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Hydrogen Fuel Cells: A Pathway to Sustainable Distributed Energy

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Authors' contributions

This work was carried out in collaboration among all authors. Authors SB, CTA, MK and IK (1) designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors CUO, IK (2) and HKN managed the analyses of the study. Authors MM and JS managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Herein, we review hydrogen fuel cell technology as a promising solution for distributed power generation. The various types of fuel cells, including polymer electrolyte membrane (PEM), alkaline, phosphoric acid, solid oxide, and molten carbonate fuel cells, are discussed. Furthermore, the critical components of fuel cells, such as the anode, cathode, electrolyte, and catalyst, and the factors influencing their performance and durability are explored. Additionally, the paper examines the different methods of hydrogen production, including electrolysis, reforming, and gasification, and assesses their environmental impact and economic viability. The potential applications of fuel cells in residential, commercial, and industrial settings are explored, emphasizing their ability to provide clean, reliable, and efficient power supply. Finally, the review discusses the current challenges and future research directions in hydrogen fuel cells, including cost reduction, durability improvement, and infrastructure development.

Keywords: Energy; hydrogen fuel cells; storage; transportation; efficiency; production.

1. INTRODUCTION

Energy is essential for advancing a contemporary state and is a significant element in sustainable development. As the global energy landscape shifts toward sustainability, distributed power generation may increase grid reliability and reduce environmental impact. Water is the sole waste from hydrogen fuel cells, which provide clean power. Due to their non-renewability, fossil fuels will eventually run out if humans don't conserve them (Shafiee & Topal, 2009). Alternative energy sources have increased energy demand, especially in the transportation sector, accounting for about 60 % of the total energy consumption (Balat & Balat, 2009). The common renewable energy sources include wind, solar, hydro and geothermal, which must meet a high energy density (120 MJ/kg) and not be a danger to the ecosystem (Dunn, 2002a; Ren et al., 2017; Tour et al., 2010). The suggested "hydrogen economy" is driven by electricity, with hydrogen serving as a method for storing electricity via chemical hydrogen bonding. Typically, 6 kg of hydrogen can propel a lightweight automobile for a distance of 500 km (Stetson, 2012; Stroman et al., 2014; Von Helmolt & Eberle, 2007).

Nonetheless, the transformation of these renewable energy sources into valuable energy forms, such as hydrogen (bio-hydrogen), biological alcohol, and biogas, requires energy-intensive devices. The significance of hydrogen fuel has recently been acknowledged, and its utilization is growing more vital. Hydrogen is a carbon-free energy source that has the potential to surpass fossil fuels and complete the global energy requirements. It is considered clean and environmentally benign since it does not liberate carbon as waste (Ball & Weeda, 2015; Samsatli et al., 2016).

Research has reported that low volumes of hydrogen are being produced from renewable energy sources compared to fossil fuels (Deben et al., 2015; Friedrich et al., 2016; Hübert et al., 2011; Kothari et al., 2010; Ni et al., 2006a). Three decades prior, hydrogen was acknowledged as a fundamental component of a sustainable energy framework, capable of delivering safe, economical, and eco-friendly energy (U.S. Department of Energy, 1995). Hydrogen is an energy source with the least toxicity and few environmental disruptions by most world energy corporations (Chamoun et al., 2015; Energy, 2003; World Energy Council, 2017). Hydrogen, as a feasible alternative fuel, consistently promises significant potential but yields minimal results (Staffell et al., 2019). Nonetheless, hydrogen could assume a significant role in the future due to its minimal carbon footprint (Council, 2017; Hanley et al., 2018; Hart et al., 2015; Martinez-Duart et al., 2015; Oener et al., 2017) that provides carbon-neutral energy. It provides an effective energy balance that is readily transportable and storable (Abbasi & Abbasi, 2011; Pudukudy et al., 2014). A more secure energy system reduces reliance on fossil fuels (Dunn, 2002b; Sheffield & Sheffield, 2007) possessing the capability to operate within the transportation sectors (Coalition-McKinsey, 2010; Tollefson, 2010), heat (Dodds et al., 2015; Dodds & Demoullin, 2013), industry (Napp et al., 2014), as well as electricity(Ball & Weeda, 2015; Samsatli et al., 2016). They constitute two-thirds of worldwide CO_2 emissions (MacCarthy et al., 2015). The fuel from hydrogen is considered for the future due to its low atomic weight, good energy density and zero emissions. It possesses more mass energy than oil/petroleum, rendering it an efficient energy source for various uses, such as autos and portable gadgets (Ni et al., 2006b). Typically, high-temperature combustion processes produce nitrogen oxides, leading to atmospheric pollution; however, using hydrogen in fuel cells for energy generation can eradicate this issue, as it does not release deleterious gases (Ahluwalia et al., 2005). Several European nations employ power-to-gas technology to store energy as hydrogen gas. Hydrogen is anticipated as a suitable, eco-friendly alternative to conventional fossil fuels. The detrimental impacts of fossil fuel burning on the environment may be alleviated by utilizing hydrogen as both an energy source and an energy carrier. Furthermore, the substantial energy density of hydrogen and its low atomic mass render it an appropriate option for alleviating the strain on global fossil fuel reserves and mitigating environmental impact by decreasing greenhouse gas (GHG) emissions. The existing literature on hydrogen production, storage, and applications is extensive. This review aims to consolidate relevant information in one location to provide both the scientific and non-scientific communities with an overview of hydrogen and fuel cell technology.

