



Hydrogen Fuel Cells: The Key to Clean Future

Hidrojen Yakıt Hücreleri: Temiz Geleceğin Anahtarı

Mehmet Ali Bektaş^{1*}, Orhan Arpa²

¹Çetinkayalar Yapı Elemanları INC. Research And Development Center, 21010, Diyarbakır, TÜRKİYE

²Dicle University, Mechanical Engineering Department, 21280, Diyarbakır, TÜRKİYE

Başvuru/Received: 16/02/2024 *Kabul/Accepted:* 20/05/2024 *Çevrimiçi Basım/Published Online:* 30/06/2024

Son Versiyon/Final Version: 30/06/2024

Abstract

Hydrogen fuel cells are an important technology that can shape the future of clean energy sources. This technology offers the key to an environmentally friendly future by enabling zero-emission energy production and sustainable vehicle systems. Hydrogen fuel cells produce electrical energy using hydrogen gas and emit only water vapor. Therefore, they offer a clean alternative to energy production and vehicle systems without releasing harmful emissions into the atmosphere. In this study; It discusses in detail the basic principles, advantages, disadvantages, sustainability potential, growth expectation, challenges encountered, steps and opportunities required for its widespread use of hydrogen fuel cells technology. Hydrogen fuel cells have growth potential as the demand for clean energy increases. Solutions such as developing green hydrogen production methods, expanding infrastructure and government incentive policies can contribute to the widespread use of this technology. The article highlights that hydrogen fuel cells technology has an important role in the future clean energy transition, demonstrating that it is a potential key to achieving sustainability goals. It also reveals the steps and potential opportunities required for the widespread use of hydrogen technology. This information makes a significant contribution to the literature towards promoting widespread acceptance and use of hydrogen technology.

Key Words

“Hydrogen Fuel Cells, Green Energy, Sustainability, Fuel Production”

Öz

Hidrojen yakıt hücreleri, temiz enerji kaynaklarının geleceğini şekillendirebilecek önemli bir teknolojidir. Bu teknoloji, sıfır emisyonlu enerji üretimini ve sürdürülebilir taşıt sistemlerini mümkün kılarak çevre dostu bir geleceğin anahtarını sunmaktadır. Hidrojen yakıt hücreleri, hidrojen gazını kullanarak elektrik enerjisi üretir ve sadece su buharı emisyonu verir. Bu nedenle, atmosfere zararlı emisyonlar bırakmadan enerji üretimi ve taşıt sistemlerine temiz bir alternatif sunarlar. Bu çalışmada; hidrojen yakıt hücreleri teknolojisinin temel prensiplerini, avantajlarını, dezavantajlarını, sürdürülebilirlik potansiyelini, büyüme beklentisini, karşılaşılan zorlukları, yaygınlaşması için gereken adımları ve fırsatları ayrıntılı bir şekilde ele almaktadır. Hidrojen yakıt hücreleri, temiz enerjiye olan talebin artmasıyla birlikte büyüme potansiyeline sahiptir. Yeşil hidrojen üretim yöntemlerinin geliştirilmesi, altyapının genişletilmesi ve hükümet teşvik politikaları gibi çözümler, bu teknolojinin yaygınlaşmasına katkı sağlayabilir. Makale, hidrojen yakıt hücreleri teknolojisinin gelecekteki temiz enerji dönüşümünde önemli bir role sahip olduğunu vurgulayarak, sürdürülebilirlik hedeflerine ulaşmada potansiyel bir anahtar olduğunu gösterir. Ayrıca, hidrojen teknolojisinin yaygınlaşması için gereken adımları ve potansiyel fırsatları ortaya koymaktadır. Bu bilgiler, hidrojen teknolojisinin yaygın kabulünü ve kullanımını teşvik etme yolunda literatüre önemli bir katkı sağlar.

Anahtar Kelimeler

“Hidrojen Yakıt Hücreleri, Yeşil Enerji, Sürdürülebilirlik, Yakıt Üretimi”

1. Introduction

World; As we move rapidly towards a sustainable and clean future in energy production and transportation, hydrogen fuel cell technology is becoming an important part of this transformation. The concept of energy and the sustainability of energy resources have been one of the world's leading issues and problems throughout history. Factors such as rapid depletion of energy resources, unconscious use of non-renewable resources such as oil, coal and nuclear energy, and the pollution caused by these resources to the environment and atmosphere have led people to use renewable (sustainable) energy resources (Külekçi, 2009). This technology has great potential not only in terms of energy production but also in meeting environmental and climate protection targets. Hydrogen fuel cells produce electricity using hydrogen gas and only emit water vapor during this process. This contributes to reducing air pollution and greenhouse gas emissions caused by fossil fuels. The feature of hydrogen gas as an energy carrier in itself offers solutions to energy storage and transportation problems. By producing electrical energy through electrochemical reactions, hydrogen fuel cells offer the key to an environmentally friendly future thanks to their high efficiency and zero-emission electricity production. This article aims to explain the role of hydrogen in clean energy conversion and what is possible in this field by discussing in detail the basic principles and sustainability potential of hydrogen fuel cells technology. In the study, the operating principles of hydrogen fuel cells are discussed and how this technology works is explained in detail.

Hydrogen fuel cells produce electricity by entering hydrogen gas into an electrochemical reaction with oxygen. During this reaction, as hydrogen gas separates into hydrogen ions, electrons become free and these electrons flow through an electrical circuit and produce electricity. The most important advantage of hydrogen as an energy carrier is that it is a non-toxic and non-corrosive element. Therefore, using hydrogen is safe and very simple. In non-polluting hydrogen recycling, it enters the natural cycle by producing water vapor, which shows that hydrogen fuel cells are an environmentally friendly energy production method (Köseoğlu, 2013). When it comes to the advantages of hydrogen fuel cells, the emphasis is on their ability to produce zero-emission electricity and provide clean vehicle systems. Since hydrogen fuel cells emit only water vapor, they protect air quality and play an important role in the fight against climate change. In addition, fuel cells are known for their high efficiency, and the storage and transportation of hydrogen can be achieved by various methods, which also contributes to energy storage problems. However, there are some challenges that prevent hydrogen fuel cells from becoming widespread. Issues such as developing green methods for hydrogen production and solving energy intensity issues are obstacles to the full potential of this technology. Therefore, hydrogen fuel cells technology requires further research and development, taking into account its advantages and disadvantages.

Another point of focus in the study is hydrogen production and green hydrogen issues. Green hydrogen is particularly important as one of the cornerstones of the clean energy transition. Green hydrogen refers to hydrogen produced using renewable energy sources, which enables hydrogen production to occur in an environmentally friendly manner. Additionally, the relationship between hydrogen fuel cells and the vehicle industry and the impact of energy conversion on vehicles are emphasized. Hydrogen-powered vehicles can be considered as an alternative to electric vehicles and will offer zero-emission vehicle solutions. The rise of hydrogen fueled vehicles in the transportation sector and the growth potential of this technology in the vehicle sector are discussed. Hydrogen infrastructure and storage is another critical issue, highlighting the need to store and distribute hydrogen safely and effectively. The high energy density of hydrogen gas makes it a gas that requires the development of storage and transportation methods. In this section, the technologies used for the safe and effective storage of hydrogen and the need for infrastructure development will be discussed, and how hydrogen can be integrated into the distribution network will be emphasized. The future of hydrogen technology and how this technology can be integrated into energy conversion is also an important focus of this article. Hydrogen fuel cells can shape a clean and sustainable future in energy production and vehicle systems. This chapter will focus on how hydrogen can be used in energy production, the importance of green hydrogen, and how hydrogen technology aligns with growth prospects and sustainability goals. Additionally, how hydrogen technology can be integrated into energy conversion and contribute to a sustainable energy future will be discussed in detail.

