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Hydrogen is the Future of Energy Security and Sustainability: A Review

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Abstract

Human society is highly dependent on energy sources to fulfill its everyday needs. As the human population grows energy consumption increases; but energy sources that fulfill their needs are limited, polluting, and exhausting in nature, so renewable energy sources are the only option to tackle the human population and industrial energy needs. Hydrogen as a renewable energy source is the best option. Solar and wind energy are intermittent in nature so they cannot provide continuous energy, so we need some other intermediate source to store this energy for a long time and use this energy when needed. Hydrogen has a high gravimetric density. It is highly flammable in nature and burns with blue flame with oxygen. Hydrogen can be used as an energy carrier for intermittent energy sources and their excess electricity production during low demand can be converted into green hydrogen using electrolysis and other processes. This hydrogen can be used to produce electricity when solar and wind can't produce electricity because of bad weather/monsoon season or any other reason, that way it can help in continuous power supply. Produced hydrogen can also be used for secondary hydrogen-based applications like FCEVs, industrial applications, and other need-based applications. In this article, hydrogen is presented as the fuel of the future and its properties, production techniques, and applications are discussed. Literature review has been done in the field of renewable energy sources, hydrogen technologies, and hydrogen as a future fuel. This paper is intended to present hydrogen's capability as a future fuel and its applications in different fields currently and in the near future.

Keywords

Future-fuel, Hydrogen storage, Hydrogen production, FCEVs.

1. Introduction

Energy plays a very important role in human life whether it is electric, chemical, mechanical, thermal, or any other form of energy. Human life is dependent on the different types of energies, from the application perspective humans directly interact with electric energy in general. Most of the appliances and utility products are based on electric energy, which is also produced from other types of energy sources. Conventional energy sources like coal, natural gas, and petroleum products have been the main energy sources for humans from the beginning of industrialization but these energy sources are limited and exhausting in nature. Conventional energy sources also produce greenhouse gases like CO_2, CO, NO_2 and other polluting gases that negatively affect the environment, as well as human life, for these reasons, the need for alternative energy sources arises.

The greatest solution to the problems caused by the depleting nature of conventional fuels, greenhouse emissions, unavailability, etc. is to adopt renewable energy sources. The majority of renewable energy sources, such as solar, wind, hydroelectricity, biomass energy, geothermal energy, nuclear power, etc., are pollution-free. However, although solar and wind power are both very intermittent and need to be coupled with either energy storage or other more reliable power sources, hydro and nuclear power are steady power sources that can supply a significant portion of the base load. Batteries work well for storing energy for the short term, but not for the long term [1].

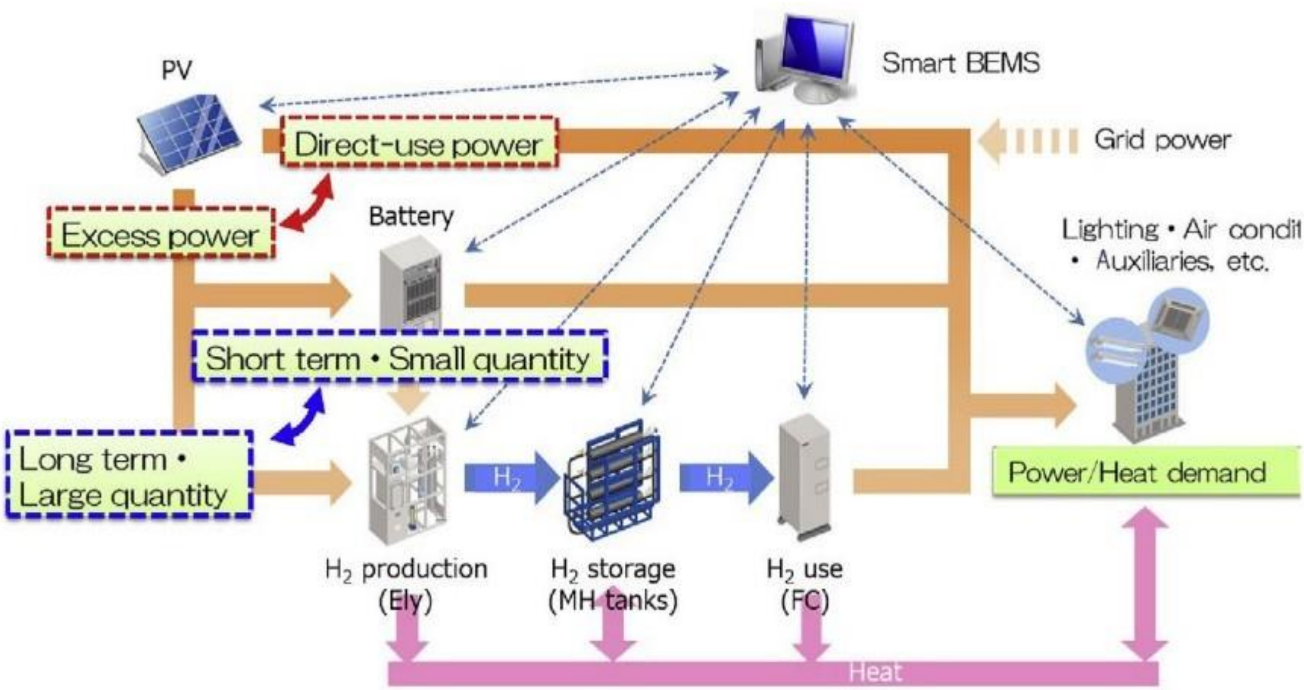

Figure 1. A schematic representation of energy flow of the renewable energy (solar energy, PV panels) and hydrogen energy (electrolyser, fuel cell) [1-2].

