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Research Article

Hydrogen Production and Storage Methods

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Abstract **–**Conventional fuels are not renewable resources and are getting depleted day by day. In addition, the by-products of the combustion of these fuels cause environmental problems. This situation, which threatens the world, has led to the search for new energy sources. Hydrogen, as an energy carrier, creates a potential for solving these problems. Hydrogen is the most abundant element in the universe, with the highest energy content per weight of all conventional fuels. But unlike conventional fuels, hydrogen is not easily found in nature and is produced from primary energy sources. Therefore, it is a renewable fuel. When used in a fuel cell, only water is produced as a by-product. From this point of view, when compared to any fuel, it stands out as a fuel with the highest energy content and does not contain carbon. The biggest problem in using hydrogen gas as a fuel is that it is not found in nature and economically cheap production methods are needed. Hydrogen can be produced in two different ways, biological and chemical. Chemical methods are not preferred because they are costly. Biological methods, on the other hand, are low-cost, sustainable, environmentally friendly methods. In this study, information of hydrogen energy and its historical development is given. Thus, a projection is made for the importance and future of hydrogen energy. Then, hydrogen production methods are explained and compared. In addition, information about hydrogen storage types is given.

Keywords – Renewable Energy, Hydrogen, Hydrogen Energy, Hydrogen Production, Hydrogen Storage

I. INTRODUCTION

One of the most critical elements of sustainable development is energy resources. Energy is the most important economic factor in industrial societies. The basic requirement for improving the quality of life along with economic and social development is energy (Ahmadi & Khoshnevisan, 2022). Today, most of the energy demand is met by conventional fuel sources (Karayel, Javani & Dincer, 2022). The change in the world population by years, prepared according to the data shared by the World Bank, is given in Figure 1. According to these data, it is seen that the world population has increased steadily from 1960 to 2023 (World Bank, 2023).Increasing population and rapidly developing industrialization in recent years have rapidly increased the energy demand of human society, which has led to massive consumption of conventional fuels (Chen, Zhou, Guo & Xia, 2022; Singla, Shetti, Basu, Mondal & Aminabhavi, 2022). Conventional fuels are non-renewable energy sources that are certain to run out one day. The reserves of conventional combustible (fossil) fuels (coal, mineral oil and natural gas) will be completely depleted in 50 to 200 years if they are used at today's rate (Ayar, Yalçın & Dağ, 2023). It is also known that environmental problems such as climate change, greenhouse effect and air pollution are caused by the burning of fossil fuels. It has been stated that the most important reason for global warming is the excessive and unconscious use of fossil fuels such as coal, oil and natural gas, which are formed underground over hundreds of thousands of years (Akın, 2006). Therefore, one of the main problems of global energy demand is how to replace current energy resources with sustainable and environmentally friendly solutions (Karayel, Javani & Dincer, 2022). As seen in Figure 2, according to the projection created, the cumulative PV capacity is expected to exceed 2,350 GW by 2027. This trend occurs Cumulative PV will surpass hydropower in 2024, natural gas in 2026 and coal in 2027. Similar to these predictions, it is seen that the wind will continue to rise in 2027 and it will rise to the fourth place among the energies, surpassing hydropower (Renewables, 2022).

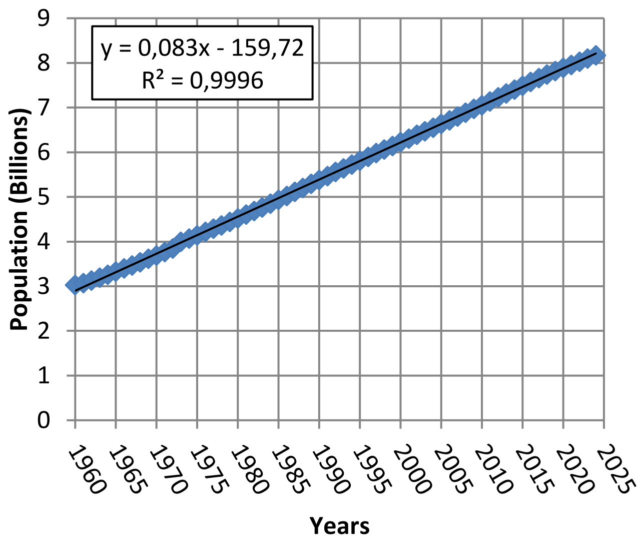

Figure 1. Population change of the World (Worldbank, 2023)

As a renewable energy carrier, naturally hydrogen will be one of the most competent fuel options in the future (Pal, Singh & Bhatnagar, 2022). Unlike fossil fuels, hydrogen is not easily found in nature and exists in the form of elements or compounds such as H_2 and H_2O (Satyapal 2017). However, it can be produced from any primary energy source and produces only water as a byproduct. Hydrogen, which can provide a large amount of energy without creating emissions and pollution on the environment, is used in large quantities in petroleum, automobile vehicles, and pharmaceutical industry, as an alternative to fuel oil and in the chemical industry. Hydrogen is a highly flammable gas. This is why spacecraft's engines use hydrogen as fuel to provide the propulsion they need. Also, although the initial set-up cost is high and expensive, maintenance costs are affordable (Singla, Shetti, Basu, Mondal & Aminabhavi, 2022).