Important studies have been carried out in the field of hydrogen and clean energy, the main ones of which are as follows: Kivrak (Kivrak, 2011) discovered the results of a closed-loop heat transfer system that increases the hydrogen storage efficiency of metal hydride tubes in order to increase the performance of a hydrogen fuel cell electric vehicle. It shows that the tube operating with the heat transfer system can feed the fuel cell for 61 minutes, while the tube operating without the heat transfer system can operate at the same power level for only 18 minutes. This has highlighted the need for more effective hydrogen storage technologies for vehicles based on alternative energy sources. Gürz (Gürz, 2017) researched and discussed basic issues such as the structures of fuel cell automobiles, technological development processes, infrastructure services and energy economies. Additionally, he evaluated the current situation and future perspective in the automotive industry by examining studies on fuel cell units. It discussed the features related to durability, distribution and dispersion problems for intended use in the automotive industry and evaluated sustainability strategies. Finally, a feasible control strategy is proposed by examining existing control systems that manage storage systems and power circuits. Aslan (Aslan, 2007) discussed the threats of fossil fuels to environmental problems and energy security and researched that hydrogen stands out as an environmentally and economically important alternative. At the same time, he examined the transition efforts of the European Union, Lithuania and Japan to the hydrogen economy and provided information on this subject. In the development process of hydrogen fuel cell vehicles, Kaya (Kaya, 2018) combined lithium ion battery and supercapacitor technologies with fuel cells in order to maximize the storage life of the vehicle and use it with high efficiency, and used the proton exchange membrane fuel cell as an effective primary energy source in this regard. In addition, this system is supported by an

appropriate energy management system and control strategy, increasing the efficiency and dynamics of the vehicle. The paper results were analyzed in terms of hydrogen consumption, energy efficiency and sustainability of control results. Gül (Gül, 2006) researched that fossil fuels cause environmental problems and energy crisis and that hydrogen, as a renewable fuel, can be an important alternative in road vehicles. The advantages and usage difficulties of hydrogen were discussed and it was emphasized that technical problems should be overcome and production costs should be reduced in order to use this alternative energy source more widely. Tanç (Tanç, 2019) found that the automotive industry is changing with rapidly advancing technology and knowledge and focusing on alternative energy sources. He emphasized that although electric vehicles are zero-emission, hydrogen is an important alternative when the emissions in energy production are taken into consideration. It has been studied that fuel cell vehicles are more effective in terms of energy consumption and hydrogen consumption than fuel cell hybrid vehicles. These results show that fuel cell hybrid vehicles are preferable. Şenol et al. (Şenol, Üçgöl, & Acar, 2006) examined fuel cells and their potential for application to vehicles, and particularly focused on polymer electrolyte plate fuel cells and their components. Additionally, a fuel cell power calculation for a normal vehicle is presented for illustrative purposes, providing an illustration of the use of this technology. Tutar et al. (Tutar & Eren, 2011) considers hydrogen energy as the "energy of the 21st century" and states that the increasing energy demand and decreasing resources around the world have increased the interest in alternative energy sources. Some developed countries have made significant progress in hydrogen energy with the influence of technological developments. He emphasized that it would be a positive step for Turkey to focus on hydrogen energy due to its dependence on foreign energy. He stated that Turkey has hydrogen energy potential and in this context, he examined it with SWOT [Strengths, Weaknesses, Opportunities and Threats] analysis. Additionally, the developments of other countries in the field of hydrogen energy are mentioned and studies on hydrogen in Turkey are included.

As a result, this study summarizes the importance of the role of hydrogen fuel cells in the clean energy future and emphasizes how this technology is a key to achieving sustainability goals. The next steps and solution suggestions are a reflection of the important steps taken towards this future.

2. Hydrogen Production Methods

According to IRENA (International Renewable Energy Agency), the hydrogen production method is classified with four different colors. These are: Gray, Blue, Turquoise and Green (Green Hydrogen for Industry: A Guide to Policy Making, 2020). This coloring varies depending on the sources and environmental impacts of hydrogen production methods. Here are more detailed explanations of these classifications:

1. **Gray Hydrogen (Production with Fossil Fuels):** The gray hydrogen method produces hydrogen through processes such as steam methane reforming (SMR) of natural gas, which are fossil resources, or gasification of coal. This method releases a significant amount of carbon dioxide (CO₂) into the atmosphere and has very high environmental impacts. While gray hydrogen is compatible with existing energy infrastructure, it does not contribute to sustainability goals.
2. **Blue Hydrogen (Carbon Capture and Storage):** The blue hydrogen method focuses on reducing CO₂ emissions, unlike gray hydrogen. While producing hydrogen from fossil sources, efforts are made to capture 85-95% of the CO₂ released into the atmosphere. This is considered a transition method to move towards zero carbon targets. Blue hydrogen includes carbon capture and storage technologies.
3. **Turquoise Hydrogen (Production with Alternative Fuels):** Turquoise hydrogen is a method that is still in the R&D stage. In this method, hydrogen is produced from solid carbon derivatives instead of fossil fuels such as natural gas. In this way, it is thought that gaseous CO₂ can be stored more easily. The aim of turquoise hydrogen is to further reduce CO₂ emissions compared to blue hydrogen.
4. **Green Hydrogen (Electrolysis with Renewable Energy):** Green hydrogen technology represents a method in which hydrogen is produced through water electrolysis and produces almost no CO₂ emissions. This method produces hydrogen using electrical energy obtained from renewable energy sources such as solar and wind. Green hydrogen production is more costly than other methods; However, it is becoming increasingly important with the decline in renewable energy costs.

Hydrogen production methods vary; Among these methods, some produce carbon by-products while others produce almost no carbon and are therefore considered an environmentally friendly and green production method. Increasing demand for energy and food causes an increase in greenhouse gas emissions in the atmosphere. Measures to limit greenhouse gas emissions should focus on sustainable energy sources. In this context, hydrogen production, called "green hydrogen production methods", should play an important role. Today, hydrogen is produced mainly by converting natural gas with steam. However, this method is a process that causes large amounts of greenhouse gas emissions. Approximately 50% of global hydrogen demand is currently met by steam reforming of natural gas, with approximately 30% provided by conversion of oil and naphtha from refinery and chemical industrial waste gases. 18% is produced through coal gasification, 3.9% through water electrolysis, and 0.1% through other sources (Muradov & Veziroğlu, 2005). In Figure 1, various areas related to hydrogen production and use are visually presented and the percentage share of hydrogen production methods such as electrolysis, coal gasification, partial oxidation of hydrocarbons and natural gas steam reforming is shown. Additionally, the usage percentages of hydrogen in different sectors are also stated. In this way, the relationship between the different sources where hydrogen is produced and the various areas in which it is used is presented in a visually understandable way.

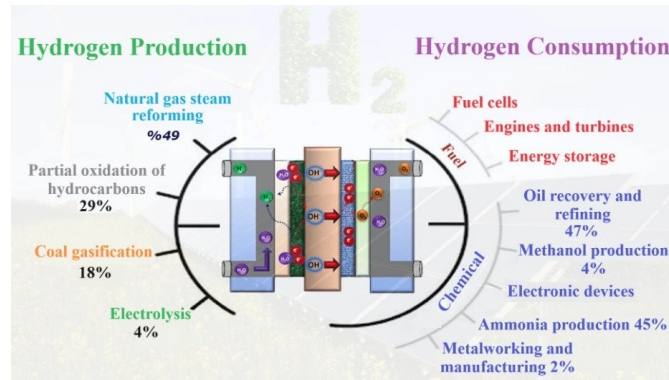


Figure 1. Percentages for hydrogen production and use (Şener, 2023)

Classified production methods such as gray, blue, turquoise and green for hydrogen production are shown in Figure 2. This color coding helps understand different hydrogen production methods by highlighting their environmental impact and sustainability. While green hydrogen is seen as the most sustainable and environmentally friendly option in the long term, other methods can contribute to carbon reduction targets during transition periods. This color coding provides guidance when evaluating the environmental impacts of different production methods and determining choices in sustainable energy conversion.

Colour	GRAY HYDROGEN	BLUE HYDROGEN	TURQUOISE HYDROGEN	GREEN HYDROGEN
Process	SMR or gasification	SMR with carbon capture or gasification (85-95%)	Pyrolysis	Electrolysis of water
Source	Methane or coal	Methane or coal	Methane	Electricity from sustainable sources

Figure 2. Classification of Different Hydrogen Production Methods (Green Hydrogen for Industry: A Guide to Policy Making, 2020)

2.1. Hydrogen Production and the Role of Green Hydrogen

Hydrogen is a gas that stands out as a clean and sustainable environmentally friendly energy source. Hydrogen is used in different industrial sectors; It can be used in a variety of applications such as energy storage, vehicle fuel, electricity generation and chemical production. Although there are various hydrogen production methods today, natural gas reforming and electrolysis methods are among the frequently used methods. These productions are carried out with various technologies. The choice of production methods may vary depending on energy sources, cost factors and environmental sustainability. Hydrogen plays an important role in achieving energy conversion and carbon emissions reduction goals and contributes to clean energy production in the future.

Various hydrogen production methods are available, as shown in Figure 3. One of the most commonly used methods is methane steam reforming, but this method is classified as gray hydrogen production and is not considered a sustainable option due to its high environmental impacts. On the other hand, it is possible to produce green hydrogen by electrolysis, which is the most sustainable method. This method produces only water vapor as a byproduct and does not contribute to carbon emissions.