Hydrogen is one of the most practical options for the long-term storage of renewable energy. The basic idea is that at times when energy output from renewable sources is higher than electricity use, excess wind or solar energy is used to create hydrogen by electrolyzing water. Intermittent renewable energy sources like solar and wind require a solution for working in every weather condition and season. Therefore, energy stored as hydrogen can be utilized and the reliability of these intermittent renewable energy sources can be increased; schematic representation of renewable sources energy flow is shown in Figure 1. In this paper, all aspects of hydrogen as future fuel were reviewed whereas the focus is kept on hydrogen production, storage, challenges, and study gap in this field [1]. Total energy consumption from various sources such as oil, natural gas, coal, nuclear, hydrogen, biofuel and waste and others are plotted in Figure 2.

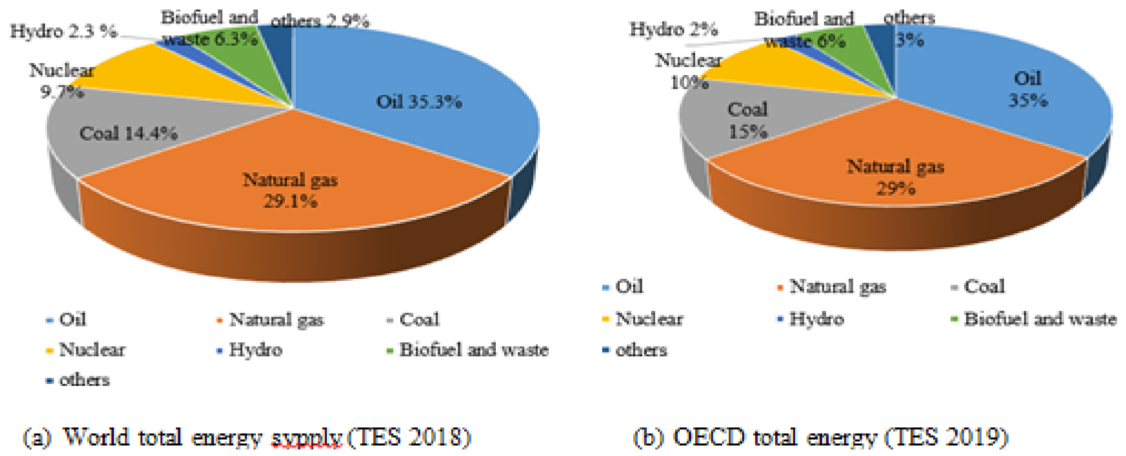

Figure 2. World's total energy (a) primary energy supply (TPES) (b) OECD total energy by energy source in 2020 (other includes geothermal, solar, wind, heat, biofuels and waste etc.) (Data from ref. [1])

2. Hydrogen Production Methods

Hydrogen is produced conventionally using non-renewable energy sources, but those methods do not solve the goal of a clean and green environment, schematic flow chart of hydrogen production methods from various sources such as fossil fuels, nuclear energy and renewable energy is shown in Figure 3.

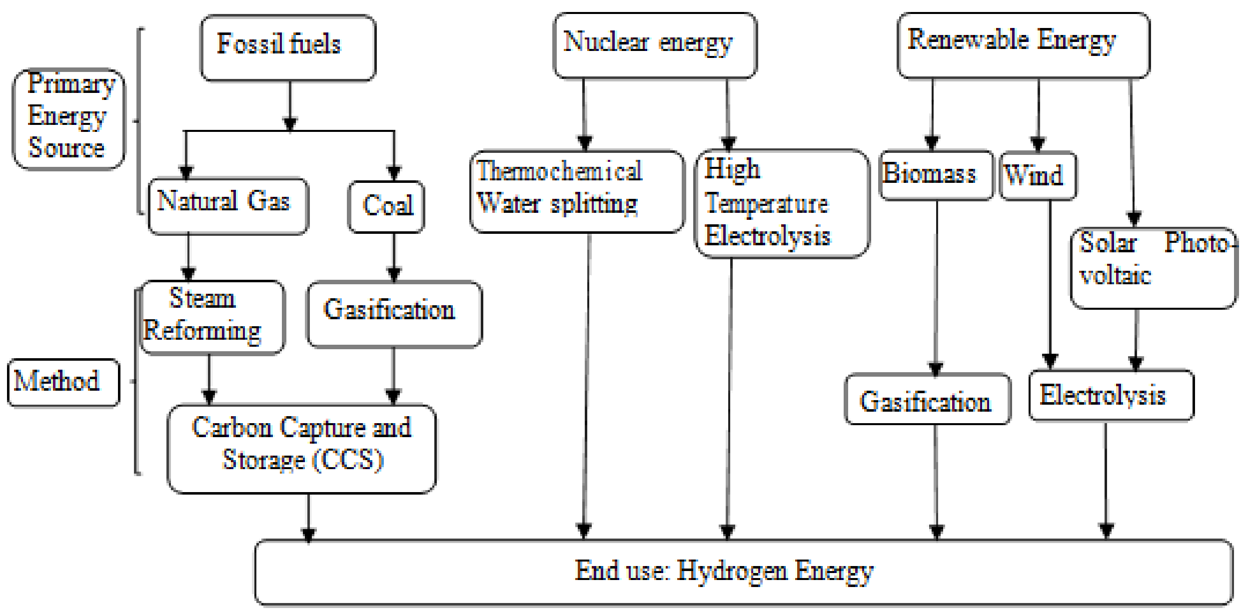

Figure 3. Hydrogen production methods (modified from Ref. [14])

Hydrogen production though photovoltaic panels, electrolyze and electric load is shown in Figure 4 as explained by Sazali [4]. We will discuss all existing and emerging hydrogen production methods based on renewable energy sources as well as non- renewable energy sources. Following are the methods of hydrogen production.