There are many publications in the literature on hydrogen production technologies and storage techniques (Dodds et al., 2015; Staffell et al., 2019; Moradi & Groth, 2019; Oliveira, Beswick & Yan, 2021; Capurso, Stefanizzi, Torresi & Camporeale, 2022). This review provides a theoretical background on production technologies, storage and separation techniques, while evaluating recent updates in the hydrogen economy (in terms of key advantages and disadvantages).

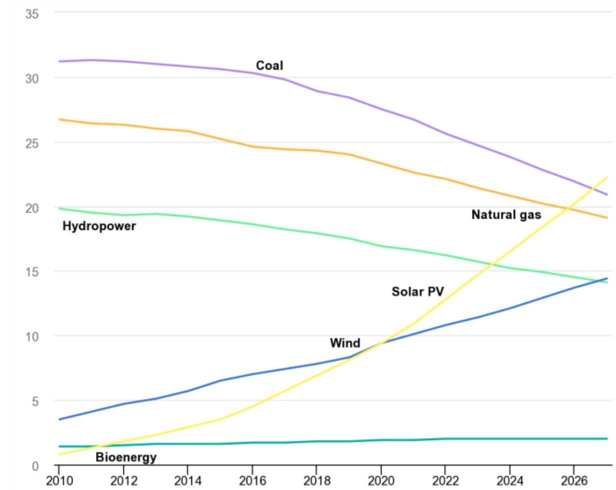

Figure 2. Share of cumulative power capacity by technology, 2010-2027 (Worldbank, 2023)

Hydrogen, Its History and Production

The origin of the word hydrogen is derived from the Greek word “Idrogono”, which means making water (Koşar, 2021). A large amount of energy is required to split water, the most abundant source of hydrogen. Based on the laws of thermodynamics, it can be stated that the energy required to split water is greater than the energy released from the hydrogen produced (Barbir, 2005). The diffusion coefficient of hydrogen is high. Its density is low and combustion energy is high. Energy ratio per unit weight is quite high. It is also non-toxic, odourless, colourless and tasteless from an environmental point of view. It has the potential to be converted into other energy forms (Singla, Shetti, Basu, Mondal & Aminabhavi, 2022).

The history of the use of hydrogen energy is quite long. The Swiss alchemist Paracelsus first obtained hydrogen in the 16th century while investigating the effect of acids on some metals (Polat, Yalçın & Şahin, 2012). In 1839, Swiss chemist Christian F. Schoenbien discovered that water and electric current emerged by the combination of hydrogen and oxygen gases. In 1845, British scientist Sir William Grove demonstrated Schoenbein's discovery on a practical scale by creating a "gas cell". Due to this success, he received the title of "Father of the Fuel Cell" (Jonas, 2009; Türe, 2021). In 1958, NASA announced that hydrogen was used as fuel. It has been shown that hydrogen can be used as a fuel in rocket propulsion in space exploration, and there has been an industrial revolution that uses hydrogen as fuel (The concept of hydrogen energy was developed in 1969 by using the exploitable properties of hydrogen (Polat, Yalçın & Şahin, 2012).

The production of low-carbon hydrogen, especially green hydrogen produced from renewable sources, makes hydrogen the energy source of the future. Unfortunately, 96% of all hydrogen today is produced from fossil fuels (brown hydrogen from the gasification of coal or gray hydrogen from natural gas) (Capurso, Stefanizzi, Torresi & Camporeale, 2022). That is, approximately 50% of the hydrogen produced worldwide is primarily obtained from natural gas through steam methane reformation, while 30% is produced from petroleum, 19% from coal, and the remaining 4% through water electrolysis (Keçebaş & Bayat, 2019). If hydrogen is to replace existing fuels in the future, suitable methods for large-scale CO-free hydrogen production must be developed. But given the inherent advantages of fossil fuels, such as the relatively low cost and existing infrastructure for distribution, hydrogen production will continue to depend on fossil fuels in the near and medium-term future. According to the production method of hydrogen, taking into account the greenhouse gas emissions that may occur during the production process, hydrogen energy is classified with color codes (Bektaş, Hakyemez, Yanık Özçelik & Yıldızca, 2021). This classification is shown in Figure 3.