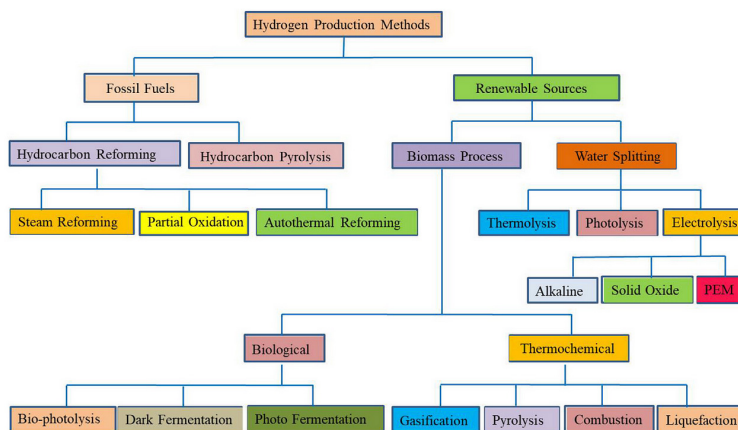


Figure 3. Hydrogen production methods (Coinmonks, 2022)

2.2. Hydrogen Gas Production by Reforming of Natural Gas

Natural Gas and Steam reformers are one of the most economical and efficient systems widely used today for hydrogen production. This method is based on a principle in which a mixture of hydrogen and carbon monoxide is produced by the interaction of a nickel-based catalyst. In the first stage, natural gas is exposed to water vapor at high temperature (392 °C) to form hydrogen, carbon monoxide and carbon dioxide. In the second stage, carbon monoxide is subjected to steam and additional hydrogen and carbon dioxide are produced. There are basically three types of reformers, and this hydrogen production process essentially involves three different types of reformers:

1. **Steam Reformer:** Steam reformer is a process that produces hydrogen by reacting natural gas with steam. This reaction is highly endothermic (heat absorbing) and reversible. Therefore, it requires high temperature, high steam/methane ratio and low pressure to drive the reaction forward and achieve maximum hydrogen conversion.
2. **Partial Oxidation Reactors:** Partial oxidation reactors involve a process in which only a portion of the methane is reacted with oxygen. These reactors produce small amounts of carbon dioxide as well as carbon monoxide and hydrogen.
3. **Thermal Cracking Reactors:** Thermal cracking reactors produce hydrogen through the cracking of methane at high temperature. In this method, carbon and hydrogen are separated and hydrogen gas is obtained.

There is also a fourth system called autothermal reformers. This system represents an approach that combines partial oxidation and steam reformers. The most efficient method for hydrogen production is autothermal reformers. This method is the most efficient method to produce hydrogen and the amount of hydrogen product is between 70% and 90% (Çuhadaroğlu, 2005).

The chemical formula of the applied process occurs in two steps (Çuhadaroğlu, 2005):

1. Step One: $C_nH_m + nH_2O \rightarrow nCO + (n + m/2) H_2$
2. Second Step: $CO + H_2O \rightarrow CO_2 + H_2$

The first reaction is known as steam reforming of methane. This reaction is highly endothermic and reversible. According to Le Chatelier's principle, this reaction should be carried out under high temperature, high vapor/methane ratio and low pressure conditions to achieve maximum hydrogen conversion. The design of the steam reforming process must be carried out in accordance with these constraints (Rostrup-Nielsen & Rostrup-Nielsen, 2002). Figure 4 plots the composition resulting from steam reforming viewed as a function of reformer exit temperature.

Another advantage of steam reforming is that the hydrogen in the water is released and added to the amount of product hydrogen. This reaction usually occurs in the temperature range of 450 to 925°C. To reach these temperatures, part of the reformer must be burned. This process is endothermic and waste heat can be recovered for reuse. Therefore, the thermal efficiency of this reaction is approximately 85%, which is an important feature of steam reforming. In addition to temperature and pressure, the fuel/water ratio is also critical. This ratio not only suppresses undesirable reactions but also increases the amount of hydrogen produced. However, the fuel/water ratio is determined by complex interactions of heat, thermal mass and hydrogen demand, which can sometimes be insufficient to adapt to ever-changing demands.

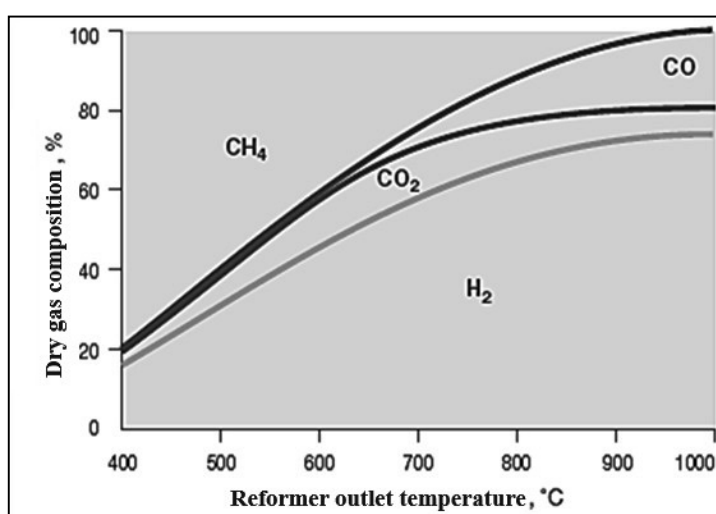


Figure 4. Graph of the composition coming out of the steam reformer under pressure between 25 and 26 bar (Zohuri, 2019)

The output products during this reaction, shown in Figure 5, include water as well as the source fuel being treated. However, light hydrocarbons can be processed by evaporation without leaving carbon residue. Additionally, hydrogen in water is released during this process and contributes to the amount of hydrogen in the final product.

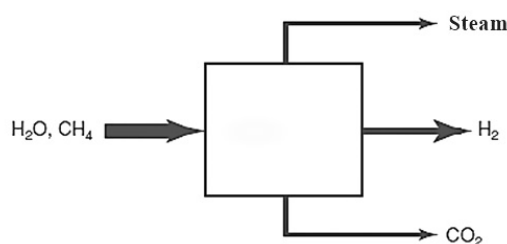


Figure 5. Reformation of methane (Çuhadaroğlu, 2005)

Since natural gas resources are limited, the sustainability of this method may pose a problem. Therefore, in the future, environmentally friendly methods such as biogas may need to be focused more on and expanded in hydrogen production. However, methane production with biogas is currently limited and developments in this field are needed. Hydrogen production is of great importance in the energy sector and a number of industrial applications. Therefore, the efficiency and environmental impacts of hydrogen production technologies play a critical role in terms of future energy conversion and sustainability goals. Steam reforming is a common method for the economical and efficient production of hydrogen, as well as a high example of the energy efficiency of this process. Steam reformers are also notable for their ability to recover waste heat. This allows the heat released in the production process to be reused as energy, increasing overall energy efficiency. The thermal efficiency of this process is approximately 85%, which is an important advantage in terms of efficient use of energy resources of hydrogen production. Traditionally, hydrogen production comes from hydrocarbons and water. However, the depletion of hydrocarbons requires the production of hydrogen using water in the future and the development of production technologies in this direction. Finally, considering the environmental impacts of hydrogen production, hydrogen production by electrolysis of water emerges as an important alternative. This process uses electrical energy to split water molecules into hydrogen and oxygen atoms. This method prevents greenhouse gas emissions and promotes the production of hydrogen, a clean energy source. In this context, it is important to develop and use alternative methods to contribute to the sustainability goals of hydrogen production.

As a result, hydrogen production methods such as steam reforming and water electrolysis play an important role in the transformation of the energy sector and environmental sustainability goals. The efficiency and effectiveness of these methods will continue to be a key element of hydrogen's future energy conversion.