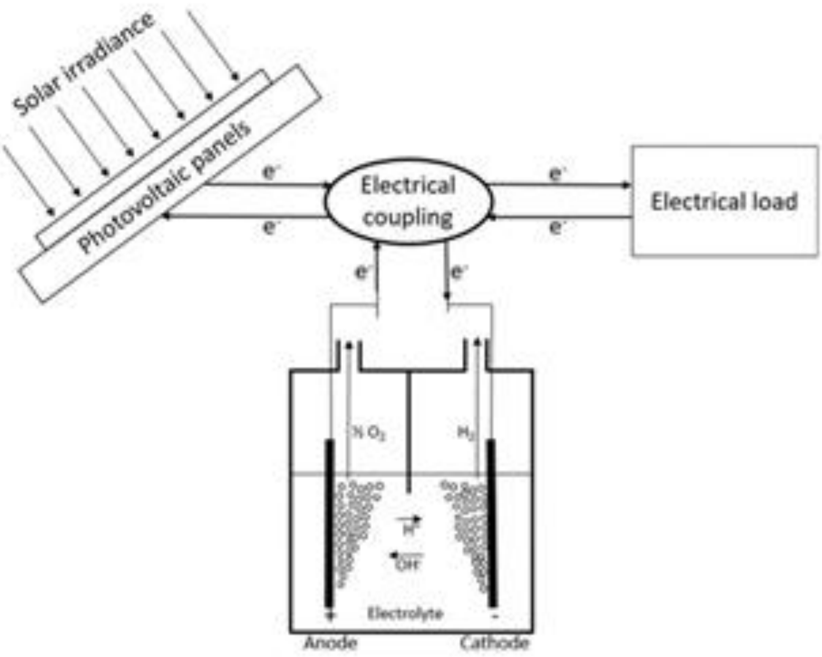

Figure 4. A simplified schematic of photovoltaic panels coupled with an electrolyser and an electrical load [4]

Prewitz et al. [5] examined the benefits and problems of using hydrogen as the fuel of the future for aeroplanes. They investigated the potential and difficulties of using hydrogen as an aeroplane fuel and compared it to the current fuel system for aircraft while taking into account the passenger ATR 72-212A. Li and Kimura [6] investigated how fuel cell electric cars and hydrogen energy might affect the environment in ASEAN nations. In this study, alternative powertrains are compared to hydrogen-based road transportation, particularly FCEVs in fleets of passenger cars, buses, and trucks in ASEAN member states (AMS), taking into account cost, CO2 emissions, ownership costs, and energy content per km. The Well-to-wheel (WTW) model for estimating the costs and emissions of hydrogen supply, as well as Total cost of ownership (TCO) models for estimating the costs and emissions of owning and operating vehicles, were developed by the author in this study. These models served as the foundation for all research and were used to compare current and future scenarios. Studying the production, distribution, and transportation economics of hydrogen. The cost of producing hydrogen through centralized and forecourt methods is still greater with the existing technology, although it varies from country to country depending on the state of the energy market, tariff structures, taxes and subsidies, and other national regulations. A sizeable amount of the overall cost of hydrogen to end consumers also goes into transportation and distribution.

A study on hydrogen storage techniques was conducted by Tarhan and Cil [7]. Hydrogen is the clean energy of the future. This research focuses mostly on hydrogen storage techniques while also discussing hydrogen generation, utilization, future potential, and safety precautions. Since it is predicted that there will be 10 billion people on the planet by the year 2050, obtaining clean, renewable hydrogen energy is one of the best solutions available to address the escalating energy demand.

In current scenario main problem with hydrogen is cost, transportation and storage for long term but with the developing technology and the research in the field has reduced the cost, studies show with historic data that cost of production will further decrease 50% up to 2030. Hence main focus is on the storage technologies and transportation infrastructure with the focus towards the future scenario.

Pareek et al. (2020) discussed advantages and challenges of hydrogen energy, recent advances, and prospects. As of now most hydrogen produced by steam methane reforming which fulfils industrial hydrogen need and only about 4 % produced using electrolysis. So, most hydrogen production depends on non-renewable energy sources, fossil fuels that produce greenhouse gases which contribute to global warming, climate change and other problems related to the environment. Hence the solution to these problems are renewable energy sources, where hydrogen as an energy carrier fits the best alternative; hydrogen production by steam reforming process is shown in Figure 5.

Medisettty et al. [9] reviewed paper on an overview on the current status of hydrogen energy research and development in India. In this paper all the current projects and research related to hydrogen production, storage, applications as well as current available technologies of hydrogen production and storage in India were analyzed. In India these technologies and applications are in their initial stages or only in research capacity. Sontakke and Jaju [10] focused on green economy for India and advantages of becoming green economy. The main issue of the 21st century is global warming and climate change that can be possibly solved by taking steps towards a green economy by all countries. In a green economy energy is produced by renewable energy sources. In which, hydrogen emerging as best alternative for fossil fuels that can help fight climate change and other issues.

Bock et al. [11] investigated thermo-economic behavior of fixed-bed chemical looping for decentralized, fuel-cell-grade hydrogen production coupled with a 3MWth biogas digester. In this paper a concept of fuel cell grade hydrogen production using biogas is presented. Thermodynamic and economic analysis was done. Also, the results obtained from the analyzed data were compared with existing models working on the same technology i.e., producing hydrogen using biogas.