2. WORKING PRINCIPLE OF A FUEL CELL

The anode receives hydrogen, which causes ionization, followed by the release of protons and the supply of air to the cathode, where negative ions are generated, as shown in Fig. 1. The orientation of the charge carriers and transfer varies with the different types of fuel cells, thus causing the release of water on either side of the electrodes. Enhancement in the liberation of hydrogen normally occurs in the presence of a catalyst, mainly made of carbon-based compounds coated with platinum. The total reaction remains consistent despite varying charge carriers eliciting distinct reactions at the electrodes(Yue et al., 2021), as shown by Equation 1.

$$2H_2\ (g) + O_2\ (g) \rightarrow 2H_2O\ (g) + \text{electricity} + \text{heat} \quad (1)$$

3. TYPES OF FUEL CELL

Fuel cells vary based on their operating temperature, efficiency, uses, and pricing. They are categorized into six principal groups based on the selection of fuel and electrolyte (Kirubakaran et al., 2009). They include Direct methanol fuel cell (DMFC), Molten carbonate fuel cell (MCFC), Alkaline fuel cell (AFC), Solid oxide fuel cells (SOFC), Phosphoric acid fuel cell (PAFC), and proton exchange membrane fuel cells (PEMFC).

3.1 Alkaline Fuel Cell

The AFC produces electrical energy using an aqueous potassium hydroxide (KOH) solution. The circuit formation results from the movement of hydroxyl ions through the electrolyte, hence the generation of electrical energy.

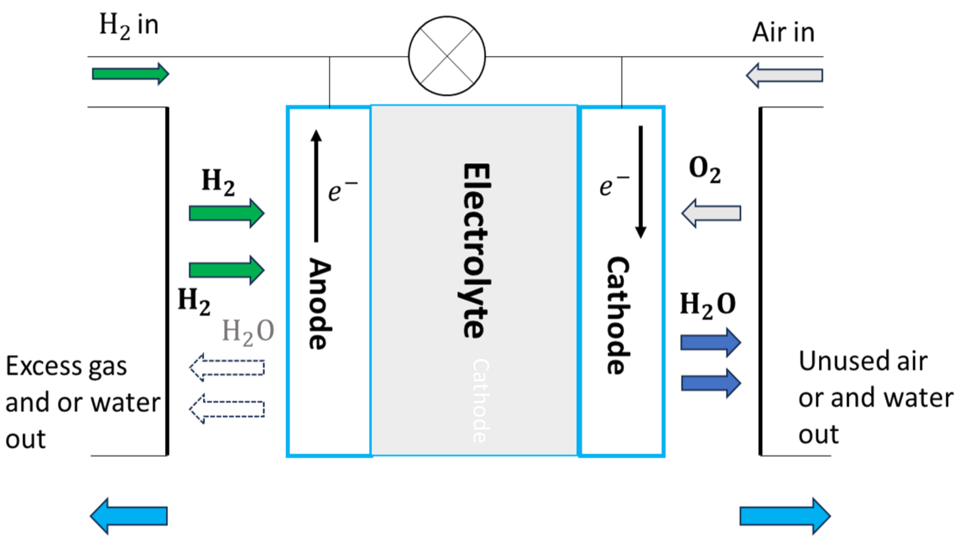

Fig. 1. A schematic representation showing the operation principle of a standard fuel cell.

The reaction at the anode occurs due to the reaction of hydrogen gas and hydroxyl ions to produce water molecules and four electrons, as shown by Equation 2 (Alhassan & Garba, 2006).

$$2H_2\,(g) + 4O.H.^{-}(aq) \rightarrow 4H_2O\,(g) + 4e^{-} \qquad (2)$$

At the cathode, an oxygen molecule and two water molecules reacted, absorbing four electrons to produce four negatively charged hydroxyl ions. The redox reaction is reduced, as detailed in Equation 3 (Alhassan & Garba, 2006).

$$O_2\,(g) + 2H_2O(g) + 4e- \rightarrow 4OH^{-}(aq) \qquad (3)$$

Fig. 2 shows the representation of an alkaline fuel cell.

3.2 Phosphoric Acid Fuel Cells (PAFC)

Phosphoric acid fuel cells comprise a phosphoric acid electrolyte and carbon paper electrodes. The hydrogen ion (H^+) acts as the charge carrier. The liberated electrons at the anode move from the electrolyte to the cathode through the external circuit, thus generating an electrical current. Platinum catalyst accelerates the reaction between oxygen, electrons and protons, leading to water production. At around 40 °C, phosphoric acid solidifies, which causes system initiation and continuous operation (Remick et al., 2010). Fig. 3 indicates that the hydrogen released at the anode dissociates into 4 protons and 4 electrons. The oxidation occurring at the anode is a redox reaction, as illustrated in Equation 4. At the cathode, the redox process involves reduction, as shown in Equation (5), wherein four protons and four electrons react with oxygen to produce water (DOD, 2010; Remick et al., 2010).

$$2H_2\,(g) \rightarrow 4H^{+}\,(aq) + 4e^{-} \qquad (4)$$

$$O_2\,(g) + 4H^{+}\,(aq) + 4e^{-} \rightarrow 2H_2O\,(g) \qquad (5)$$

The electrons traverse the external circuit while the protons move through the electrolyte. The outcome is the production of electrical current and thermal energy. Heat is often utilized for water heating or steam generation at atmospheric pressure; however, steam reforming reactions generate carbon monoxide (CO) at the electrodes.