2.3. Hydrogen Gas Production by Electrolysis Reaction

Water electrolysis is a critical electrochemical phenomenon for the production of green hydrogen, an emission-free technology. This reaction refers to the process of splitting water into hydrogen and oxygen gases. Water molecules are subjected to an electrical charge, causing the hydrogen and oxygen atoms to separate. Among the charged particles formed, hydrogen ions carry a positive charge and collect at the negative electrode, while oxygen moves to the positive electrode because it is negatively charged. Conductors such as electrolytes increase the conductivity of water and increase the efficiency of the process. At 25°C temperature and 1 atm pressure, the voltage required for the electrolysis of pure water is 1.24 volts. The minimum amount of energy required for the electrolysis of one mole of water was determined as 65.3 watt-hours. Likewise, the minimum amount of energy required to produce one cubic meter of hydrogen has been determined as 4.8 kW-hour. This occurs under the influence of many factors. Since the water electrolysis reaction is an electrochemical process, it is affected by a number of factors such as electrode materials, type of electrolyte, temperature, pressure and other environmental conditions. Additionally, the design of the electrolysis cell is also a reason for this difference. In practical application, factors such as the internal resistance of the electrolysis cell, the surface properties of the electrodes and the potential losses in the cell explain the difference between the theoretical voltage and the experimental voltage. Therefore, when producing green hydrogen by water electrolysis, the design and operating conditions of the electrolysis cell must be carefully adjusted, taking into account the experimental voltage. This is important to ensure a more efficient and effective hydrogen production process. Over the last two centuries, the electrolysis of water has become a well-known method for the production of green hydrogen. However, only 4% of the hydrogen produced worldwide, approximately 65 million tons, can be produced through the electrolysis of water. This shows that hydrogen production should be achieved by various methods. Electrolyzers, especially PEM (Proton Exchange Membrane) electrolyzers, are extremely sensitive to the purity of water. Therefore, desalination and demineralization of water are necessary before electrolysis. For example, if salty water, such as seawater, is supplied to an electrolyzer, it is more likely to produce oxygen rather than chlorine (Dincer & Acar, 2015). Various methods are available in the literature to prevent side reactions during electrolysis, especially undesirable side effects such as chlorine formation. One of these methods is the use of ion-selective membranes to desalinate water. These membranes select ions in the water, allowing unwanted salts and minerals to be removed before the electrolysis process. For example, one method proposed by El-Bassuoni and his team is to desalinate water using ion-selective membranes. In this way, side reactions such as undesirable chlorine formation during the electrolysis process are prevented (El-Bassuoni, Sheffield, & Veziroglu, 1982). Additionally, the use of catalysts such as magnesium can also promote oxygen formation rather than chlorine formation. In this way, the electrolysis process can be made more efficient

and the formation of undesirable by-products can be prevented (Ni, Leung, Sumathy, & Leung, Potential of renewable hydrogen production for energy supply in Hong Kong, 2006).

2.4. Alkaline Water Electrolysis

Alkaline water electrolysis, invented by Troostwijk and Diemann in 1789, is considered one of the most effective electrolysis systems worldwide with very high hydrogen production capacity. This technology, along with various developments, was first implemented in 1939 with a large-scale industrial alkaline water electrolyzer system with a capacity of 10,000 Nm³/hydrogen/hour (Schmidt, et al., 2017).

Alkaline water electrolysis works with a concentrated alkaline solution (usually 5M KOH/NaOH) and is generally operated at a temperature between 30-80 °C. In this process, nickel (Ni) coated stainless steel electrodes and asbestos/ZrO₂ based diaphragms are used. The ionic charge carrier is hydroxyl (OH⁻) ions, which include KOH/NaOH solution and water leaking through the porous structure of the diaphragm to support the functioning of electrochemical reactions. In alkaline water electrolysis, in the presence of electricity, two different half-cell reactions, hydrogen formation at the cathode and oxygen formation at the anode, occur. In the first stage, two moles of alkaline solution are reduced at the cathode, producing one mole of H₂ and two moles of OH⁻. The produced H₂ gas can be separated from the cathode and the remaining OH⁻ ions are transported through the porous separator to the anode side under the influence of the electric circuit. OH⁻ ions in the anode region are separated from the system and used to create ½ mole O₂ and 1 mole water (Şener, 2023). Alkaline water electrolyzer cell structure and working principle are given in Figure 6.

The alkaline water electrolysis cell has a structure that includes diaphragms, gas diffusion layers, separator plates and end plates. Typically, asbestos/zirconium/nickel coated perforated stainless steel material is preferred as a separator in alkaline water electrolysis. The nickel mesh serves as an element of the gas diffusion layers, and stainless steel/nickel-plated spacers are used in the bipolar and end plates, respectively. The investment cost of an alkaline water electrolysis system generally varies between 500-1000 \$/kW and the life of the system is calculated as approximately 90,000 hours. This technology is a reliable and widely used method for hydrogen production on an industrial scale.

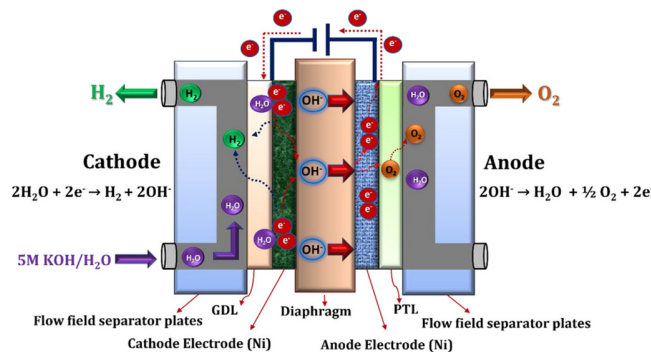


Figure 6. Cellular structure and working principle of alkaline water electrolyzer (Kumar & Lim, 2022)

2.5. Electrolysis with Anion Exchange Membrane (AEM)

Anion exchange membrane water electrolysis (AEM), a technology developed for green hydrogen production in recent years, has attracted increasing attention due to its low installation costs. This technology is similar to the alkaline water electrolysis method, but the main difference between them is the use of quaternary ammonium ion exchange membranes instead of asbestos. It also has the advantage of being able to use lower concentrated solutions. Despite these positive aspects, more research is needed on the stability of membrane electrode assemblies and cell efficiency. AEM is an electrochemical water splitting technique that involves the use of anion exchange membrane and electrical energy. This electrochemical process consists of two separate half-cell reactions involving the formation of hydrogen and oxygen. On the cathode side, water molecules are processed to form H₂ and dissociate into OH⁻ ions. As a result, hydrogen gas is released from the cathode. OH⁻ ions, on the other hand, lose electrons as they move towards the anode side and are guided by the positive attraction of the ion exchange membrane and the anode. In the anode region, OH⁻ ions dissociate into water and oxygen molecules, then the resulting oxygen is released by the anode. Figure 7 shows in detail the cellular structure and operating principle of the anion exchange membrane water electrolyzer.

The basic building blocks of the anion exchange membrane water electrolysis cell include the membrane, electrode materials, current collector, separator plates and end plates. Typically, transition metal-based electrocatalysts are preferred as anode and cathode electrode materials; Especially nickel and NiFeCo alloy materials are among the frequently used options in this context. Nickel foam and carbon fabric with porous nickel mesh are used as gas diffusion layers. Stainless steel and nickel-plated stainless steel are preferred for separator plates and are used within the cell as bipolar and end-pole plates, respectively. This evolving technology offers a more efficient and economical option for green hydrogen production.

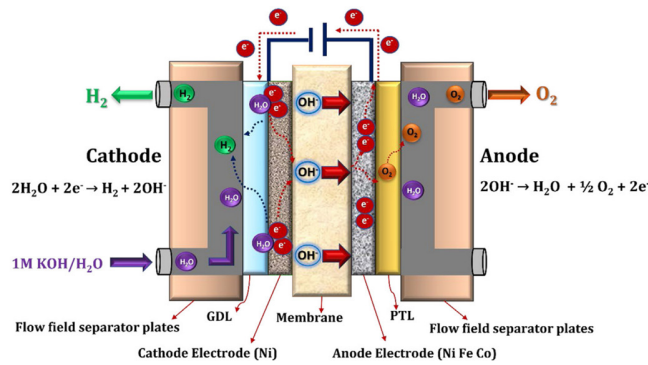


Figure 7. Cellular structure and operating principle of anion exchange membrane water electrolyzer (Kumar & Lim, 2022)

2.6. Electrolysis with Proton Exchange Membrane (PEM)

In this electrolysis cell, H⁺ (proton) ions serve as ion carriers and the proton-conducting membrane ensures the functionality of the water electrochemical reaction. The PEM method is performed at higher current densities (1-2 A/cm²) and lower temperatures (30-80 °C). With this process, it is possible to produce hydrogen and oxygen with 99.9% purity. The kinetics of the hydrogen evolution reaction occurs faster than alkaline water electrolysis due to the large active surface area of platinum electrodes and the low pH level of the electrolyte. Additionally, PEM lacks caustic (alkaline) electrodes and requires a smaller footprint, making it a safer option compared to alkaline water electrolysis. The reported stability of the PEM method is approximately 60,000 hours. However, the cost of components such as electrode materials, current collectors and bipolar plates is quite high. Water in the PEM cell; At the anode side, O₂ is decomposed to form H⁺ and electrons (e⁻). Oxygen and remaining protons expelled from the anode are transported from the proton-conducting membrane to the cathode side, and electrons are transported from the external circuit to the cathode. At the cathode, protons and electrons recombine to produce H₂ gas.

