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Introduction to Hydrogen Fuelled Power Generation Systems

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Abstract

Hydrogen is a clean fuel with minimal impact on the environment and ecology. Its availability from the hydrogen carrying items and its conversion into water upon oxidation in exothermic reaction makes it a potential substitute to the fossil fuels. The concerns for protecting environment and sustainability of flora and fauna make it inevitable to look for clean energy sources. Hydrogen has emerged as a solution to these problems. This chapter details the prospects of hydrogen as a fuel for power generation. A brief discussion about the methods for getting hydrogen and methodologies for using it for power generation is presented herein. It also describes the challenges posed in vast utilization of hydrogen in power generation and mobility solutions.

Keywords: Power Generation, Hydrogen Production, Pyrolysis, Reforming

1.1 Introduction

Present civilization is energy intensive, and all activities are revolving around the energy availability. The pattern of production and consumption depends on the energy that is obtained from burning of fossil fuels. The concerns about regulating carbon footprints are visible across the world and necessitate shifting to green energy options.

It dates back to 1990s when the researchers started looking at hydrogen production and using it for power generation as a potential contributor to decarbonize power generation routes. Hydrogen is zero carbon substitute for existing power generation options. It is an essential ingredient in fertilizer production, petrochemical processing, steel manufacturing, etc., and is likely to be extensively used for power transmission, transportation, etc., in times to come. The high energy density of hydrogen being 120–142 MJ/kg, ease of availability, and clean nature make it suitable to substitute fossil fuels in the future. Burning of hydrogen being devoid of CO_x and soot emissions along with its generation through electrolysis using electrical energy and water make it environment friendly [1].

Various technologies exist today that can produce, store, and transport hydrogen while minimizing costs and the environmental impact during their entire life cycles. Hydrogen can be produced by a variety of processes that emit carbon in different ways, depending on the methods and materials used. Around the world, 120 million tons of hydrogen are produced annually, with just a third being pure hydrogen. Nearly 95% of the hydrogen produced is created using natural gas and coal. About 5% of the total is made up of electrolysis products. The use of hydrogen for getting power for transportation and electricity generation has been successfully attempted through different technological routes. But hydrogen as an energy carrier has certain inherent limitations with regard to storage and transportation.

1.2 Hydrogen Production

There are numerous routes for hydrogen production that rely on extraction of H_2 from hydrogen-containing molecules in water or fossil fuels. Getting hydrogen from ways involving smaller carbon footprint is critical. As per the IEA report [2], out of the total demand for hydrogen, around 95% of 90 million tons/year is obtained from coal gasification or steam methane reforming, which are fossil fuel driven emission intensive routes with the cost of hydrogen production being $0.5-1.7$ US$ per kg of H_2. This cost of hydrogen production rises to $1.0-2.0$ US$ per kg of H_2 when combined with carbon capture and storage. Different ways for getting hydrogen include its production from renewable and non-renewable sources including fossil fuel or biomass based, microbial hydrogen production, electrolysis, and thermolysis of water and thermochemical cycles [3]. But the challenge of having sustainable, cost-effective, and green route for hydrogen production is to be taken care for its widespread use. Among different routes (Table 1.1),

Table 1.1 Methods of hydrogen generation [13].

Method	Process	Raw material	Energy	Emissions
Thermal	Reformation	Natural gas	Steam and high temperature	CO_2
	Thermochemical hydrolysis	Water	Heat from nuclear energy	No emissions
	Gasification	Coal and biomass	Steam, oxygen, heat, and pressure	Few
	Pyrolysis	Biomass	Steam at medium temperature	Few
Electrical	Electrolysis	Water	Electricity	Varies
	Photo electrochemical	Water	Sunlight	No emissions
Biological	Photobiological	Water and algae	Sunlight	No emissions
	Anaerobic digestion	Biomass	Heat	Few
	Fermentation	Biomass	Heat	Few

the bio-hydrogen production is said to be reliable, stable, efficient, and having a good generation rate. The key hydrogen production methods are as follows [4].