3.3 Solid Oxide Fuel Cells (SOFCs)

Solid oxide fuel cells are high-temperature fuel cells with a metallic oxide solid ceramic electrolyte. These cells use a mixture of hydrogen and carbon monoxide produced from hydrocarbon fuels, and air acts as the oxidant (Ormerod, 2003). Due to its good ionic conductivity and thermal stability, the electrolyte commonly made from Yttria stabilized zirconia (YSZ)is used in most SOFCs (Singhal, 2000; Will et al., 2000). Fig. 4 shows a representation of a solid fuel cell.

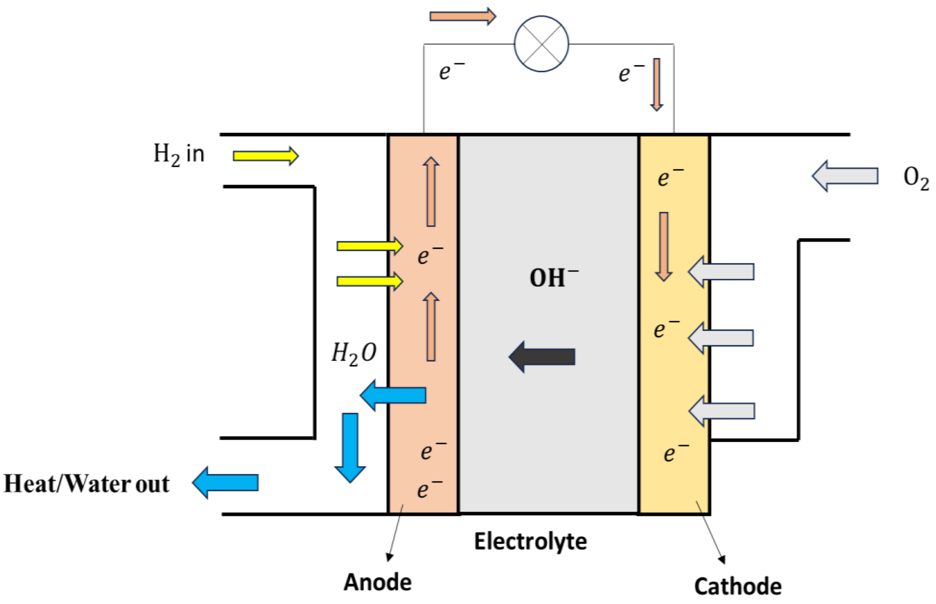

Fig. 2. A schematic representation of an Alkaline fuel cell

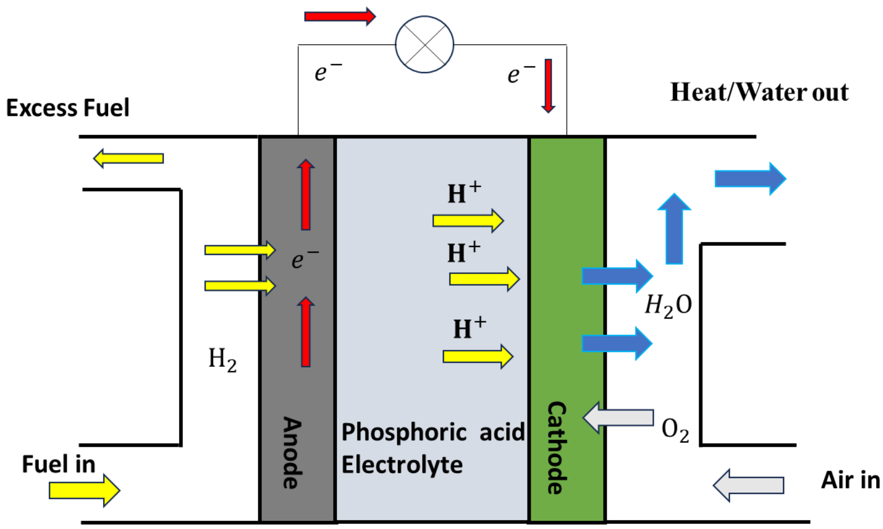

Fig. 3. A schematic representation of a phosphoric acid fuel cell

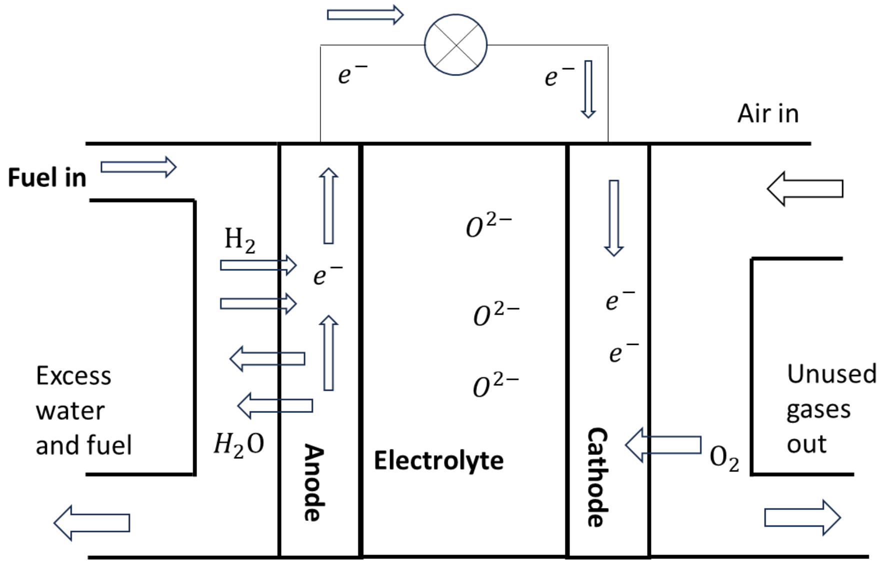

Fig. 4. A schematic representation of a solid–oxide fuel cell

At the cathode, a reduction reaction occurs, which causes oxidation of oxygen to occur at a temperature of 1000 °C, as shown in Equation 6, while the anode fuel oxidation takes place, as detailed by Equation 7. The porosity of the anode facilitates the removal of oxidation by-products from the fuel electrode and the electrolyte interfaces, thus enabling fast fuel conduction (Sahibzada et al., 1999; Tanaka et al., 2000).

$$O^{2-}{}_{(S)} + H_2\,(g) \rightarrow H_2O\,(g) + 2e^- \quad (6)$$

$$1/2\ O_2\,(g) + 2e^- \rightarrow O^{2-}(s) \quad (7)$$

Solid Oxide Fuel Cells (SOFCs) are extensively utilized in large-scale distributed power production systems with capacities reaching hundreds of megawatts. The by-product heat is typically utilized to produce additional power by driving gas turbines, thus enhancing the CHP efficiency to between 70 and 80 %.

3.4 Molten Carbonate Fuel Cell (MCFC)

These fuel cells contain a molten carbonate electrolyte comprising a ceramic matrix of beta alumina solid electrolyte whose structure is porous (Lee et al., 2006).

In this fuel cell, the reaction at the hydrogen electrode involves the reaction of hydrogen and carbonate ions, resulting in the production of electrons, carbon dioxide and water, as shown in Fig. 5. Carbon dioxide, hydrogen and carbon monoxide production occurs at the anode by transforming water and methane gas (CH_4), as shown in Equation 8.