Key elements of the PEM cell include the membrane electrode array, gas diffusion layers, separator plates, and end plates. Nafion brand membranes, especially Nafion 115, 117 and 212, which are among the frequently preferred types, are used for PEM. Nafion provides several advantages such as high proton conductivity, high current density, strong mechanical strength and chemical stability. A 10 MW PEM cell with a current density of 1 A/cm² uses 2.3 mg/cm² of catalyst for only approximately 15 kg of iridium. Porous titanium/titanium mesh and carbon fabric are used as gas diffusion layers, and bipolar plates made of platinum or gold-coated titanium material serve as separator and end plate. However, a key challenge of this system is the high cost of separator plates, accounting for 48% of the total cell cost. PEMs are particularly suitable for vehicle applications using hydrogen due to their high power density, simple structure, greater sensitivity characteristics, low startup time, small size and maintenance-free characteristics (Mekhilef, Saidur, & Safari, 2012), (Kumar & Jain, 2014), (Salvi & Subramanian, 2015). Figure 8 shows the cell structure and working principle of the proton exchange membrane water electrolyzer.

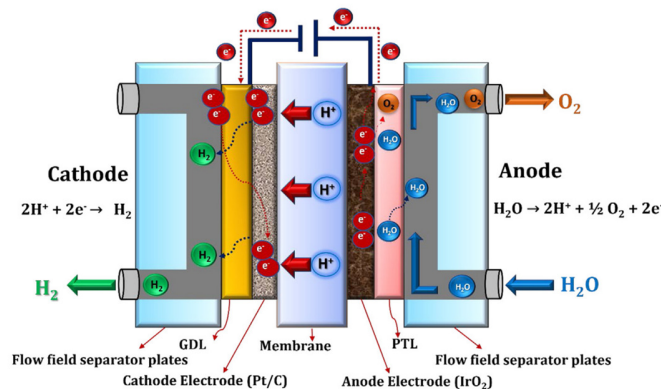


Figure 8. Cellular structure and operating principle of proton exchange membrane water electrolyzer (Kumar & Lim, 2022)

2.7. Solid Oxide Water Electrolysis

Solid oxide water electrolysis cell (SOLID OXIDE) is an important type of cell used in electrochemical transformations. The development of this technology dates back to the 1970s. The SOLID OXIDE cell operates with water vapor, which can operate at high temperatures, typically between 500-850 °C. This higher temperature can increase energy efficiency by reducing the amount of energy required to split water. This increase could lead to a strong decrease in the cost of hydrogen production, since power consumption is one of the main cost drivers of hydrogen production. The SOLID OXIDE cell has two main advantages over other

electrolysis methods. First, the high operating temperature allows superior spin efficiency in terms of thermodynamics and reaction kinetics. Second, the SOLID OXIDE cell can be easily thermally integrated with other industrial products such as dimethyl ether and ammonia. However, the solid oxide water electrolysis cell has some difficulties in terms of long-term stability, which has hindered its commercialization. SOLID OXIDE cells produce green hydrogen by operating at higher temperatures using water vapor. During the reactions, at the cathode, initially the water molecule is separated into hydrogen (H₂) and oxide ions (O²⁻) by adding two electrons. Hydrogen released from the cathode and remaining oxide ions are transported through the ion exchange membrane towards the anode. At the anode, oxide ions are further reduced to produce oxygen and electrons, which are released from the anode surface and electrons are conducted to the cathode side through the external circuit. The solid oxide cell consists of two porous anode and cathode electrodes equipped with a dense ceramic electrolyte. Zirconium dioxide, which is widely preferred as an electrolyte, is generally stabilized with yttrium, which shows impressive performance at high temperatures such as 700-850 °C. This electrolyte not only offers high ionic conductivity (10⁻² - 10⁻¹ S/cm), but also shows top performance in terms of chemical and thermal stability. The hydrogen (cathode) electrode material generally consists of YSZ and Ni-YSZ ceramic materials, these materials have high electronic conductivity. The oxygen (anode) electrode material is generally chosen among perovskite materials such as LSCF (La_{0.58}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-δ}) and LSM ((La_{1-x}Sr_x)_{1-y}MnO_{3-δ}). LSCF provides high electrical and ionic conductivity as well as having high oxygen diffusion properties, meanwhile, LSM is considered as the reference material as it shows good performance. Figure 9 shows the solid oxide cell structure and operating principle in detail.

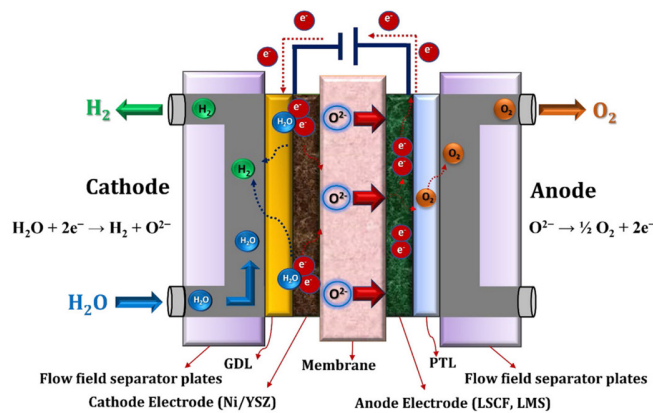


Figure 9. Solid oxide cellular structure and principle of operation (Şener, 2023; Kumar & Lim, 2022)

Considering electrolysis technologies, the most economical method for 1 MW electricity generation seems to be the alkaline water electrolyzer, although it is not currently suitable for commercial use. Therefore, the proton exchange membrane electrolysis (PEM) method is a more suitable option for commercial use. PEM is notable for its cost effectiveness and ability to produce high purity hydrogen and oxygen. However, the cost of the components of the PEM method, especially the electrode materials and separator plates, is high and these costs need to be reduced. Therefore, many research and development studies focusing on the PEM method are ongoing in scientific studies. Table 1 shows different electrolysis methods; It shows which method is more advantageous under which conditions by comparing critical features such as cost, energy efficiency, operating temperature and stability. The advantages and disadvantages of electrolysis methods are given in Table 2. Each electrolysis method has its own advantages and disadvantages, and the method to be used should be chosen depending on the specific application requirements. Therefore, factors such as cost, energy efficiency and long-term stability should be considered when making a choice between electrolysis technologies.

3. Hydrogen Storage, Infrastructure and Distribution

Hydrogen has significant potential as an energy carrier. Having high specific energy offers advantages in terms of energy storage and transportation. However, hydrogen, a physically light gas, has a low density, which brings some difficulties in storage and transportation. Although hydrogen has high specific energy, it has a low physical density of 90 g/m³, so it needs to be stored in large volumes. Hydrogen is significantly superior in energy density compared to other energy carriers such as gasoline. It has the capacity to carry more energy per unit mass. However, it occupies a large volumetric area, so some difficulties are encountered in terms of storage and transportation. Compared to other gaseous energy carriers, the liquefaction of hydrogen is an extremely challenging process. Hydrogen cannot simply be compressed like LPG or butane. In order to be liquefied, it must be cooled to approximately -252.9°C (22 K) and its density in liquid state is quite low, measured as approximately 71 kg/m³ (Larminie & Lowry, Electric Vehicle Technology Explained 2nd ed., 2012).

Turning hydrogen into gas or liquid is one of the methods used in storage and transportation processes. We can evaluate hydrogen storage options under two main categories: physical storage and chemical storage. Physical storage methods include storing hydrogen as a compressed gas, storing hydrogen in liquid form, reversible metal hydride hydrogen stores, and carbon nanofibers. Chemical

methods used in storage include chemical compounds such as methanol, alkali metal hydrides, sodium borohydride and ammonia (Larminie & Dicks, Fuel cell systems explained. 2nd ed., 2003), (Sandy Thomas, 2009). However, large areas are needed to store it in gaseous form. Therefore, hydrogen can be stored in underground facilities or natural gas pipelines. Liquefied hydrogen can be stored more densely. Compressed hydrogen (CGH2) means storing hydrogen in gaseous form under pressure. It is used as fuel gas with pressure levels of 350 bar to 700 bar used in hydrogen storage tanks. This approach is preferred for mobile storage in hydrogen vehicles (Hua, ve diğerleri, 2011). Nowadays, the compressed hydrogen storage method is considered the most efficient option compared to other options despite all its limitations, although it has the best performance and the highest development potential for automotive applications (Von Helmholt & Eberle, 2007).