Guo and Sepanta [12] examined a new combined energy system performance to produce electricity and hydrogen with energy storage option. In which they presented a concept of hybrid energy production and storage of excess energy. They used wind energy for this study, a 10KW wind-turbine was used for electricity generation and then that electricity is further used in electrolysis for hydrogen production. The excess electricity generated by wind-turbine is stored using Pumped-hydro com- pressed air (PH-CA) system that can store the energy in the form of compressed-air and pressurized water system.

2.1. Steam reforming

It is now the most widely used and cost-effective method of manufacturing hydrogen. Natural gas is cleaned of any impurities before being mixed with steam and sent across a reactor that is externally heated, where carbon monoxide (CO) and hydrogen (H_2) are created. This process is known as steam reforming. After that, a catalytic water gas shift mechanism converts the CO and water into hydrogen and carbon dioxide (CO_2). The hydrogen gas is then cleaned. Large reformers (e.g., 100,000 tonnes yearly) may attain yields of more than 80% with this method. Lower efficiency can be found in smaller reformers, especially those utilised in micro fuel cells [14].

2.2. Coal gasification

Due to the availability of coal reserves found around the world and commercially available technology, coal is a practical choice for creating hydrogen in large facilities. Compared to currently employed methods (like electrolysis), gasification is a better choice for converting coal to hydrogen. Coal is partially oxidized with steam and oxygen in a high-temperature, high-pressure reactor during the coal gasification process. Syngas is one of the main final products, mostly composed of CO and H_2. To increase the output of hydrogen, the syngas undergoes a shift procedure. The gas can be cleaned using the customary procedures to obtain elemental sulphur or create sulfuric acid. Some of the syngas might be used in a gas turbine to provide electricity. The major cause for concern when thinking about coal gasification is the high carbon content of coal and the higher CO_2 emissions compared to alternative feedstock sources. To address this problem, CCS (Carbon Capture and Storage) systems are being developed.

In a major coal gasification plant today, it costs slightly more to produce hydrogen than it would if it were produced from natural gas. However, compared to those employed in the steam reforming of natural gas, coal gasification procedures are less clearly defined. Comparing the economics of producing hydrogen from coal to that of other fossil fuels, Figure 6 shows that coal gasification facilities have higher unit capital costs, but their unit raw material prices are lower [8, 14].

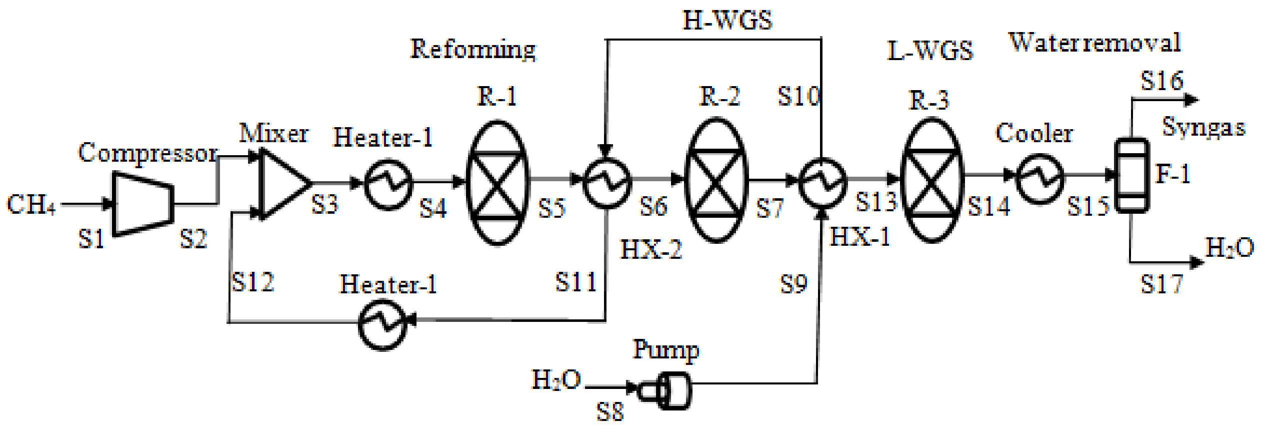

Figure 5. Schematic of production of hydrogen by steam reforming process [8, 14]