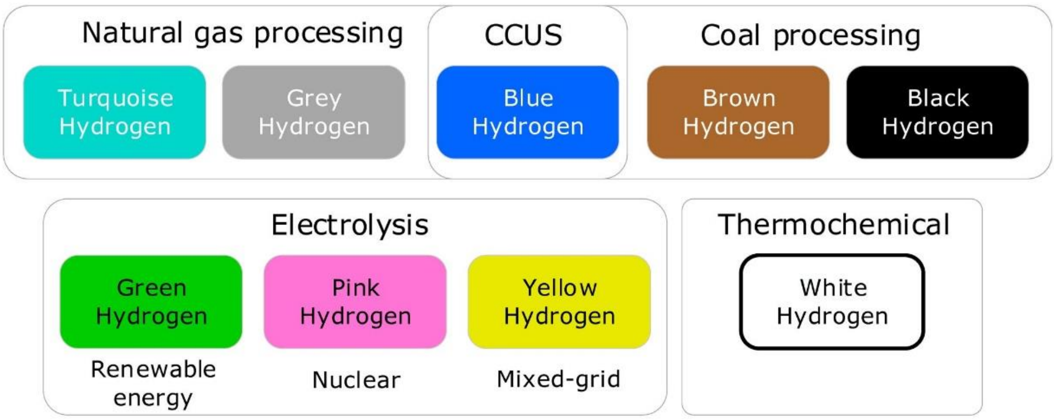

Figure 3. Hydrogen Energy Colors According to Hydrogen Production Methods (Panić, Cuculić, & Ćelić, 2022).

Hydrogen Production Options

Consisting of only one proton and one electron, hydrogen (the only element without neutrons) is the simplest element in the universe and the most abundant element in the universe. Hydrogen is not found free in nature, but in combination with other elements such as oxygen and carbon. Since it is found in combination with water or hydrocarbons, these substances must be reformed to obtain H_2. Various energy sources can be used in hydrogen production. These are mainly fossil fuels, nuclear, solar, wind, hydroelectric and geothermal energy. There are various production options for hydrogen production from these various energy sources. The most commonly used methods for hydrogen production are methane steam reforming, electrolysis and thermochemical cycles. Methane steam reforming is the most common method for hydrogen production and a very large proportion of the hydrogen produced, 95%, is produced by this method.

It is an important option to produce hydrogen from fossil fuel gas. However, if the carbon produced during this production is not captured or used, carbon emission will continue in the atmosphere. Carbon capture, utilisation and storage (CCUS) means including carbon capture and storage (CCS), carbon capture and utilization (CCU) and thus where the CO_2 is both used and stored (IEA, 2023). In this process, hydrogen is usually produced from natural gas by steam reforming. The resulting carbon dioxide is largely trapped and stored underground. It is estimated that this technology will be very useful in the transition to the clean energy era. In the production of "turquoise" hydrogen, hydrogen and solid carbon are produced using methane pyrolysis. "Blue" hydrogen is sometimes touted as a clean alternative. However, it is differentiated from gray hydrogen by the fact that carbon dioxide emissions are captured during production.

Hydrogen synthesis by thermochemical method is based on the production of hydrogen and oxygen from water. Nuclear energy, chemical reactions, concentrated solar energy or waste heat of reactions are used for this. This method produces potentially low or no greenhouse gas emissions (Energy, 2023).

Steam Reform of Natural Gas

Syngas is produced by steam contacting natural gas at 700-1000°C in the presence of a catalyst. As a result of this process, hydrogen (H_2) is formed from carbon monoxide (CO) and carbon dioxide (CO_2). The natural gas steam reforming process (SMR), which consists of two steps, the natural gas reforming reaction and the shift reaction, is the most economical and efficient method for large-scale hydrogen production. However, the fact that natural gas reserves will be depleted in the future and carbon dioxide emissions and its impact on the environment and climate are its negative sides (Liu, 2009). Unfortunately, the SMR method is not environmentally friendly. Because a facility that produces 1,000,000 m^3 of H_2 produces an average of 300,000-400,000 m^3 of CO_2. Hydrogen production from fossil sources emits very large amounts of CO_2, reducing the attractiveness of hydrogen as a clean fuel (Muradov, & Veziroğlu, 2005). The reaction also produces a large number of pollutants such as mercury (Hg), nitrogen oxide (NOx), sulfur oxide (SOx) and other particles. Integrating the technologies developed in the field of carbon capture, storage and use in the production of hydrogen from fossil fuels into production processes can offer significant benefits in minimizing environmental impacts (Bektaş, Hakyemez, Yanık Özçelik & Yıldızca, 2021).