Table 1. Comparison of electrolysis techniques (IRENA, 2020)

	Alkaline	AEM	PEM	Solid Oxide
Anode reaction	$2\text{OH}^- \rightarrow \text{H}_2\text{O} + \frac{1}{2}\text{O}_2 + 2\text{e}^-$		$\text{H}_2\text{O} \rightarrow 2\text{H}^+ + \frac{1}{2}\text{O}_2 + 2\text{e}^-$	$\text{O}_2^- \rightarrow \frac{1}{2}\text{O}_2 + 2\text{e}^-$
Cathode reaction	$2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$		$2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$	$\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + \text{O}_2^-$
Overall cell	$\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$		$2\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$	$\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$
Electrolyte	KOH/NaOH (5 M)	DVB polymer support with 1 M KOH/NaOH	Solid polymer electrolyte (PFSA)	Yttria stabilized Zirconia (YSZ)
Separator	Asbest/Zirfon/Ni	Fumatech	Nafion	Solid electrolyte YSZ
Electrode/Catalyst (Hydrogen side)	Nickel coated perforated stainless steel	Nickel	Iridium oxide	Ni/YSZ
Electrode/Catalyst (Oxygen side)		Nickel or NiFeCo alloys	Platinum carbon	Perovskites (LSCF, LSM) (La,Sr,Co,FE) (La,Sr,Mn)
Gas Diffusion layer	Nickel mesh	Nickel foam/carbon cloth	Titanium mesh/carbon cloth	Nickel mesh/foam
Bipolar Plates	Stainless steel/Nickel coated stainless steel		Platinum/Gold-coated Titanium or Titanium	Cobalt coated stainless steel
Voltage range (limits)	1,4-3 V	1,4-2 V	1,4-2,5 V	1-1,5 V
Operating temperature	70-90 °C	40-60 °C	50-80 °C	700-850 °C
Cell pressure	<3 MPa	<3,5 MPa	<7 MPa	0,1 MPa
H2 purity	<%99,9998	%99,9 – 99,9999	%99,9 – 99,9999	%99,90
Efficiency	%50 – 78	%57 – 59	%50 – 83	%89 (laboratory)
Lifetime (stack)	60000 h	>30000 h	50000-80000 h	20000 h
Development status	Mature	R&D	Commercialized	R&D
Electrode area	1-3.104 cm ²	<300 cm ²	1500 cm ²	200 cm ²
Nominal current density	0,2-0,8 A/cm ²	0,2-2 A/cm ²	1-2 A/cm ²	0,3-1 A/cm ²
Capital costs (stack) minimum 1 MW	USD 270/kW	Unknown	USD 400/kW	>2000 \$/kW
Capital costs (stack) minimum 10 MW	USD 500–1000/kW	Unknown	USD 700–1400/kW	Unknown

One of the biggest challenges of hydrogen storage in automotive applications is the need to keep storage weight and volume as low as possible (Cipriani, ve diğerleri, 2014). Additionally, the storage of hydrogen in vehicles has been noted as one of the biggest challenges in the development of the hydrogen economy (Berry, Pasternak, Rambach, Ray, & Schock, 1996). The need to physically store hydrogen as a cryogenic liquid or compressed gas adds to the complexity of this issue.

Transporting hydrogen can be accomplished by a variety of methods, including pipelines, cryogenic tank trucks, tube trailers, and railcars. While it can be transported in cryogenic liquid form over long distances, road transport may be preferred over short distances. However, the storage and transportation costs of hydrogen are quite high. This makes it difficult for hydrogen to compete with energy sources. Recent studies aim to encourage the production and use of hydrogen in regions where it is needed. Thus, it is aimed to reduce the transfer cost. More research and development studies are needed to overcome these challenges in the storage and transportation of hydrogen. The potential of hydrogen is of great importance in contributing to a green and sustainable future in the energy sector, but technical and economic challenges must be overcome to fully exploit this potential.

Table 2. Advantages and disadvantages of electrolysis technologies (IRENA, 2020)

Electrolysis Technology	Advantages	Disadvantages
Alkaline	Pervasive technology	Limited current densities
	Commercialized for industrial applications	Passage limit of gases
	Use of noble metal-free electrocatalyst	Use of highly concentrated liquid electrolyte
	Relatively low cost	
	Stable in the long run	
AEM	Use of noble metal-free electrocatalyst	Limited stabilization state
	Use of low concentrated electrolytes	Development continues
PEM	Use of low concentrated electrolytes	Cell elements are expensive
	Operation at high current densities	Use of noble metal electrocatalysts
	High gas purity	Use of acidic electrolytes
	Compact system design	
	Fast production	
Solid Oxide	High operating temperature	Limited stabilization state
	High efficiency	Development continues

4. Hydrogen Fuel Cells and Vehicle Industry

Hydrogen fuel cells stand out as an important technology for an environmentally friendly and sustainable future in the energy production and vehicle sectors. This innovative technology, Hydrogen fuel cell vehicles, is used to propel the vehicle through electric motors. In these vehicles, the source that provides electricity is produced using a combination of hydrogen and oxygen, and water is released as a result of use. Fuel cell vehicles could be a key technology that supports long-range, emission-free driving. (Oettle, 2010). This feature makes hydrogen fuel cells an environmentally friendly option over other energy sources.

Hydrogen is preferred as a clean energy carrier because it is significantly superior to fossil fuels in terms of energy density. Considered an ideal energy carrier, hydrogen has a distinct advantage in terms of energy content compared to liquefied natural gas, automotive gasoline and diesel. Hydrogen offers more than twice the energy compared to these fuels, with an energy content of 120.0 MJ per kg. For example, the energy content of hydrogen is quite high compared to the energy content of liquefied natural gas, automotive gasoline and diesel fuels, which are 54.4 MJ/kg, 46.4 MJ/kg and 45.6 MJ/kg per kg, respectively (Ni, Leung, Sumathy, & Leung, 2006).

Hydrogen fuel cells have great potential for the vehicle industry. This technology has the capacity to deliver zero-emission electricity generation and clean vehicle systems. Compared to traditional internal combustion engines, hydrogen-powered vehicles protect air quality and play an important role in combating climate change. Hydrogen-fueled vehicles can significantly improve urban air quality by providing zero-emission vehicle solutions. This contributes to solving air pollution problems, especially in big cities.

Hydrogen fuel cells are experiencing a huge rise in the vehicle industry. Hydrogen-powered vehicles, which can be considered as an alternative to electric vehicles, attract attention with their long range and fast filling advantages. Hydrogen's high energy density offers greater power and range in vehicles. This is especially important for trucks and buses that carry heavy loads. With the proliferation of hydrogen fueled vehicles, the vehicle industry is moving towards a cleaner and more sustainable future. However, there are also some difficulties for the rapid widespread use of hydrogen fuel cell technology. Green methods for hydrogen production need to be developed, energy intensity problems need to be solved and more infrastructure investments are needed. Hydrogen fuel cells offer the key to a clean and sustainable future in the vehicle industry. This technology stands out as an environmentally friendly and effective energy production method. Hydrogen fuel cells can contribute to environmental and climate protection goals with their growth potential in the vehicle sector. However, more R&D work and investment is required for the technology to become widespread, so hydrogen fuel cells can play an important role in shaping the vehicles and energy production of

the future. Fuel cell electric vehicles use electricity, like battery electric vehicles, to power electric motors. However, unlike other electric vehicles, FCEVs (Fuel Cell Electric Vehicles) initially generate electricity using hydrogen-fed fuel cells as the main energy source (Fernandez, Cilleruelo, & Martinez, 2016).

The first studies on fuel cells were carried out by Sir William Grove in 1839, and since then, hydrogen fuel cells have signaled that they have great potential in the field of energy production. However, the applicability of hydrogen fuel cells to electric vehicles depends on their ability to produce sufficient power. At this point, in 1939, British engineer Francis Thomas Bacon developed a fuel cell with a fixed power of 5 kW, increasing the use potential of hydrogen fuel cells.

One of the important steps in the development of hydrogen fuel cell technology was taken in 1955 by chemist W. Thomas Grubb, who worked at General Electric (GE). Grubb introduced a novel fuel cell design using sulfonated polystyrene ion exchange membrane as electrolyte. More importantly, GE chemist Leonard Niedrach integrated platinum deposition into the membrane in 1958, which acts as a catalyst for hydrogen oxidation and oxygen reduction reactions. These developments contributed to the development of fuel cell technology by institutions such as GE, NASA and McDonnell Aircraft.