$$CH_4\ (g) + H_2O\ (g) \rightarrow CO\ (g) + 3H_2\ (g) \quad (8)$$

The oxidation reactions, which are electrochemical in nature, utilize hydrogen and carbon monoxide in the presence of an electrolyte containing a carbonate, leading to the formation of electrons, as shown by Equations 9 and 10, respectively.

$$H_2\ (g) + CO_3^{2-}(aq) \rightarrow H_2O\ (g) + CO_2\ (g) + 2e^- \quad (9)$$

$$CO\ (g) + CO_3^{2-}(aq) \rightarrow 2CO_2\ (g) + 2e^- \quad (10)$$

The cathode reactions that constitute reduction cause the formation of carbonate ions from carbon dioxide and oxygen, the transportation of which occurs through the electrolyte to the anode. Electrodes can be used to collect electric current and cell voltage (Chudej et al., 2008).

3.5 Proton Exchange Membrane Fuel Cell (PEMFC)

In PEMFC, hydrogen is activated by a catalyst to produce proton ions and eject electrons at the anode. The proton traverses the membrane, while the electron is compelled to flow into the external circuit, thereby generating electricity. The electron subsequently returns to the cathode, interacting with oxygen and proton ions to produce water, as shown in Fig. 6. The chemical reactions at each electrode are detailed in Equations (11) and (12).

$$H_2\ (g) \rightarrow 2H^+\ (aq) + 2e^- \quad (11)$$

$$1/2O_2\ (g) + 2H^+\ (aq) + 2e^- \rightarrow H_2O\ (g) \quad (12)$$

Bipolar plates and membrane electrode assemblies (MEA) make up the PEMFC. A membrane, catalyst, and gas diffusion layer (usually carbon cloth) make up the MEA. The membrane lets protons go from anode to cathode but blocks electrons and reactants. The gas diffusion layer distributes fuel evenly. Electrons from the anode generate electricity in the external circuit.

3.6 Direct Methanol Fuel Cell (DMFC)

The direct methanol fuel cell is an advanced variant of the PEM-FCs. Its low-temperature operation, extended lifespan, and efficient refueling system attributes make it appropriate for portable energy applications. Furthermore, it requires no recharging and is classified as a clean, renewable energy source. Methanol is the energy source for DMFC systems.