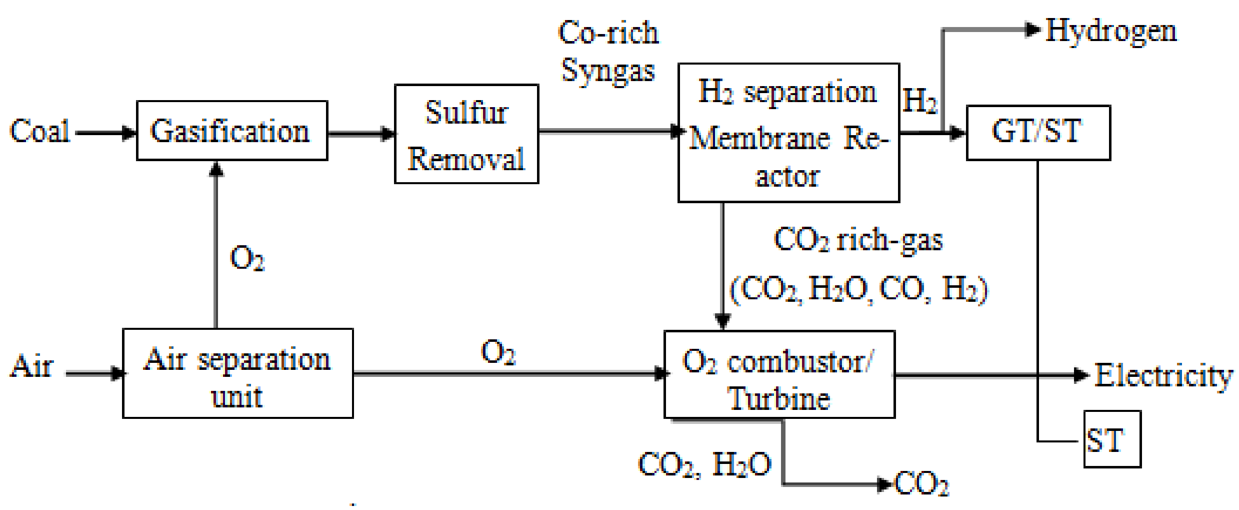

Figure 6. Schematic showing hydrogen production via coal gasification [8, 14]

2.3. Thermochemical water splitting

Nuclear reactors can use thermochemical water-splitting cycles to create hydrogen when the temperature is 500 °C or higher. At higher temperatures, better efficiency and reaction speeds may be attained. More than 100 potential high-temperature thermochemical water-splitting processes have been proposed thus far. In the 1970s, the thermochemical Cu-Cl cycle was initially postulated. Some Cu-Cl cycles that are currently on the market are being tested. Cu-Cl cycles are predicted to have efficiencies of around 40% at operating temperatures of about 550 °C (cogeneration of electricity is omitted).

One of the main problems with thermo-chemical Cu-Cl cycles is lowering the temperatures needed for high efficiency. Higher efficiency can be attained using thermochemical S-I cycles (about 60% with cogeneration of electricity). These cycles, however, need temperatures between 825 and 900 °C. To carry out these thermochemical cycles, specialized reactors made of specially designed chemically inert materials that can withstand high temperatures are required [15].

2.4. High-temperature electrolysis

Even though the efficiency of converting electricity to hydrogen may increase to as much as 80% under pressure, the efficiency of nuclear power plants is confined to about 33% with current reactors. The low-efficiency issue could be resolved by creating reactors that operate at higher output temperatures. For instance, at 950 °C, the 20% efficiency from 350 °C rises to around 50% [16].

2.5. Electrolysis

A diagram of the electrolysis process for producing hydrogen may be shown in Figure 7. Water is converted into hydrogen and oxygen during the electrolysis process by the introduction of electrical current. Two electrodes—a cathode and an anode—are frequently used in an aqueous solution containing KOH electrolyte. This thing is called an electrolyser. Electrolysers can be small or large, depending on how much hydrogen is produced on a small or large scale, respectively. This method is suitable for the production of dispersed hydrogen. Electrolysis can create hydrogen while emitting no greenhouse gases, depending on the energy source utilized to split the water molecules. In order to substitute energy for electrolysis, experts are focusing on wind energy or the nuclear option. The two primary benefits of this process are that there are no greenhouse gas emissions, and it may be used to generate renewable energy. The key difficulty with this technology is lowering the price of making electrolysers while also increasing the process's effectiveness. To avoid the expense of a separate compressor, which is desirable for high-pressure hydrogen storage, another difficulty is to interface the compressor in an electrolyser [8].

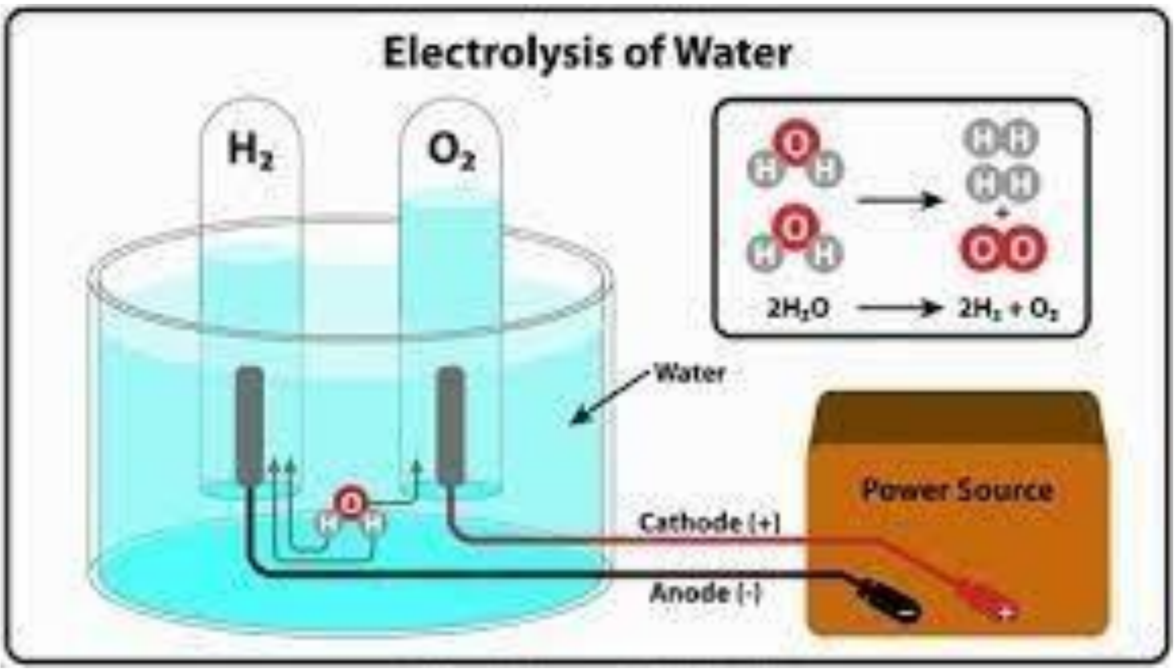

Figure 7. Schematic showing hydrogen production via. Electrolysis [8]