In the early 1960s, NASA used hydrogen fuel cells in the Gemini and Apollo space programs using proton exchange membrane fuel cells (PEMFCs) and alkaline fuel cells (AFCs) (Sharaf & Orhan, 2014). This marked the period when the first commercial use of a fuel cell took place. Today, almost all major automotive manufacturers are developing hydrogen-powered car concepts and prototypes. In particular, commercial hydrogen fuel cell vehicles such as the Honda Clarity FCEV (105 kW and 460 miles of range), the Hyundai Tucson FCEV (100 kW and 365 miles of range), and the Toyota Mirai FCEV (114 kW and 312 miles of range) shown in Figure 10 are already available on the market. . These vehicles offer zero-emission vehicle solutions with their high power generation capacity and long range. These developments highlight the growth potential of hydrogen fuel cells in the automotive industry and indicate that more hydrogen-powered vehicles may be on the roads in the future. This is an important step towards achieving environmental sustainability goals.

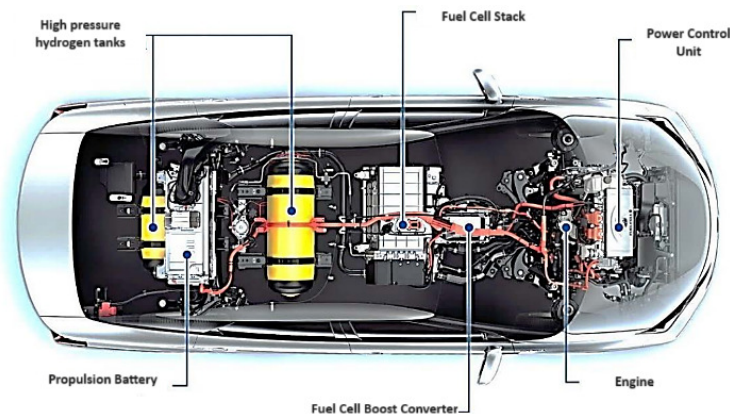


Figure 10. Toyota Mirai fuel cell system (Kendall, 2018)

5. Discussion

Innovations in hydrogen production and renewable energy are essential to reduce carbon emissions. This system, which combines hydrogen production with renewable energy sources, aims to move away from dependence on fossil fuels and move towards sustainability (Khalil & Dincer, 2024). As the demand for environmentally friendly energy continues to increase, hydrogen production from renewable sources is becoming increasingly important. This shift not only helps reduce carbon emissions, but also moves towards a more sustainable energy environment by reducing dependence on fossil fuels. By integrating hydrogen production with renewable energy sources, the energy system can contribute to a cleaner and more sustainable future by moving away from fossil fuels. Innovations in hydrogen production and renewable energy technologies are of great importance in realizing this transition and reducing the environmental impacts of energy production and consumption.

The results of the article contain various information summarized below:

1. Sustainability of Green Hydrogen: Green hydrogen is a method obtained by separating water through electrolysis. This method offers a sustainable and environmentally friendly energy source when produced using renewable energy sources.
2. Limited Efficiency of Natural Gas: Natural gas resources are limited and run the risk of running out one day. Additionally, reforming, one of the traditional hydrogen production methods, uses natural gas and produces environmental harmfuls such as greenhouse gases as byproducts. Therefore, natural gas may not be an efficient option as a long-term source of hydrogen production.
3. Electrolysis and Clean Energy Use: Electrolysis is a sustainable hydrogen production method by using clean energy sources to decompose water into hydrogen and oxygen gases. When powered by renewable sources such as solar energy or wind energy,

electrolysis enables zero-emission hydrogen production. This method reduces dependence on fossil fuels and contributes to environmental protection goals.

4. Energy Storage and Transport Capacity of Hydrogen: The high energy density of hydrogen gas provides a solution to energy storage and transport problems. Hydrogen energy can be used as an option for electrical energy storage and can be used to transport energy to remote areas. This increases reliability in meeting energy demand and energy distribution.

5. Zero Emission Vehicle Solutions: Hydrogen fuel cell vehicles protect air quality and contribute to the fight against climate change by providing zero-emission vehicle solutions. These vehicles have the potential to reduce air pollution caused by fossil fuels. It also offers advantages such as longer range and faster refueling.

6. High Efficiency and Longer Range: Hydrogen fuel cell vehicles are known for their high efficiency. At the same time, storage and transportation of hydrogen can be achieved by various methods. This highlights the ability of hydrogen energy to offer longer range and more efficient energy consumption.

7. Alternative to Fossil Fuels: Hydrogen energy stands out as an alternative to the environmental problems and energy security threats of fossil fuels. Considering the risk of depletion and environmental impacts of fossil fuels, hydrogen energy offers a long-term solution.

8. Increase in Investments: Investments in renewable energy resources are increasing around the world. This encourages greater use of hydrogen energy in the future and increases the resources required for green hydrogen production.

9. Development of Hydrogen Infrastructure: Development of hydrogen infrastructure enables hydrogen energy to have wider use. Improving the storage, transportation and distribution infrastructure contributes to the widespread use of hydrogen energy.

10. Flexibility in Energy Storage and Distribution: Hydrogen energy provides great flexibility in energy storage and distribution. It can be used to maintain the balance between electricity production and energy demand and compensate for the fluctuations of renewable energy sources.

6. Conclusion

Hydrogen energy appears to be an important alternative as a clean, sustainable energy source. At a time when energy needs are increasing and fossil fuels pose threats to environmental problems and energy security, hydrogen has a high potential to provide a solution to this need. Therefore, the hydrogen economy is of great importance in replacing fossil fuels and contributing to a clean energy future.

Hydrogen energy is considered an important step towards an environmentally friendly and sustainable future in the energy sector. In order for this transformation to occur successfully, the effectiveness and sustainability of the methods used in hydrogen production, storage and distribution are of great importance. Hydrogen production is generally carried out from natural gas or through electrolysis of water. These two basic methods have different advantages and disadvantages.

Natural gas-based hydrogen production occurs through the method called gray hydrogen. In this method, hydrogen is obtained as a result of processing natural gas with steam methane reforming (SMR). One of the advantages is that existing natural gas infrastructure can be used and hydrogen production in large quantities is possible. However, this method also has a big disadvantage; During the SMR process, a significant amount of carbon dioxide (CO₂) is released into the atmosphere, which negatively affects the environmental impact.

On the other hand, another method used for hydrogen production is electrolysis. Electrolysis is based on the separation of water into hydrogen and oxygen with the help of electric current. This method is considered environmentally friendly because it creates almost no CO₂ emissions, especially when powered by renewable energy sources. However, producing hydrogen by electrolysis can be costly, especially when using technologies that are still developing. The electrolysis method also includes different types. These include different approaches such as alkaline electrolysis, proton exchange membrane electrolysis (PEM), solid oxide electrolysis. Each electrolysis method has its own advantages and challenges. For example, alkaline water electrolyzers may be low cost and long lasting, but they tend to operate at limited current density. The PEM method may be more attractive for commercial use, but cell materials are costly.

Different methods used for hydrogen production have advantages and disadvantages. Considering these, it is understood that hydrogen can play an important role as the energy source of the future. However, in order to fully utilize this potential, technical, economic and infrastructural difficulties must be overcome. Therefore, further research, investment and cooperation are required to develop and popularize hydrogen technology. In particular, green hydrogen production can promote environmentally friendly energy production through the use of renewable energy sources. Which method is preferred depends on a number of factors such as energy efficiency, cost, environmental impact and existing infrastructure. Therefore, it should not be forgotten that these different production methods require further research and development in order for hydrogen energy to contribute to future energy conversion in a sustainable manner. Studies in this area could enable hydrogen to play a broader role in clean energy conversion. Advantages of hydrogen include its ability to produce zero-emission electricity and deliver clean vehicle systems. Hydrogen fuel cells produce electricity by entering hydrogen gas into an electrochemical reaction with oxygen. During this reaction, only water vapor emission occurs, which contributes to maintaining air quality and combating climate change. The high energy density of hydrogen offers solutions to energy storage and transportation problems. However, there are also some challenges to the hydrogen economy.

Issues such as developing green methods for hydrogen production and solving energy intensity issues are obstacles to the full potential of this technology. The development of hydrogen production and storage infrastructure highlights the need to store and distribute hydrogen safely and effectively. However, creating this infrastructure can be a costly and complex process.