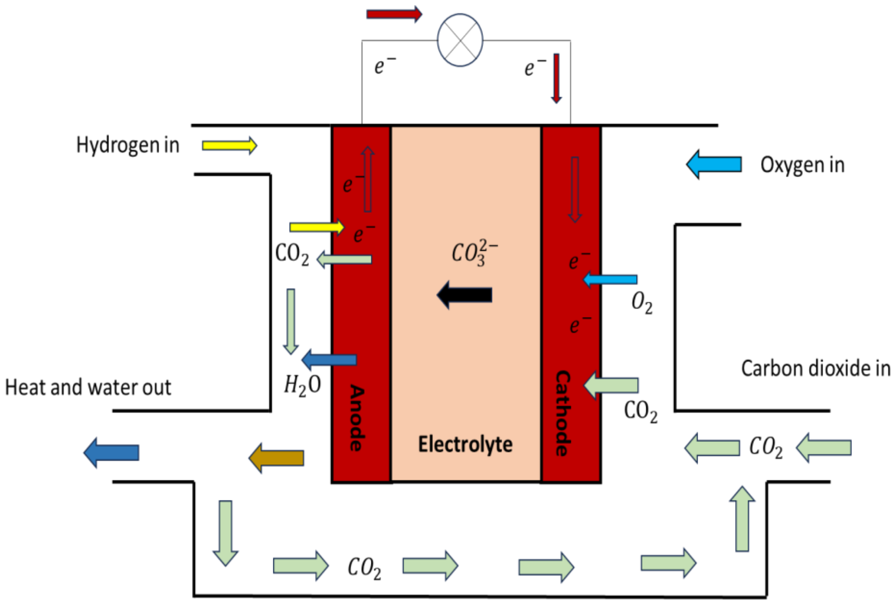

Fig. 5. A schematic representation of a Molten carbonate fuel cell.

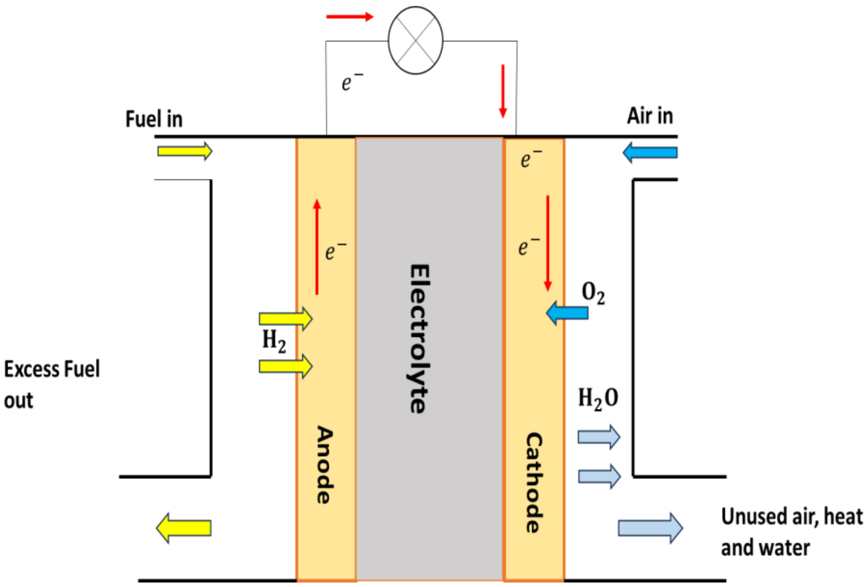

Fig. 6. A schematic representation of a Proton exchange membrane fuel cell

At the anode, methanol is converted into carbon dioxide (CO_2), as shown by Equation 13.

$$CH_3OH\ (l) + H_2O\ (l) \rightarrow CO_2\ (g) + 6H^+\ (aq) + 6e^- \quad (13)$$

Steam or water is produced at the cathode utilizing oxygen in the atmosphere, as shown by Equation 14.

$$3/2O_2\ (g) + 6e^- + 6H^+\ (aq) \rightarrow 3H_2O\ (g) \quad (14)$$

Fig. 7 shows a schematic representation of a Direct methanol fuel cell.

4. PRODUCTION OF HYDROGEN

Three types of hydrogen production exist: green, blue, and red. Blue hydrogen comes from coal gasification and natural gas, frequently with carbon capture and storage (CCS) technology, while green hydrogen comes from renewable energy. Red hydrogen is only made from fossil fuels. Although green hydrogen is usually derived from renewable sources, most hydrogen is still produced via the CO_2-intensive steam methane reforming (SMR) process. Traditional electrolysis splits water into oxygen and hydrogen, providing green hydrogen without carbon emissions. This technique can use renewable energy. However, lowering hydrogen production costs, especially green hydrogen, remains challenging. Hydrogen from steam reforming costs three times more than natural gas. At an energy cost of five cents per kWh, electrolysis may produce hydrogen, which is almost twice as expensive as natural gas. The natural gas pipeline infrastructure now in place can transport lower hydrogen concentrations, which will also help reduce CO_2 emissions from the current natural gas reforming plants. Several causes are bringing attention to hydrogen fuel, with the following possibly the most essential:

i. Many energy sources produce hydrogen.
ii. Fuel cells and combustion produce water from hydrogen, as the least harmful element.
iii. Residential applications, hydrogen fuel cell vehicles, energy storage, and combined heating and power generation systems employ hydrogen to address different energy needs.

Utilizing off-grid offshore wind energy to produce clean fuel (hydrogen/ammonia) could substantially aid in decarbonizing the maritime industry. Hydrogen is the optimal substance for the transportation and potential storage of energy. Based on the literature and research reports (Pinjari et al., 2023; Zhu et al., 2020), three primary hydrogen production methods exist, utilizing diverse technologies and potential sources. The concept of colour has evolved due to using significant sources in hydrogen production. CO_2 and other greenhouse emissions result from fossil fuel-based hydrogen generation. Grey hydrogen denotes the technique of hydrogen synthesis and its corresponding source (K. Chen et al., 2019). Blue hydrogen was developed through the application of grey hydrogen combined with carbon capture technologies to reduce greenhouse gas emissions (Dickel, 2020; Voldsund et al., 2016). Recent literature(Boretti, 2021; Manna et al., 2021; Rabiee et al., 2021) has reported the application of renewable energy sources for hydrogen production. Green hydrogen is an additional by-product generated by electrolyzers utilizing renewable energy sources. Bioenergy sources, notably biomass combustion and biomethane, could produce green hydrogen. Scholars and enterprises are increasingly focused on enhancing green hydrogen production, as green hydrogen generated through various methods results in net zero gas emissions (Hoelzen et al., 2022; Kumar & Lim, 2022).