1.2.1 Pyrolysis

Pyrolysis is a chemical process that involves the decomposition of organic materials by heating them in the absence of oxygen. During pyrolysis, the material is subjected to high temperatures (typically between 400 and 800 °C) in a closed container, where it breaks down into smaller molecules such as gases, liquids, and solids. The procedure of producing hydrogen through pyrolysis (Figure 1.1) uses the heat breakdown of organic waste or biomass to produce hydrogen. In the procedure, organic material is heated in a reactor at high temperatures (usually 700–1000 °C) in the presence of steam. Steam combines with the material to produce hydrogen gas (H_2) and other by-products such as carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4). Since pyrolyzed hydrogen burns cleanly and only releases water vapor when it is burned, it can be utilized as a fuel for both transportation and power generation. Moreover, hydrogen can be used as a raw material in the synthesis of compounds like methanol and ammonia. As it may use a variety of organic resources, including biomass, municipal trash, and agricultural waste, pyrolysis can be a desirable method for producing hydrogen. To provide a reliable source of hydrogen, the process can also be combined with other renewable energy sources like solar and wind energy.

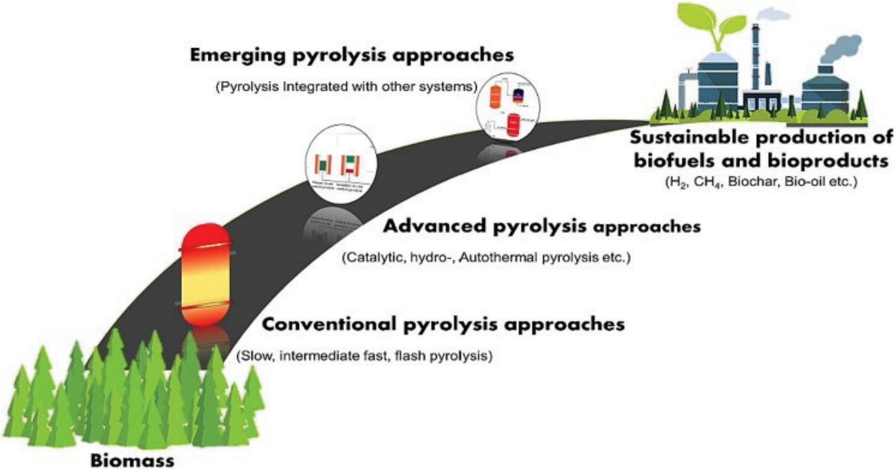

Figure 1.1 Biomass pyrolysis [5].

The procedure does present certain difficulties, though, such as the requirement for high temperatures and the potential creation of dangerous by-products. The quality and composition of the organic material utilized as a feedstock might also have an impact on the process's efficiency. Overall, the pyrolysis method for manufacturing hydrogen is a potential way to provide clean and renewable fuel, but more research and development are required to improve the method and guarantee its environmental sustainability.

1.2.2 Gasification and reforming

Hydrogen production from water gas comprising hydrogen, carbon monoxide, and carbon dioxide using fixed-bed gasifier is quite common and around 18% of hydrogen requirement is met from coal-derived hydrogen, which has been prevalent since 1833. Natural gas and oil could also be used for getting hydrogen through syngas method. As sources for hydrogen production, the natural gas and liquid hydrocarbons amount to 48% and 30% of total hydrogen sources. Water gas shift reaction is required for getting hydrogen.

Production of hydrogen from biomass through gasification route is an attractive way (Figure 1.2). The forest residue, agricultural waste, municipal waste, etc., can be used for economic production of hydrogen through gasification technology using suitable gasification agents. Amongst different thermochemical processes used for hydrogen production, the steam gasification produces the maximum of hydrogen. However, the type of biomass,