As a result, hydrogen energy stands out as one of the keys to a clean and sustainable future. However, in order to fully utilize this potential, various difficulties must be overcome. Overcoming these challenges is of great importance for hydrogen to shape a sustainable future in energy production and vehicle systems.

This article discusses in detail the future role of hydrogen energy as a clean and sustainable energy source, helping us understand and evaluate the potential in this field. Experts, researchers and policy makers in the energy sector can benefit from this article to develop energy transition strategies by understanding the advantages and challenges of hydrogen. Additionally, by examining the potential of hydrogen technology to contribute to the future and sustainability goals, this article may stimulate advances in this field and contribute to wider acceptance of hydrogen energy. Therefore, it can be an important resource for researchers working in the field of energy and those shaping energy policies.

Referanslar

- Aslan, Ö. (2007). Hidrojen Ekonomisine Doğru. *İstanbul Ticaret Üniversitesi Sosyal Bilimler Dergisi*, 6(11), 283-298.
- Berry, G. D., Pasternak, A. D., Rambach, G. D., Ray, S. J., & Schock, R. N. (1996). Hydrogen as a future transportation fuel. *Energy*, 21(4), 289-303.
- Cipriani, G., Dio, V. D., Genduso, F., Cascia, D. L., Liga, R., Miceli, R., & Galluzzo, G. R. (2014). Perspective on hydrogen energy carrier and its automotive applications. *International Journal of Hydrogen Energy*, 39(16), 8482-8494.
- Coinmonks. (2022, May 29). *Hydrogen Production Methods*. medium: <https://medium.com/coinmonks/hydrogen-production-methods-9b4504d26269> adresinden alındı
- Çuhadaroğlu, H. (2005). Hidrojen enerjisi ve yakıt hücreleri teknolojisi. Sakarya üniversitesi yüksek lisans tezi.
- Dincer, I., & Acar, C. (2015). Review and evaluation of hydrogen production methods for better sustainability. *International Journal of Hydrogen Energy*, 40(34), 11094-11111.
- El-Bassuoni, A. M., Sheffield, J. W., & Veziroglu, T. N. (1982). Hydrogen and fresh water production from sea water. *International Journal of Hydrogen Energy*, 919-923.
- Fernandez, R. A., Cilleruelo, F. B., & Martinez, I. V. (2016). A new approach to battery powered electric vehicles: A hydrogen fuel-cell-based range extender system. *Int J Hydrogen Energy*, 41(8), 4808-4819.
- (2020). *Green Hydrogen for Industry: A Guide to Policy Making*. Birleşik Arap Emirlikleri: International Renewable Energy Agency.
- Gül, K. E. (2006). *Hidrojenin İçten Yanmalı Motorlarda Yakıt Olarak Kullanılması Ve Performansa Etkileri*. YTÜ: yüksek lisans tezi.
- Gürz, M. (2017). Hidrojen Yakıt Hücreleri Ve Otomotiv Sektörü İçin Pem Yakıt Hücresinin Uygulanabilirliğine Yönelik Analiz. İskenderun teknik: YÜKSEK LİSANS TEZİ.
- Hua, T. Q., Ahluwalia, R. K., Peng, J. K., Kromer, M., Lasher, S., Mckenney, K., & vd. (2011). Technical assessment of compressed hydrogen storage tank systems for automotive applications. *International Journal of Hydrogen Energy*, 36(4), 3037-3049.
- IRENA. (2020). *Green Hydrogen Cost Reduction Scaling Up Electrolyzers To Meet The 1.5 oC Climate Goal*. United Arab Emirates: International Renewable Energy Agency.
- Kaya, K. (2018). Hidrojen yakıt hücreli araçlarda kontrol stratejisinin geliştirilmesi. İskenderun teknik: yüksek lisans tezi.
- Kendall, M. (2018). Fuel cell development for New Energy Vehicles (NEVs) and clean air in China. *Progress in Natural Science*, 28(2), 113-120.
- Khalil, M., & Dincer, I. (2024). Investigation of a community-based clean energy system holistically with renewable and hydrogen energy options for better sustainable development . *Journal of Cleaner Production*, 440, 140895.

- Kıvrak, M. F. (2011). Hydrogen Fuel Cell Powered Electric Vehicles And An Application Of Improvement For The Desorption Efficiency Of A Metal Hydride Storage. *Yüksek Lisans tezi*. içinde İTÜ.
- Köseoğlu, E. (2013). *Suyun Elektrolizinden Hidrojen Gazı Üretimi İçin Yeni Bir Yöntem Geliştirildi / Suyun Elektrolizinden Hidrojen Gazı Üretimi İçin Yeni Bir Yöntemin Geliştirilmesi*. Yıldız Teknik Üniversitesi Yüksek Lisans Tezi.
- Kumar, L., & Jain, S. (2014). Electric propulsion system for electric vehicular technology: A review. *Renewable and Sustainable Energy Reviews*, 29, 924–940.
- Kumar, S. S., & Lim, H. (2022). An overview of water electrolysis technologies for green hydrogen production. *Energy reports*, 1(8), 13793-13813.
- Külekçi, Ö. C. (2009). Yenilenebilir Enerji Kaynakları Arasında Jeotermal Enerjinin Yeri ve Türkiye Açısından Önemi. *Ankara Üniversitesi Çevre Bilimleri Dergisi.*, 1(2), 83-91.
- Larminie, J., & Dicks, A. (2003). *Fuel cell systems explained*. 2nd ed. United Kingdom: John Wiley & Sons.
- Larminie, J., & Lowry, J. (2012). *Electric Vehicle Technology Explained* 2nd ed. United Kingdom: John Wiley & Sons.
- Mekhilef, S., Saidur, R., & Safari, A. (2012). Comparative study of different fuel cell Technologies . *Renewable and Sustainable Energy Reviews*, 16(1), 981–989.
- Muradov, N. Z., & Veziroğlu, T. N. (2005). From hydrocarbon to hydrogencarbon to hydrogen economy. 2005;30:225e37. *International Journal of Hydrogen Energy*, 30(3), 225-237.
- Ni, M., Leung, M. K., Sumathy, K., & Leung, D. Y. (2006). Potential of renewable hydrogen production for energy supply in Hong Kong. *International journal of hydrogen energy* , 31(10), 1401-1412.
- Ni, M., Leung, M. K., Sumathy, K., & Leung, D. Y. (2006). Potential of renewable hydrogen production for energy supply in Hong Kong. *International Journal of Hydrogen Energy*, 1401-1412.
- Oettle, G. (2010). *Fuel cells for automotive application*. Munich: GRIN Verlag.
- Rostrup-Nielsen, J. R., & Rostrup-Nielsen, T. (2002). Large-Scale Hydrogen Production. *CATTECH*, 6, 150-159.
- Salvi, B. L., & Subramanian, K. A. (2015). Sustainable development of road transportation sector using hydrogen energy system. *Renewable and Sustainable Energy Reviews*, 51, 1132-1155.
- Sandy Thomas, C. E. (2009). Transportation options in a carbon-constrained world: Hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles. *International Journal of hydrogen energy*, 34(23), 9279–9296.
- Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. *International Journal of Hydrogen Energy*, 42(52), 30470–30492.
- Sharaf, O. Z., & Orhan, M. F. (2014). An overview of fuel cell technology: Fundamentals and applications. *Renewable and sustainable energy reviews*, 32, 810-853.
- Şener, O. (2023, Temmuz 26). *Yeşil Hidrojen Üretiminde Elektroliz Yöntemleri*. Kasım 01, 2023 tarihinde <https://yeserenerji.com/yesil-hidrojen-uretiminde-elektroliz-yontemleri/> adresinden alındı
- Şenol, r., üçgül, i., & acar, m. (2006). Yakıt pili teknolojisindeki gelişmeler ve taşıtlara uygulanabilirliğinin incelenmesi. *Mühendis Makina*, 47(563), 37-50.
- Tanç, B. (2019). *Hidrojen yakıt hücresi hibrit elektrikli araç için destek bataryasının enerji görünümü ve araç performansı üzerindeki etkilerinin analizi*. İskenderun teknik.
- Tutar, F., & Eren, M. (2011). Geleceğin Enerjisi: Hidrojen Ekonomisi ve Türkiye. *International Journal of Economic and Administrative Studies*, 6.
- Von Helmholt, R., & Eberle, U. (2007). Fuel cell vehicles: Status 2007. *Journal of power sources*, 165(2), 833-843.
- Zohuri, B. (2019). Large-Scale Hydrogen Production. *Hydrogen energy: challenges and solutions for a cleaner future*, 229-255.