4.1 Blue Hydrogen

The commonly used hydrogen-producing plants combine carbon capture and utilization systems to recycle the emitted carbon dioxide. The increase in the demand for hydrogen is addressed using traditional manufacturing techniques that use renewable energy sources. The best hydrogen production method occurs through fossil fuels, particularly the partial oxidation of methane and the reformation of natural gas. The elimination of hydrogen sulphide from natural gas occurs through desulfurization. A process normally called the Claus is used to recover from gaseous hydrogen sulphide.

Hydrogen generation often uses coal gasification. Air separation supplies the gasifier with oxygen from the atmosphere. Air is separated via membrane separation, cryogenic air separation, or pressure swing adsorption. Steam and oxygen are needed for coal pyrolysis after air separation. Pyrolysis breaks coal into volatiles and char. After gasification, products are allowed to rapidly cool (Sazali, 2020).

4.2 Purple Hydrogen

This is generated through nuclear energy; however, due to the high reactor temperature and thermochemical processes, other forms of hydrogen may be liberated. The splitting of Uranium leads to the generation of nuclear energy, which is used in the driving of the turbines which are helpful in the generation of electricity (Calise et al., 2019; IRENA, 2018). Nuclear power stations do not combust fuel directly; therefore, they do not release greenhouse gases in this manner. Fission reactions are employed due to their controllability in reactors utilized in nuclear power facilities. These reactions are sources of thermal energy as they act as heat sources in the nuclear power plant (Ping et al., 2018; Pinsky et al., 2020; Zhiznin et al., 2020). Nuclear energy is produced through the fission of atoms, which leads to the conversion of water into steam that enables the turbine to generate power.

4.3 Turquoise Hydrogen

The decomposition of compounds containing only carbon and hydrogen results in the generation of Turquoise hydrogen. This can be achieved through several means. The most advanced research approach, with the highest potential for commercialization, is the method of producing hydrogen and carbon black using plasma. Other techniques include the use of cold plasma, methane catalysis, and thermal splitting for molten metal pyrolysis (Amin et al., 2011). All these techniques use hydrocarbons, particularly those from natural gas, as the feedstock and electricity as the main source for each.

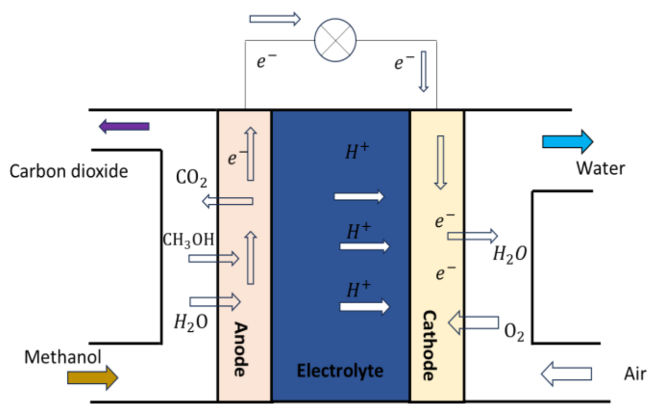

Fig. 7. A schematic representation of a Direct methanol fuel cell.

4.4 Grey Hydrogen

When coal or natural gas are steam reformatted, grey hydrogen is created without any carbon being incorporated, used, or stored. Most chemical reactions produce a by-product that accounts for more than 40 % of grey hydrogen (Kannah et al., 2021). A new term was introduced by the North American Council for Freight Efficiency for this type of hydrogen "white hydrogen" (Roeth, 2021). The main applications for grey hydrogen are in the petrochemical industry and ammonia production (Ji & Wang, 2021). The primary drawback of grey hydrogen lies in the substantial CO_2 emissions produced during its synthesis, estimated at approximately 830 million tons annually (Carlson, 2020).

4.5 Green Hydrogen

Green hydrogen refers to the production of hydrogen derived from renewable energy sources. It is generated when electricity generated from low-carbon materials is passed through water during the process of electrolysis. The electrolysis process is comprehensively examined before addressing the particulars of diverse green hydrogen production methods. The most well-established and economically feasible technique for producing H_2 from H_2O is electrolysis. The splitting of water leads to the liberation of hydrogen to the cathode while OH^- to the anode due to the application of an electric potential. Water electrolysis can be shown through several methods, such as proton exchange membrane, alkaline water electrolysis, alkaline anion exchange membranes, and solid oxide water electrolysis (Dash et al., 2023). Alkaline anion exchange membrane's water electrolysis may replace traditional noble metal electrocatalysts with more economical transition metals. It has been applied due to its good durability, cost-effectiveness, power efficiency, ease of handling, and relatively novel technology (Vincent & Bessarabov, 2018).