One of the most common methods used to resolve carbon emissions is carbon sequestration. This process takes the form of capturing carbon dioxide and then storing it underground or in the ocean (Ozturk, Ozek & Yuksel, 2010). A schematic diagram of an SMR hydrogen plant via capture of CO_2 in the ocean is shown in Figure 4.

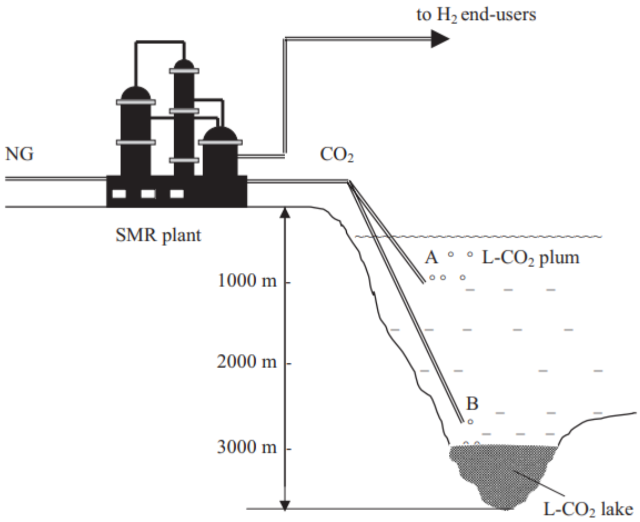

Figure 4. Schematic diagram of the process of capturing CO2 in the ocean in the production of H2 by SMR method: (A) liquid CO2 mixes with the water as droplet smoke, (B) liquid CO2 is kept in the form of a lake in the appropriate region at the bottom (Muradov, & Veziroğlu, 2005).

According to Muradov and Veziroglu (2005), producing both hydrogen and carbon through catalytic cracking of natural gas is the most advantageous option. According to the authors, the large amounts of carbon that will be produced by the decomposition of natural gas can be used in the production of building and construction materials, in electricity generation with carbon fuel cells, and in applications such as soil reclamation. Steam reforming not only produces hydrogen from natural gas, but also from other fuels such as ethanol, propane and gasoline.

Hydrogen Production by Electrolysis:

The process of separating water into hydrogen and oxygen by applying direct current is called electrolysis. Electrolysis is the most important method of obtaining hydrogen from water (Bektaş, Hakyemez, Yanık Özçelik & Yıldızca, 2021; Ursua, Gandia, & Sanchis, 2012). Water is decomposed into hydrogen and oxygen by passing an electric current between two electrodes. The conversion is fast and simple, and pure H_2 is produced after separation. No sulfur, carbon or nitrogen by-products are formed during or after the process (Al & Ateş, 2022). Since it is suitable for direct use in low-temperature fuel cells, such purity levels offer great advantages over both fossil fuels and biomass-based processes (Ursua, Gandia, & Sanchis, 2012).

The most important difference between steam reforming and hydrogen production method is the use of primary energy. The electrolysis method, which uses electricity from renewable sources, is an important method that needs to be developed for hydrogen production in terms of environmental sustainability compared to steam reformation using natural gas (Çiçek & Aliyeva Çiçek, 2022). There is no emission of polluting gases and no energy consumption based on fossil or nuclear sources, so it is attracting increasing attention today (Ursua, Gandia, & Sanchis, 2012). Furthermore, when there is abundant renewable energy available from energy sources such as solar, wind, wave, etc., it is possible to store this excess energy in the form of hydrogen by water electrolysis. This stored hydrogen can be used in fuel cells to generate electricity or can be used as fuel gas. (Zeng & Zhang, 2010).

The most widely used electrolysis method is alkaline electrolysis cells (AECs). Electrolysis and solid oxide electrolysis cells (SOEC) with proton exchange membrane (PEM) are also being developed (Çiçek & Aliyeva Çiçek, 2022).