2.6. Biomass gasification

One of the potential energy sources for the production of hydrogen is biomass. It is commonly referred to as biological organic energy resources and includes waste materials including animal and human waste, forest wastes, witch grass, and wheat straw. Energy may be produced from biomass using a variety of techniques, including physical, thermal, chemical, and biological conversion. Heat, electricity, solid fuels like coal, liquid fuels like bio-oil and methanol, and petrol fuels like hydrogen and syngas may all be produced from biomass [8]. In order to create an energy carrier, feedstocks (such as biomass, lignocellulosic residues, agricultural waste, refuse-derived fuel, and organic wastes) are destroyed by the thermochemical process known as gasification. However, the approach using only steam results in higher energy expenses due to the steam's rising temperature. Additionally, because the steam gasification reaction is an exothermic reaction, air is also employed in the partial oxidation (exothermic reaction) reaction of biomass to lower the energy cost. As a result, when biomass reacts with steam and oxygen at high temperatures and pressure, a combination of hydrogen, carbon monoxide, and carbon dioxide can be produced. A gasifier is the device utilized to carry out such processes. By using heat, steam, and oxygen present in the gasifier, this method breaks down biomass chemically to generate the synthesis gas. Additionally, the water gas shift process, which is comparable to the gasification of coal, transforms carbon monoxide (CO) into carbon dioxide (CO_2) and hydrogen (H_2), leading to the separation of hydrogen [8].

2.7. Biological hydrogen production

Biological hydrogen production the bio-hydrogen technique of hydrogen generation has exploded in popularity over the past two decades due to the need to reduce waste and the increased percentage of waste materials. Microorganisms that are found in an aqueous environment, at atmospheric pressure, and at room temperature catalyze biological processes. Such procedures can be used in areas with readily accessible supplies of biomass or biodegradable garbage. Thus, the natural availability of these precursors lowers the original raw material's energy and transportation costs. One must be able to choose these materials for producing effective hydrogen energy due to their availability, low cost of raw materials, carbohydrate content, and biodegradability. Generally speaking, biological activities take place across a variety of anaerobic bacteria or algae. Contrary to previous approaches, bio-hydrogen is an intriguing sustainable methodology that calls for technical advancement in order to produce hydrogen efficiently and profitably. Hydrogen generated biologically is a by-product of numerous microorganism metabolic activities [8]. Biological hydrogen production methods can be classified as follows:

- Direct bio-photolysis
- Indirect bio-photolysis
- Photo fermentation
- Dark fermentation
- Two-stage process (integration of dark and photo fermentation)
- Bio-catalyzed electrolysis

Various hydrogen production and storage technologies are given in Table 1, as discussed by a few researchers.

Table 1. Various hydrogen production and storage technologies.

Authors	Hydrogen Production Technology	Storage technology	Contribution	Remarks
Egeland-Eriksen et al. (2021)	Electrolysis using solar or wind electricity	Compressed gas storage Metal hydride storage	Review of energy storage in power systems. Review of energy management and control systems	Best solution is hybrid systems where hydrogen combined with short-term energy storage technologies like batteries, super capacitors
Rabiee et al. (2021)	Electrolysis using solar electricity	Not specified	SC-MPOPF model is developed for optimal Scheduling of generators and P2H units.	Increasing the wind penetration level results in a considerable reduction in both TC and WC.
Prewitz et al. (2020)	-	Compressed gas Chemical, metal hydrides	Minimum gravimetric storage density for empty fuel tank total mass	About 65% of fuel mass can be reduced only by substituting hydrogen as fuel but volume increase enormously.
Pareek et al. (2020)	SMR, coal gasification, electrolysis, biomass gasification, photo electrochemical, advance pro- duction techniques	-	-	The 95% of today's hydrogen demands are fulfilled by natural gas as it proves to be promising technique relative to present scenario.
Bock et al. (2021)	Using biogas	-	99.999% Pure hydrogen production using biogas	Using this concept, we can obtain pressurized hydrogen
			for FCEV use. Efficiency enhancement of such system	production, which will save energy for storage of hydrogen as compressed gas.
Guo and Sepanta (2021)	Electrolysis	-	Pumped-Hydro Com- pressed air (PH-CA) storage system for excess electricity was given	The concept prioritize hydrogen production, whereas PH-CA used for energy storage.

3. Hydrogen Storage Techniques

Hydrogen mainly can be stored in three forms i.e., compressed, liquid, and solid.

3.1. Compressed hydrogen storage

In order to enhance the storage density seen in Figure 8, hydrogen gas is compressed and stored under pressure. For hydrogen tank systems in cars, compressed hydrogen in hydrogen tanks at 350 pressure and 700 bar is employed. Because storing hydrogen at greater pressure is technologically more advanced and, in comparison, easier than other techniques of storage, this approach is now employed to store hydrogen. Additionally, compressed hydrogen storage is easier to transport than other storage options since the infrastructure is already in place [17].