5. FUEL CELL VEHICLES

They are used in numerous parts of the world to reduce environmental stress and fossil fuel consumption (Tanç et al., 2019). A fuel cell is usually used in a vehicle's power system; these vehicles can be classified as either pure fuel cell vehicles (PFCV) or fuel cell hybrid electric vehicles (FCHEV). Fuel cells, specifically PEMFCs, serve as the primary power source for the systems. At the same time, lithium batteries and ultracapacitors are incorporated as auxiliary systems to manage peak power demands and rapid transient conditions in FCHEVs (Gherairi, 2019). Fig. 8 shows four different types of fuel cell vehicles, particularly those made by Toyota, Honda, Roewe and Audi.

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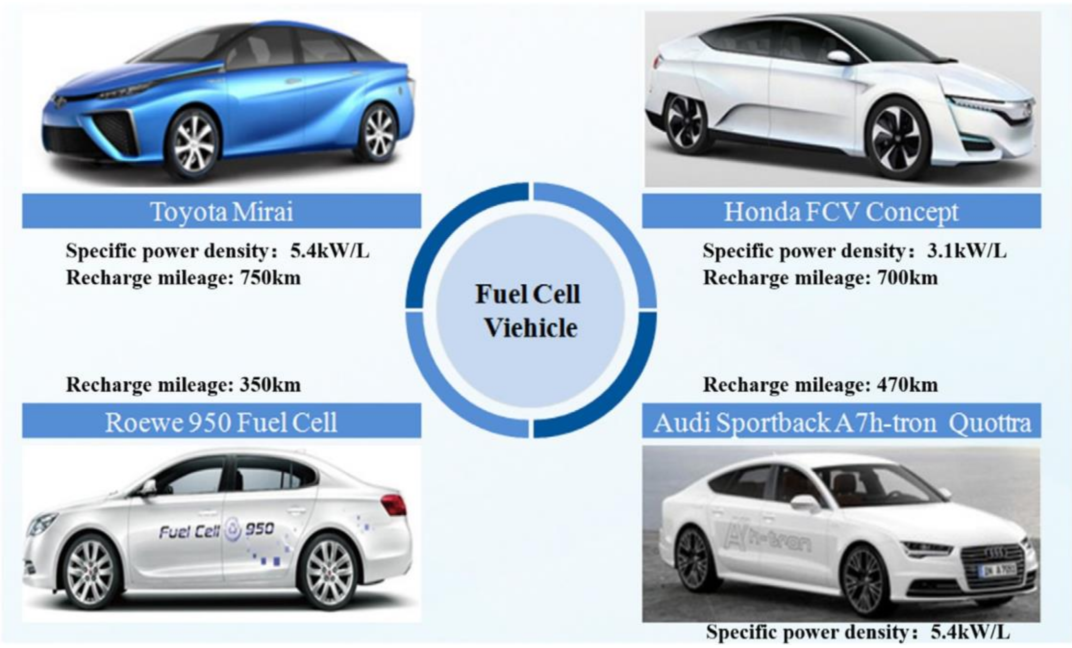

Fig. 8. A diagrammatic representation of fuel cell vehicles from Toyota, Honda, Roewe and Audi (Nonobe, 2017)

6. HYDROGEN STORAGE IN FUEL CELL VEHICLE

Hydrogen storage research is crucial for fuel cell vehicle development. Innovative storage methods are being developed to suit consumer needs and address hydrogen's low energy density. Low energy density makes storing enough hydrogen aboard a vehicle for a suitable driving range hard without making the containers too heavy(US DOE, 2019).

6.1 Pressurized Tank Storage

Carbon-fibre-wrapped cylinder pressure tanks are strong and impact-resistant, ensuring collision safety. These 34 MPa tanks hold 32.5 kg of compressed hydrogen in 186 L, enough for 500 kilometers. The storage capacity is 90 %/55-gallon drum, which is substantial for automotive uses. Fig. 9 shows a fuel cell vehicle with a storage unit. The aim of 6 wt % hydrogen storage is possible, but tank volume reduction is difficult. The report from the Office of Technology Policy (Davis et al., 2003) claims that high-pressure canisters containing hydrogen are used in Honda and Toyota vehicles. Lower density makes hydrogen harder to store in tanks than other gases. Some companies are conducting small-scale research on storing liquid hydrogen at low temperatures, which is impractical for ordinary vehicles. Liquid hydrogen storage systems confront daily boiling losses of up to 1 % of storage volume. Liquid hydrogen storage requires refrigeration at 20 K, which adds complexity and energy (Davis et al., 2003).

6.2 Hydrogen Absorption in Metal-based Compounds

Metal hydration can be used to store hydrogen above room temperature and pressures below 3 – 4 MPa however, due to the excessive weight, the metals are rarely used (Das, 2016). Lithium nitride has been discovered to store substantial quantities of hydrogen reversibly. This material rapidly stores hydrogen within the temperature range of 170–210 °C and achieved a 9.3 wt % absorption when kept for 30 minutes at 255 °C. Below temperatures of 200 °C and at a high vacuum temperature, 2/3 of hydrogen is liberated. For 1/3 of the hydrogen to be released, the temperature must be higher than 320 °C. The absorption of hydrogen formed lithium amide (LiNH2) and lithium hydride (LiH). To find more realistic hydrogen storage pressures and temperatures, the scientists suggested studying metal-N-H systems (P. Chen et al., 2002).