Another method that can be used - first developed as part of the GEMINI spaceship project - is to use a proton exchange membrane as the electrolyte. PEM electrolysis is a water electrolysis method suitable for hydrogen production from renewable energy sources. Unlike alkaline electrolysers, PEM electrolysers can operate at more variable current densities. Thus, it is easier to integrate renewable energy sources whose energy production level is constantly variable (Genç & Kallioğlu, 2018). Water is supplied to the PEM electrolyser from the anode section. In the PEM electrolyser, the water supplied by the anode decomposes into oxygen gas, hydrogen ions and hydrogen electrons in the anode catalyst layer. Oxygen gas is taken out of the cell and hydrogen ions (H+) pass from the electrolyte to the cathode. Electrons pass from the external circuit to the cathode. The cathode combines with the hydrogen ions in the catalyst layer and ultimately forms hydrogen gas. Water transport (electroosmotic drift) occurs when protons pass across the membrane. PEM electrolysers are often attractive for applications where hydrogen must be stored or utilised at high pressure. This is because they are capable of producing hydrogen (and optionally oxygen) at pressures up to 200 bars with little additional power consumption (Barbir, 2005). Another electrolysis method is the solid oxide electrolysis cells (SOEC) method. The process is called high temperature electrolysis or steam electrolysis. The key components of a SOEC are a dense ionic conductive electrolyte and two porous electrodes. When steam is fed through the porous cathode and an electric potential is applied between the two electrodes, electrolysis occurs. At the cathode-electrolyte interface, dissociation takes place to form hydrogen gas and oxygen ions. The hydrogen gas produced is emitted and collected on the cathode surface. Then, the dense electrolyte carries oxygen ions to the anode. Oxygen ions are converted to oxygen gas here. Oxygen is transported from the pores of the anode material to the its surface (Ni, Leung & Leung, 2008). Solid Oxide Electrolysis Cell (SOEC) has lower equilibrium potential than Proton Exchange Membrane (PEM) electrolysis. Also the reaction kinetics is faster. For this reason, it has been stated by researchers that it has higher efficiency in hydrogen production (Zhang, Change, Fu, Ren & Li, 2023). SOEC requires lower electrical energy to produce hydrogen at a higher chemical reaction rate (Ni, Leung & Leung, 2008).

Storage of Hydrogen

Niemann, Srinivasan, Phani, Kumar, Goswami & Stefanakos (2008) listed the critical properties of hydrogen storage materials as i) light weight, (ii) cost and availability, (iii) high bulk density and gravimetric hydrogen density, (iv) kinetic rate, (v) ease of use, (vi) low decomposition or dissociation temperature, (vii) favorable thermodynamic properties, (viii) long-term cycle stability, and (ix) high reversibility. Hydrogen can be stored in various ways. The most suitable storage system for hydrogen is physical storage. Due to the low density of hydrogen, high pressure or extremely low temperatures are required for its storage (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014). There are four main approaches to storing hydrogen (Niemann, Srinivasan, Phani, Kumar, Goswami & Stefanakos, 2008): (i) compressed gas, (ii) liquefied, (iii) solid state, and (iv) chemical. Hydrogen is compressed when stored as a gas because it is more efficient to store it this way. High pressure tanks of 350-700 bar are used to store the compressed hydrogen gas. Storing hydrogen in liquid form is also an efficient option. To liquefy hydrogen, the boiling temperature must be lowered (below minus 252.8°C. This cooling requires 64% more energy than hydrogen gas compression (Elberry et al., 2021). Gaseous hydrogen is stored in pressurized tanks. The most common material used in the construction of H_2 tanks is steel. The fact that the tanks are made of reinforced composite materials with new technologies has made them lighter and more durable. The liquefied hydrogen storage tank pressure is lower compared to compressed hydrogen storage. Therefore, it eliminates the cost of the carbon fiber reinforced composite tank used in compressed hydrogen storage (Koşar, 2021). A cryogenic tank is used to store the hydrogen in the liquid phase.

Conclusion

Hydrogen is an important energy carrier and can be produced from a wide variety of sources. It can be converted into electrical energy with high efficiency. The resource used to ensure clean hydrogen production should be met from renewable energy sources. Thus, it is possible to reduce the carbon dioxide emissions and other wastes that occur in the use of other hydrogen production methods. The most environmentally friendly form of hydrogen production is through water electrolysis. Hydrogen production through water electrolysis is the production of hydrogen from renewable resources. Excess energy produced in wind and solar farms is stored as hydrogen and profits are made. However, this method also has disadvantages. These systems have low efficiency and high capital costs. Since the electrolysis method is an expensive technology, it is not the primary preferred method among hydrogen production methods. Steam reforming is not the environmentally friendly option. But it is still the most popular hydrogen production method. Because it has high conversion efficiency and cost-effectiveness compared to other hydrogen production methods. Thus, it has gained its popularity on an industrial scale. About 95% of hydrogen products are produced by this method.

Hydrogen is a gas that can be liquefied at -253 °C, and so storage of hydrogen is an important step to harness hydrogen energy. High energy is required to cool it to this temperature. It is possible to store hydrogen as a gas or as a liquid.

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