Figure 8. Compressed Hydrogen Storage Tank [17]

3.2. Liquefied hydrogen storage

Since hydrogen has a boiling point of 252.8°C at one atmosphere of pressure, storing it as a liquid requires cryogenic temperatures. The Kobe port in Japan provides a location for storing liquid hydrogen (L H_2) tanks used in vehicles like the BMW Hydrogen 7 model. Similar to how liquefied natural gas (LNG) is held at 162 °C, hydrogen is liquefied by cooling it to 252.8 °C. 4.26 kWh/kg out of 33.3 kWh/kg, or a theoretical efficiency loss of just 12.79%, may be obtained. In liquefying hydrogen gas 30% of its energy content is used, which is a big share of its energy, so research on more efficient methods and devices for liquefying is ongoing. Boil-off gas is a major issue of liquid hydrogen which should be minimized with better technology, so that storage for long periods can be possible with liquid hydrogen [17].

3.3. Solid hydrogen storage (Chemical storage)

Additionally, materials' surfaces and interiors may also be used to store hydrogen through adsorption and absorption, respectively. Due to the large storage densities, chemical storage may provide good storage performance. For instance, saturated dimethyl ether and methanol both have densities of 42.1 mol H2/L at 30 °C and 7 pressure, but supercritical hydrogen only has a density of 15.0 mol/L at 30 °C and 500 bar [17].

4. Applications

- Industrial application- oil refining, ammonia production, methanol production, and steel production is shown in Figure 9 [18-19].

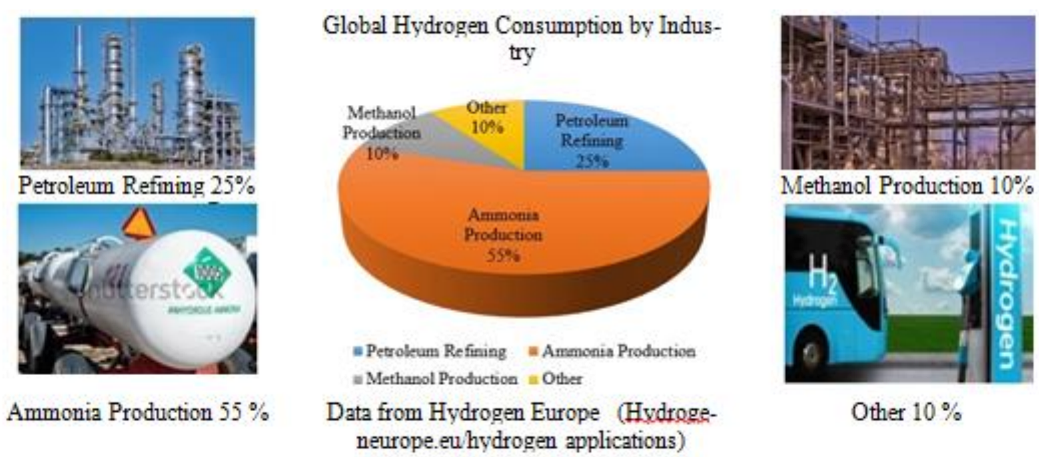

Figure 9. Various industrial application of hydrogen [18-19]

- Outer space application- For combustion with oxygen or fluorine, hydrogen has been utilized as a main rocket fuel.
- Fuel cell application- Atoms of hydrogen and oxygen are combined to create power in hydrogen fuel cells. In an electrochemical cell like a battery, hydrogen and oxygen combine to create electricity, water, and a tiny quantity of heat.

5. Challenges and Safety

Hydrogen is safer to handle and use than many of the current fuels because of a number of its characteristics. Hydrogen, for instance, is harmless. Additionally, as hydrogen is considerably lighter than air, it evaporates quickly when released, allowing for the fuel to disperse relatively quickly in the event of a leak.

To guarantee the safe usage of hydrogen, several of its features need extra technical controls. In particular, hydrogen may ignite more readily than petrol or natural gas due to its wide range of combustible concentrations in the air and lower ignition energy. In order to create safe hydrogen systems, sufficient ventilation and leak detection are crucial components. Special flame detectors are needed since hydrogen burns with a practically undetectable flame.

Additionally, some metals can become brittle when exposed to hydrogen, making it crucial to use the right materials when designing secure hydrogen systems. A crucial component of guaranteeing the safety of hydrogen use is training in safe hydrogen handling procedures in addition to designing safety elements into hydrogen systems.

Hydrogen can be generated, stored, and supplied securely, as demonstrated by testing of hydrogen systems such as tank leak tests, garage leak simulators, and hydrogen tank drop tests. As more and more hydrogen demonstrations get going, the safety track record of hydrogen can improve and inspire confidence that hydrogen can be just as safe as the fuels currently in general use [13].

6. Conclusion

In this article discussed the storage and production of hydrogen, which will be future fuel, all aspects, needs, and challenges. Presently available fuels are fossil fuel based which is very harmful to the environment and humans. These fuels are also limited and exhausting in nature so eventually, they will exhaust but hydrogen is renewable in nature so we can use it for a long time. Hydrogen does not exist freely in nature, so we must produce it. Future opportunities with hydrogen are abundant because it can be used in every field of life. We can use it with a fuel cell that has a wider projected area of work like passenger vehicles, trucks, trains, aircraft, and in the household application. We can expect liquid hydrogen in passenger vehicles so that the driving range of vehicles can be increased, although it has many challenges. However, research is ongoing for such applications and storage devices.

Scope of future research in hydrogen fuel technology has many areas like advanced green hydrogen production methods, molecular dynamics-based research for increase in efficiency of hydrogen production methods, liquid hydrogen storage tanks for mobile applications, safety device for hydrogen leakage detection, research to reduce boil-off in liquid hydro- gen, hydrogen distribution infrastructures for the mass population, the efficiency of electrolyser, standalone hydrogen pro- duction and storage, and many more.