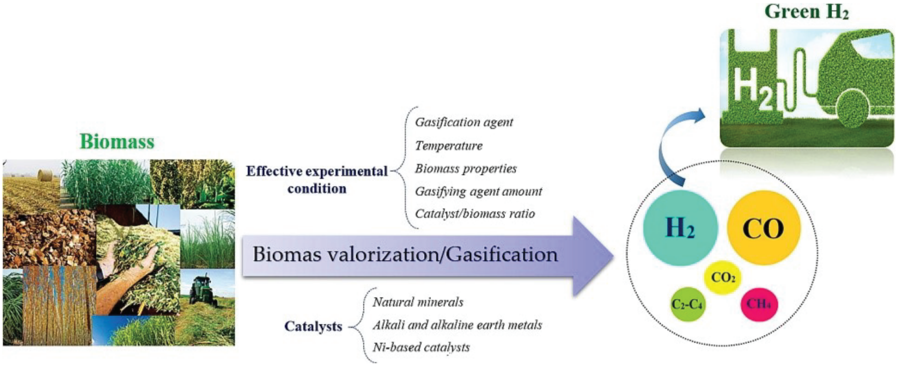

Figure 1.2 Biomass gasification for getting green hydrogen [6].

feed quality, solvent, temperature/pressure during reaction, catalyst, ratio of sorbent to biomass, residence time, etc., influence the yield of hydrogen in gasification.

For example, the hydrogen production from methane is governed by the following set of reactions:

$$CH_4 + 2O_2 \rightarrow 2\ H_2O\ +\ CO_2.$$

Endothermic reaction yielding hydrogen:

$$CH_4 + H_2O - >\ 3H_2 + CO$$

$$CO + H_2O \rightarrow H_2 + CO_2.$$

Combining the above equations, the vapor reforming of methane occurs at moderate pressure of 2−3 MPa and high temperature of around 1200 K.

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2\ .$$

Methane can also be oxidized to hydrogen through faster reaction rate; however, in the case of partial oxidation, the cost is quite high.

$$2CH_4 + O_2 \rightarrow 4H_2 + 2CO.$$

1.2.3 Photosynthesis

The process of producing hydrogen through photosynthesis involves splitting water molecules (H_2O) into their component elements of hydrogen (H_2) and oxygen (O_2) using sunlight (O_2). Photosynthetic pathway yields hydrogen using solar energy. This is also termed as biological hydrogen production and requires smaller temperature in range of 10–40 °C in the presence of hydrogen donor like salt water. Temperature requirement is small as compared to chemical/physical routes of hydrogen production requiring temperatures of the order of 1000 K. Such production is clean. The employment of specific photocatalysts, such as titanium dioxide, that can absorb sunlight and use that energy to start the photolysis of water molecules is the most promising method for producing hydrogen through photosynthesis. These photocatalysts are often incorporated into a system that also contains a hydrogen collection system and a water source (such as a water tank or membrane).

One benefit of producing hydrogen through photosynthesis is that it makes use of abundant and renewable resources (sunlight and water) to create a sustainable and clean fuel. Also, the method is environmentally benign because it does not emit any toxic gases. This method still faces significant difficulties, such as the relatively poor photocatalyst efficiency, the requirement for specific materials, and the high implementation costs. Despite these difficulties, researchers are still looking into and developing this promising hydrogen generating technique.

1.2.4 Water electrolysis

Water electrolysis is a process in which hydrogen gas (H_2) is produced by splitting water (H_2O) into its constituent elements of hydrogen and oxygen using an electric current. This process involves passing an electric current through water, which causes the water molecules to split into hydrogen and oxygen ions.

In order to electrolyze water, a device called an electrolyzer is commonly used. It has two electrodes (an anode and a cathode) that are separated by an electrolyte solution. Hydrogen ions (H^+), which are drawn to the cathode when an electric current is run through the electrolyte solution, interact with the cathode's electrons to produce hydrogen gas. At the same time, oxygen ions (O^{2-}) are drawn to the anode and join forces with anode electrons to create oxygen gas. It is found that for generating 1 kg of hydrogen (Figure 1.3), there is a requirement of electrolysis of 9 L of water and around 50 kWh in an electrolyzer working with 70% electrical efficiency [1].