6.3 Storage of Liquid Hydrogen Cryo-genically

By reaching a cryogenic temperature of −259.2 °C, hydrogen is kept in liquid form using the cryogenic liquid storage method. One litre of liquid hydrogen (LH_2) weighs about 71.37 × 10^{-3} kg, indicating its low density (8.52 MJ) of energy may be obtained from one litre of hydrogen. It is very difficult to maintain hydrogen at such low temperatures therefore, insulation is required, which raises expenses. Liquid hydrogen becomes volatile upon interaction with specific gases; therefore, before refilling the tank with

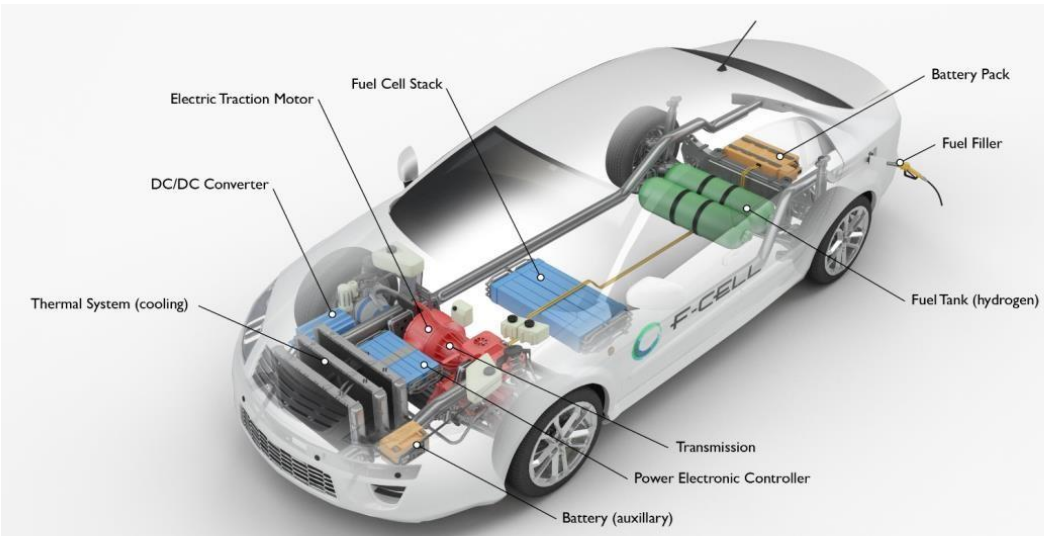

Fig. 9. Fuel cell vehicle containing a storage unit (US DOE, 2019).

hydrogen, it is advisable to utilize nitrogen gas to purge the leftover gases within the tank (Ehsani et al., 2018; Greene et al., 2008; Jorgensen, 2011).

7. CHALLENGES

Hydrogen fuel cell technology has to be advanced by addressing cost, power, efficiency, and longevity. On-board hydrogen storage tanks need to be less expensive as well. Because fuel cells' part-load efficiency is higher than their rated load efficiency, increasing power can cause them to operate at high-efficiency levels above their regular operating threshold. Today's large fuel cell trucks need to be more efficient since they use a lot of hydrogen. The current fuel cell for hydrogen lasts 18,000 hours. To achieve a driving range of 1.2 million to 1.5 million kilometres, it must accumulate 25,000 hours by 2025 and 30,000 to 35,000 by 2030. Proton exchange membrane, membrane electrode, bipolar plate, hydrogen storage system (which comprises bottles, valves, pressure-reducing valves, and other components), and electric stack comprise hydrogen fuel cell systems. The catalyst and proton exchange membrane have not progressed, and the valve significantly depends on imports. Even with few impurities, water electrolysis is the costliest method of producing hydrogen. Industrial reformation produces large amounts of inexpensive hydrogen, but toxic by-products render it unsuitable. It is, therefore, necessary to create anode anti-toxicity catalysts that let hydrogen pass across the reaction interface while obstructing other substances. By designing molecularly selective channels that let just hydrogen into the reaction site, hydrogen anti-toxication can be accomplished. The aim is to construct more active and stable catalysts. In 2012, Tianfeng Securities compared lithium batteries and China's hydrogen fuel cell industry. Top-down policy backing, technology ready for industrialization, firms hastening strategic positioning, industrial chain localization, and capital market investment and financing activities are all present. China's hydrogen fuel cell industry is growing like Japan and the U.S., creating a trillion-dollar sector(Ke & Pang, 2024).

8. CONCLUSION

Hydrogen fuel cells present a promising avenue for distributed power generation, offering a clean, efficient, and reliable alternative to traditional energy sources. Their ability to operate in various settings, from residential and commercial buildings to remote locations, makes them a versatile solution for addressing energy needs. However, the widespread adoption of hydrogen fuel cells is contingent on several factors, including developing cost-effective hydrogen production and storage methods, improvements in fuel cell durability and efficiency, and establishing a robust hydrogen infrastructure. As research and development continue to advance, hydrogen fuel cells are poised to play a significant role in the transition to a decarbonized energy future. By overcoming the challenges associated with hydrogen production and distribution and by addressing the technical limitations of fuel cell technology, we can harness the potential of this clean energy source to create a more sustainable and resilient energy landscape.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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