In the current scenario, 95% of hydrogen production is using natural gas but these production methods produce CO_2 and other gases. However new methods include carbon capture technology, but still natural gas is a non-renewable energy source. The adoption curve of the hydrogen economy should be smooth because fossil fuels-based energy sources have a strong and industry-dependent infrastructure. Many countries are already making policies for a hydrogen-based economy and future targets for a completely carbon-free and green energy-based economy.

India also has many opportunities with a hydrogen-based economy and infrastructure. The Indian government has a net-zero emission target by 2070. For a completely renewable energy-based economy in which green hydrogen can play a very important role, therefore more advanced research for hydrogen-based technology and infrastructure should be carried on with a focus on Indian demographics as well as energy needs.

References

[1]. T. E. Eriksen, A. Hajizadeh, & S. Sartori, “Hydrogen-based systems for integration of renewable energy in power systems: Achievements and perspectives,” International journal of hydrogen energy, vol.46, no.63, pp.31963-31983, 2021. https://doi.org/10.1016/j.ijhydene.2021.06.218

[2]. A. Rabiee, A. Keane & A. Soroudi, “Green hydrogen: A new flexibility source for security constrained scheduling of power systems with renewable energies,” International journal of hydrogen energy, vol.46, no.37, pp.19270-19284, 2021. https://doi.org/10.1016/j.ijhydene.2021.03.080

[3]. N. A. Burton, R. V. Padilla, A. Rose, et al., “Increasing the efficiency of hydrogen production from solar powered water electrolysis,” Renewable and Sustainable Energy Reviews, vol.135, 2021. https://doi.org/10.1016/j.rser.2020.110255

[4]. N. Sazali, “Emerging technologies by hydrogen: A review,” International Journal of Hydrogen Energy, vol.45, no.38, vol.18753- 18771, 2020. https://doi.org/10.1016/j.ijhydene.2020.05.021

[5]. M. Prewitz, A. Bardenhagen & R. Beck, “Hydrogen as the fuel of the future in aircrafts challenges and opportunities,” International Journal of Hydrogen Energy, vol.45, no.46, pp.25378-25385, 2020. https://doi.org/10.1016/j.ijhydene.2020.06.238

[6]. Y. Li & S. Kimura, “Economic competitiveness and environmental implications of hydrogen energy and fuel cell electric vehicles in ASEAN countries: The current and future scenarios,” Energy Policy, vol.148, 2021. https://doi.org/10.1016/j.enpol.2020.111980

[7]. C. Tarhan & M. A. Çil, “A study on hydrogen, the clean energy of the future: Hydrogen storage methods,” Journal of Energy Storage, vol.40, 2021. https://doi.org/10.1016/j.est.2021.102676

[8]. A. Pareek, R. Dom, J. Gupta, et al., “Insights into renewable hydrogen energy: Recent advances and prospects,” Materials Science for Energy Technologies, vol.3, pp.319-327, 2020. https://doi.org/10.1016/j.mset.2019.12.002

[9]. V. M. Medisetty, R. Kumar, M. H. Ahmadi, et al., “Overview on the current status of hydrogen energy research and development in India,” Chemical Engineering & Technology, vol.43, no.4, pp.613-624, 2020. https://doi.org/10.1002/ceat.201900496

[10]. U. Sontakke, & S. Jaju, “Green hydrogen economy and opportunities for India,” In IOP Publishing Conference Series: Materials Science and Engineering, vol.1206, no.1, pp. 1-14, 2021. https://doi.org/10.1088/1757- 899x/1206/1/012005

[11]. S. Bock, B. Stoppacher, K. Malli, et al., “Technoeconomic analysis of fixed-bed chemical looping for decentralized fuel cell grade hydrogen production coupled with a MWth biogas digester,” Energy Conversion and Management, vol.250, 2021. https://doi.org/10.1016/j.enconman.2021.114801

[12]. X. Guo & M. Sepanta, “Evaluation of a new combined energy system performance to produce electricity and hydrogen with energy storage option,” Energy Reports, vol.7, pp.1697-1711, 2021. https://doi.org/10.1016/j.egyr.2021.03.026

[13]. A. Keçebaş & M. Kayfeci, “Chapter 1-Hydrogen Properties,” Solar Hydrogen Production, pp.1-47, 2019. https://doi.org/10.1016/B978-0-12-814853-2.00001-1

[14]. C. Acar & I. Dincer, “Comparative assessment of hydrogen production methods from renewable and nonrenewable sources,” International journal of hydrogen energy, vol.39, no.1, pp.1-12, 2014.

[15]. B. Yildiz & M. S. Kazimi, “Nuclear energy options for hydrogen and hydrogen-based liquid fuels production. Massachusetts Institute of Technology center for Advanced Nuclear Energy Systems,” Nuclear Energy and Sustainability Program, 2003. [accessed 29.06.22]

[16]. S. Fujiwara, S. Kasai, H. Yamauchi, et al., “Hydrogen production by high-temperature electrolysis with nuclear reactor,” Progress in Nuclear Energy, vol.50, no.2, pp.422-426, 2008.

[17]. D. A. J. Rand & R. M. Dell,” Fuels Hydrogen Production Coal Gasification,” Encyclopedia of electrochemical power

sources, pp.276-292, 2009. Hydrogen storage - Wikipedia [accessed 29.06.22]

[18]. Production and applications of hydrogen, https://www.britannica.com/science/hydrogen/Production-and-applications-of-hydrogen [accessed 29.06.22]

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