The common electrolyzers used for hydrogen production include solid oxide electrolyzer cell (SOEC), polymer electrolyte membrane electrolyzer (PEM), and alkaline electrolyzer [1]. Depending on variables like efficiency, cost, and scalability, each style has advantages and cons of its own. Nejadian

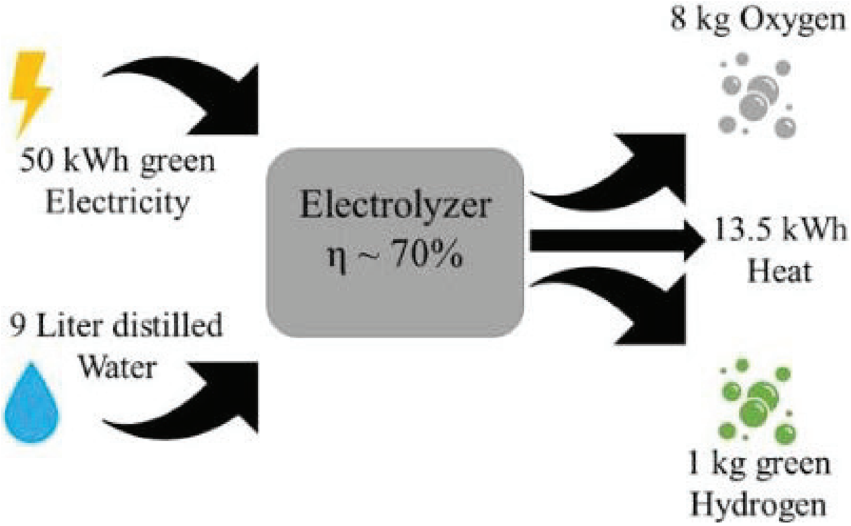

Figure 1.3 Electrolysis of water for producing hydrogen [1].

et al. [8] showed that amongst these, SOEC works at high temperatures and offers the maximum hydrogen production rate at the cost rate of 0.9372 $/s, while the highest cost rate of 3.54 $/kg is found in the PEM system, and the cheapest is from the alkaline system at 2.94 $/kg.

One benefit of producing hydrogen by water electrolysis is that the necessary electric current can be produced using sustainable energy sources like solar and wind power [7]. The method is also environmentally benign because it does not emit any toxic gases. However, there are still some difficulties with this method, including the relatively high cost of installing electrolysis devices, the demand for highly pure water, and the need for substantial amounts of electricity to generate considerable amounts of hydrogen. Notwithstanding these difficulties, water electrolysis is a promising method for producing hydrogen, and more research and development are anticipated to result in even greater gains in effectiveness and cost-savings.

1.3 Hydrogen in Power Generation

Petroleum can be replaced with hydrogen fuel in several industries as fuel for power generation with fuel cell systems. Today, steam methane reforming accounts for more than 95% of all hydrogen generation, and it is strongly encouraged to manufacture green hydrogen by water electrolysis. In addition, industrial waste streams with a high hydrogen content can yield hydrogen with only a preliminary purification step. Using a fuel cell system, this hydrogen is used to balance the grid when necessary. It is also blended with the natural gas grid and used as feedstock in industrial processes in steelmaking, chemical, and refinery plants (power-to-gas). Hydrogen is also used as fuel in the transportation sector. Due to its adaptability, hydrogen is a very compelling option, and because of this, important nations and regions including India, Canada, Australia, USA, Japan, and Europe have established several development roadmaps and strategies. Nowadays, more research on how hydrogen is used is being conducted, particularly in the power sector, and how it may support a variety of power cycles, such as those in hydrogen-fired, integrated gasification combined cycle, and co-combustion power plants.

Oxy-hydrogen (HHO) fuel, which is also called Brown's gas, can be used for heating and power generation. HHO holds the potential to run internal combustion engines, boilers, welding, cutting, etc., applications wherever larger amount of heat is required. Figure 1.4 shows the potential of HHO as an energy source.

