated in terms of their technical feasibility and economic viability compared to methods that rely on polluting fossil fuels. Based on the findings of several studies published in the literature, it appears clear that all biochemical methods for producing hydrogen utilizing renewable energy sources are more

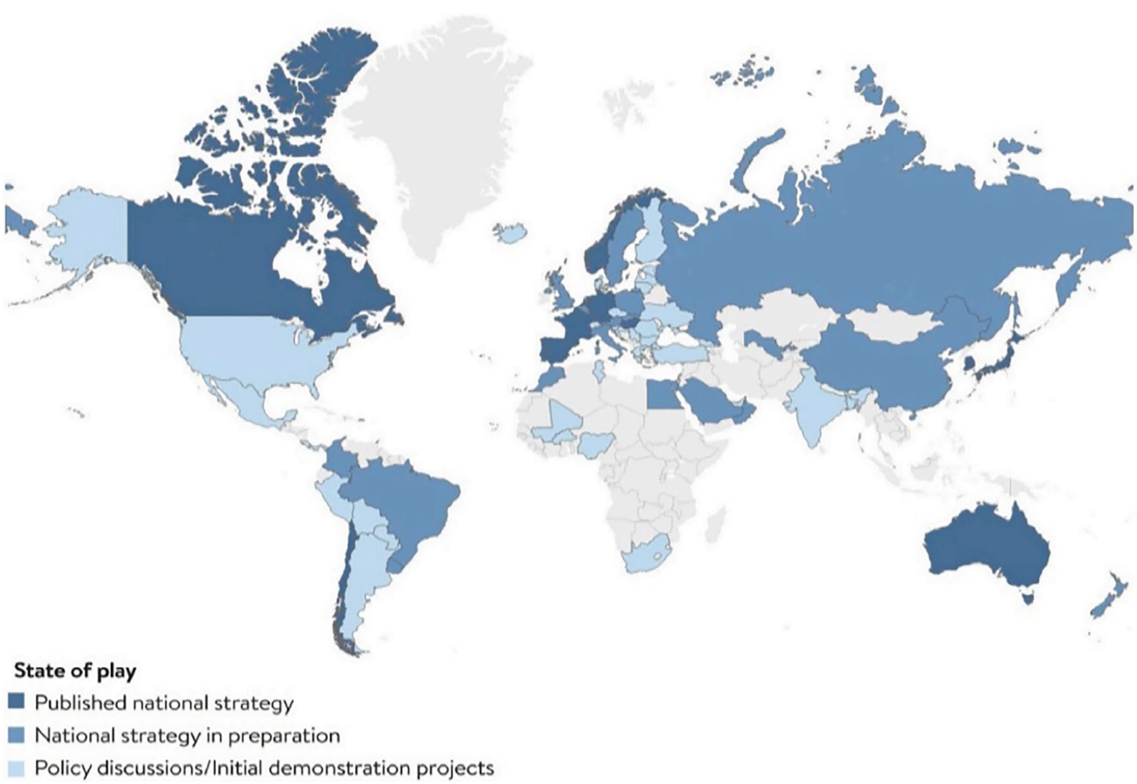


Fig. 9 A graphical view of the worldwide hydrogen development policies (Qureshi et al. 2022b)

environmentally friendly than methods using fossil fuels as either a feedstock or energy source. Before hydrogen can be widely used, the cost of producing it with renewable energy sources must be reduced dramatically. It is pertinent to note that in addition to the production of hydrogen, its transport and storage are also technically challenging. In contrast, a centralized hydrogen production system leads to higher distribution costs, while a distributed or decentralized system leads to higher production costs. It is comparable to compressed hydrogen storage in that it raises safety concerns, or if it is stored in liquid form, it suffers from a lower heating value (1/4 of gasoline fuel) and requires a more substantial amount of energy to convert into liquid form. The storage of hydrogen in metal hydrides is in its infancy, and the use of expensive metals for adsorbing hydrogen molecules is required. By summarizing the opportunities and challenges in hydrogen production and storage, this review would help the global realization of the hydrogen economy and provide a scientific basis for policymakers and technology advancement.

Abbreviations

AC: Alternate current; AEL: Alkaline water electrolysis; AEM: Alkaline anion exchange membrane; AUD: Australian dollar; BHEL: Bharat Heavy Electrical Limited; BHU: Banaras Hindu University; CCS: Carbon capture and storage; CI: Compression ignition; CNG: Compressed natural gas; DC: Direct current; DOE: Department of Energy; EBG: Electronic band gap; FCEV: Fuel cell electric vehicles; FMEA: Failure mode and effect analysis; FTA: Fault tree analysis; GHG: Greenhouse gas; GIFT: green initiative for future transport; GIP: Green initiative for power generation; HAZOP: Hazard operability analysis; HCNG: Hydrogen compressed natural gas; HTSE: High-temperature steam electrolysis; ICI: Imperial chemical industries; IEA: International Energy Agency; IPHE: International Partnership for Hydrogen and Fuel Cell in the Economy; LOCH: Liquid organic hydrogen carrier; L & T: Larsen and Toubro; NFPA: National Fire Protection Association; NISE: National Institute of Solar Energy; NTPC: National Thermal Power Corporation; PBG: Photonic band gap; PEC: Photo-electrochemical cell; PEM: Proton exchange membrane; PV: Photo voltaic; RIL: Reliance Industries Limited; SCWG: Supercritical water gasification; SMR: Steam methane reformation; SOE: Solid oxide water electrolysis; TRL: Technology readiness level; USD: US dollar

Symbols

°C: Degree Celsius; K: Kelvin; %: Percentage; H2: Hydrogen; CO: Carbon monoxide; CO2: Carbon dioxide; O3: Ozone; SO2: Sulfur dioxide; NO: Nitrogen oxides; $: Dollar; H2O: Water; H2S: Hydrogen sulfide; CH4: Methane; MJ: Megajoule; kg: Kilogram; L: Liter; MPa: Megapascal; Mt: Metric tonnes; Ni: Nickel; Zn: Zinc; Nb: Niobium; Ti: Titanium; Pc: Critical pressure; Tc: Critical temperature; OH−: Hydroxide ions; H3O+: Hydronium ions; kPa: Kilopascal; ZrO2: Zirconium dioxide; KOH: Potassium hydroxide; H+: Hydrogen ion; OH−: Hydroxide ion; kW: Kilowatt; UV: Ultraviolet; TiO2: Titanium dioxide; Au: Gold; Al: Aluminum; Mg: Magnesium; LiBH4: Lithium borohydride; NaBH4: Sodium borohydride; kJ: Kilojoule; MgH2: Magnesium hydride; Ca: Calcium; CaH2: Calcium hydride; Mg(OH)2: Magnesium hydroxide; CoCl2: Cobalt(II) chloride; NOx: Nitrogen oxide; SOx: Sulfur oxide; ppm: Parts per million; NH3: Ammonia; Na: Sodium; Li: Lithium; B: Boron; N: Nitrogen; TTBNc: Tetra-tert-butyl-2,3-naphthalocyanine; nm: Nanometer; mol: Mole; Re: Rhenium; Co: Cobalt; m3: Cubic meter; kWh: Kilowatt hour; Cu: Copper; Cl: Chlorine; S: Sulfur; I: Iodine; GW: Gigawatt

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Declarations

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