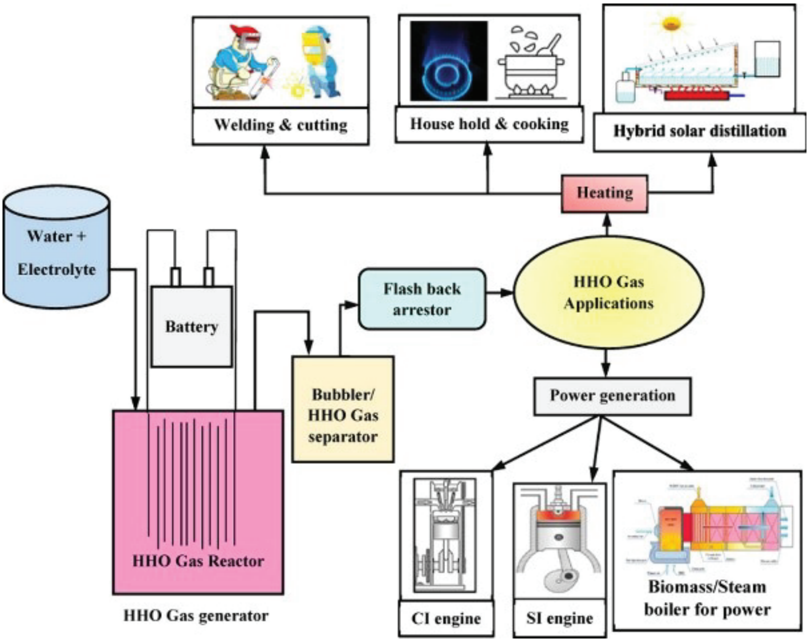

Figure 1.4 Potential of oxy hydrogen as an energy source [12].

1.3.1 Co-combustion (natural gas—hydrogen mix)

Existing natural gas-fired power stations could use hydrogen as a means of decarbonization. Global natural gas-fired generating capacity stood at about 1900 GW as of 2020. Natural gas and hydrogen mixtures are generally compatible with CCGTs in use. However, the maximum amount of hydrogen that can be present in the mixture varies depending on the make and type of the turbine [9]. The challenges brought on by hydrogen's greater flame temperatures, faster laminar flame, and shorter auto-ignition delay compared to natural gas will be mitigated by new turbine designs and materials. Given that these power plants reduce GHG emissions, enhance fuel variety, and encourage technical advancement, nations may decide to commission them.

Coal-fired power stations might decarbonize with hydrogen as well. In Japan, experiments are being conducted to see if co-firing coal and the hydrogen-carrying ammonia it contains is technologically and economically feasible. Global coal-fired capacity was 2150 GW as of 2020 [9]. If green ammonia is employed, co-firing coal with ammonia up to 20% by energy content will cut these facilities' annual CO_2 emissions by almost 1.7 billion t. [9]. Co-firing would enable coal-fired power facilities to continue operating, despite the lack of viable decarbonization options. However, coal-fired power facilities all around the world are being pushed to shut down earlier than their design life permits, either by market forces or government legislation. As a result, co-firing ammonia and coal could be a transition fuel.

1.3.2 Blended hydrogen fuel IC engine

For quite some time, the simultaneous pressures of energy conservation and environmental preservation are making it essential to identify new clean energy sources and all attempts are made to replace conventional internal combustion engines with some suitable alternatives. As a consequence, the hydrogen is seen as a potential source of energy that offers clean and efficient combustion. Also, the regenerative capabilities of hydrogen demonstrate possibilities of its becoming a replacement to the conventional fossil fuels as an excellent fuel for internal combustion engines. Hydrogen fuel has a very low energy of ignition compared to other conventional fossil fuels. During the combustion of hydrogen, the flame diffuses very fast and also has small quenching distance. This also helps in better homogeneity of the combustibles, short duration of combustion, increased engine power, better economy and stability, and less harmful emissions. In certain cases, the internal combustion engines employ hydrogen as a fuel extender by mixing it to gasoline/diesel for deriving the benefits of hydrogen combustion [14].

Literature shows that there are several studies that report about the research works on reciprocating engines and rotary engines that run on gasoline blended with hydrogen. Also hydrogen blending to natural gas and alcohol is separately tried in different types of engines. Ji et al. [15] performed experimental studies on the Z160F rotary engine's combustion and emissions employing hydrogen blending in gasoline. The study claimed that after H_2 enrichment, the pressure of combustion, cylinder temperature, brake mean effective pressure, and thermal efficiency all rose. They also discovered that CO emissions fell after H_2 blending and that HC emissions declined by 44.8% when 5.2% hydrogen (volume percentage) was added. The effects of the quantity of H_2 addition (ranges from 6% to 18% by volume) on the combustion process and NO production in a hydrogen-blended diesel engine were examined by Wang et al. [17] using a numerical simulation model. According to simulation results, the ignition delay was found to be longer, premixed combustion was found to be improved, and the diffusion of diesel combustion was found to be encouraged after H_2 addition. Additionally, they reported that the injection of H_2 might reduce soot emissions and limit the rise in NO emissions (as shown in Figure 1.5).

In recent years, some researchers have combined hydrogen with other low heat value gases, such as dimethyl ether (DME), methane (CH_4), or biogas (primarily CNG, N_2, and CO_2) and used the resulting mixtures as fuels in engines in addition to using hydrogen as an additional fuel in gasoline, diesel, natural gas, and alcohol engines [14]. Kekec and Karyeyen [17] looked at how CH_4-H_2 blending fuels (i.e., 60% CH_4 – 40% H_2, 50% CH_4 – 50% H_2, and 60% CH_4 – 60% H_2) burned and released pollutants under standard and color-less distributed combustion (CDC) circumstances in a cyclonic combustor. At a specific oxygen content, they found that color-less distributed combustion resulted in a sizable reduction in NOx and a beneficial reduction in CO.

Worldwide research works show significant advancements and achievements in hydrogen blending to different fuels such as gasoline, diesel, alcohol, and natural gas for various types of engines. The effects of H_2 blending on the performance of combustion, emission, output from these engines, implementation of lean combustion, innovations and control strategy optimization, studying the influence of various process variables on the performances, emission standards of the engines, etc., are the main components of this advancement.

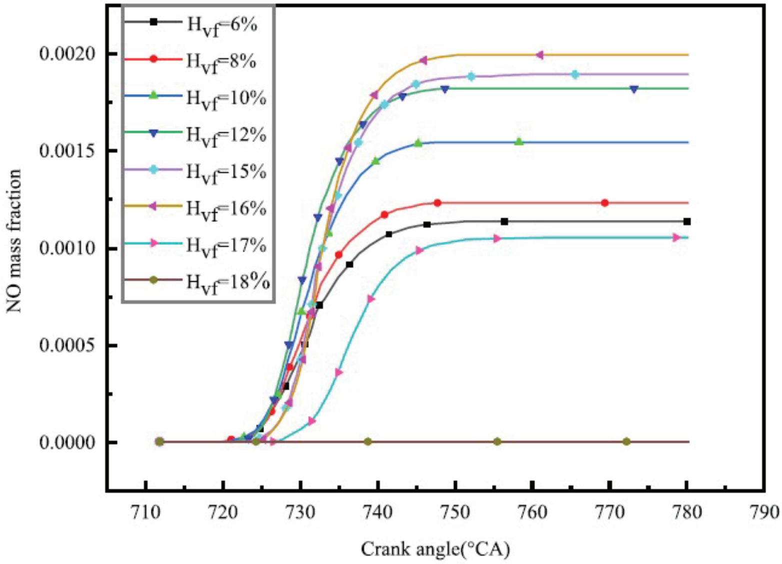

Figure 1.5 Variations of NO emissions at different volume fractions of H_2 in a hydrogen-blended diesel engine [16].

1.4 Global Trends for Green H_2 Production

With the help of goals, policies, and strategies defined by many nations, the market for decarbonized hydrogen is growing. As of August 2022, 38 nations and the European Union (EU) had declared decarbonized hydrogen policies with explicit goals for increasing electrolyzer capacity and producing hydrogen, according to CEEW's study [18]. Among them, 29 are advanced economies. The EU intends to install 40 GW of electrolyzer capacity by 2030 in order to produce 10 MTPA of green hydrogen. For this, investments in electrolyzers and renewable energy will total USD 46 billion and USD 520 billion, respectively. China has set a goal of adding 80 GW of electrolyzer capacity by 2060, which is the highest in Asia. With a goal of 0.42 MTPA by 2030, Japan has begun harnessing solar energy in Fukushima to produce green hydrogen. By 2030, India's National Green Hydrogen Mission, which was first announced in 2021, hopes to add 5 MPTA of green hydrogen. Major oil producers in the Middle East and North Africa (MENA) area are diversifying their energy portfolios. The largest green ammonia plant in the world is being built in Saudi Arabia, using 4 GW of renewable energy capacity for electrolysis to create 1.2 MTPA of green ammonia. Africa's contribution to the world's total renewable energy capacity in 2020 was only 54 GW, or less than 2%. Only seven of the 604 low-carbon hydrogen projects listed in the International Energy Agency's (IEA) database are being developed on the African continent: in South Africa, Mauritania, Egypt, and Morocco. The only African nations with specified green hydrogen targets are Namibia and South Africa. With lofty goals of 5- and 25-GW electrolyzer capacity increase by 2025 and 2030, respectively, Chile has assumed leadership in Latin America. The 3-GW target for Colombia by 2030 is similar to that of advanced nations like Austria, the Netherlands, and Portugal.

1.5 Challenges with Hydrogen as Fuel

Along with several advantages of hydrogen fuel is the process of decarbonizing the environment. Given the differences between hydrogen and many conventional hydrocarbon fuels, there are hurdles that must be acknowledged even though using hydrogen can result in lower CO_2 emissions. There are several challenges that need to be addressed for utilizing hydrogen as a fuel in power generation. Hydrogen is two times more energetically dense than methane on a mass basis (Table 1.2). However, the comparison of energy per unit volume between hydrogen and methane shows that the latter has three times more than the former. As a result, hydrogen requires a flow of three times the volume to produce the same amount of heat (energy) as methane. Therefore, a fuel accessory system setup for the requisite flow rates is needed to operate a gas turbine on 100% hydrogen [10].

With hydrogen, there are extra operational difficulties that concern general security. First off, a hydrogen flame is dim and challenging to view

Table 1.2 Lower heating value and flame speed of fuels [10, 11].

Name of fuel	Chemical formula	Lower heating value (LHV)	Laminar flame speed at stoichiometric conditions
Hydrogen	H_2	120.0 MJ/kg 10.8 MJ/m^3	170 cm/s
Methane	CH_4	50.0 MJ/kg 35.8 MJ/m^3	38.3 cm/s
Ethane	C_2H_6	47.8 MJ/kg 27.3 MJ/m^3	40.6 cm/s
Propane	C_3H_8	46.4 MJ/kg 23.1 MJ/m^3	42.3 cm/s
Ethanol	C2H6O	26.7 MJ/kg 21.1 MJ/m^3	45.5 cm/s

with the naked eye. This necessitates the use of flame detection devices designed specifically for hydrogen flames. Second, despite being thought of as airtight or impenetrable to other gases, hydrogen can seep through seals. As a result, welded connections or other suitable parts may need to be utilized in place of conventional sealing systems used with natural gas. Third, the lower flammability limit for hydrogen is 4%, whereas it is 5% for methane (in air). As a result, hydrogen leaks could lead to higher safety concerns, necessitating modifications to industrial practices, safety/exclusion zones, etc. There might also be other plant-level safety issues that need to be looked at.

The storage of hydrogen is also one of the major deterrents for its use in certain applications of power generation. The underground and overground storage options have to be integrated for realizing the hydrogen energy chain. Its large quantity storage in salt caverns, unserviceable hydrocarbon reservoirs, aquifers, hard rock caverns, etc., are being attempted; however, it requires huge structures depending upon the storage cycles, capacities, and hydrogen purity needed at the time of its retrieval. The overground storage of hydrogen is good for applications that are of stationary or mobile nature needing small capacity and fast storage cycle. The storage of hydrogen is done in different forms like compressed, cryogenic, or its combination in the pressure vessels. Also, there is a possibility of storing hydrogen by adsorbing or absorbing it in different materials; however, its selection depends upon the specific application for which hydrogen is the energy source.

The presence of hydrogen in different fuels, whether in small or large quantity, makes them suitable for being used to run gas turbines, but the hydrogen alone has extraordinary capabilities and environment friendliness for powering these gas turbines. Undoubtedly, there are various difficulties in the use of hydrogen as fuel in gas turbines and other engines, which need to be sorted out in due course of time. Many of the technical problems regarding the suitability of this fuel for power generation applications have been resolved as a result of industrial experience with hydrogen-based fuels. Consequently, it is important to think of retrofitting of current gas turbine power facilities as an integral part of any future power to hydrogen ecosystem.

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