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Review Article

A Comprehensive Review on Exploring Fuel Cell Potential in Energy Sector

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Abstract

Fuel cells are emerging as a game-changing solution to address the pressing environmental and energy concerns caused by the transportation and industrial sectors, both of which are major contributors to greenhouse gas emissions. This review examines recent advancements in fuel cell technologies and their diverse applications, focusing on key types like Proton Exchange Membrane Fuel Cells (PEMFCs), Alkaline Fuel Cells (AFCs), Phosphoric Acid Fuel Cells (PAFCs), Solid Oxide Fuel Cells (SOFCs), and Direct Methanol Fuel Cells (DMFCs). The fundamental principles, material requirements, and unique applications of each type are explored in detail, covering areas such as transportation, portable devices, stationary energy systems, and aeronautics. Fuel cells stand out for their high efficiency, minimal emissions, and adaptability to a wide range of energy needs. However, challenges remain, including high production costs, durability of materials, and effective hydrogen storage. This review highlights ongoing innovations aimed at overcoming these obstacles and emphasizes the transformative potential of fuel cells in supporting sustainable energy systems across various sectors.

Keywords: Fuel cell, PEMFC, AFC, PAFC, SOFC, DMFC.

Graphical abstract

1. Introduction

The transportation and industrial sector are one of the biggest consumers of fuel which produce large quantity of greenhouses gases (GHG) and controlled discharges such as; nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), carbon dioxide (CO_2) and particulates Matter (PM), which are recognized to perform a significant role in climatic impact and atmospheric environmental damage [1]. According to study international transportation and industries emitted 796 million tons of CO_2, NO_x and SO_x emissions are 15% and 13% respectively. Fuel cell is a very promising technology for lesser NO_x formation, reduce SO_x and CO_2 emission with high energy efficiency and pollution free environment [2-4]. The fuel cell's application is best for electricity supply in the transportation and industries for various vehicles and plants rather than using different sorts of fuels i.e. hydrogen, diesel or LNG [5, 6].

A fuel cell is a device that continuously converts chemical energy into electrical energy. Unlike a battery, it doesn't store energy but transforms it directly [7]. It works by combining a fuel (like hydrogen) and an oxidant (like oxygen) through a chemical reaction within the cell. Mechanism that involve types of ions transferred, operating conditions and by products formed on either side of cell assembly are different for different types of fuel cells. **Figure 1** shows the general representation of fuel cell assembly. This reaction generates electricity, which can be used to power various devices. The key components of a fuel cell are electrodes and an electrolyte, which facilitate the chemical process [8]. The fuel cell commonly has energy efficiency up to 40 to 60 % but recovery of waste heat with cogeneration scheme can be made it up to 85% [9-11]. A basic fuel cell consists of two electrodes, anode oxidizes the hydrogen fuel known as Hydrogen Oxidation Reaction (HOR) on the other hand oxygen reduced at cathode known as oxygen reduction reaction (ORR). During electrochemical reaction H_2 is converted into hydrogen ions H^+ and electrons e^- as shown in eq. 1, which then combines with O_2 to produce electricity and water as a byproduct as shown in eq. 2. The following equations show the electrochemical reactions [12].

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2)$$

The electrolyte is like a barrier that keeps the fuel and oxidant apart but allows charged particles to pass through [13, 14]. This controlled movement of particles generates electricity [15]. The porous electrodes help the reaction happen efficiently by providing lots of surface area for the chemicals to interact [15, 16]

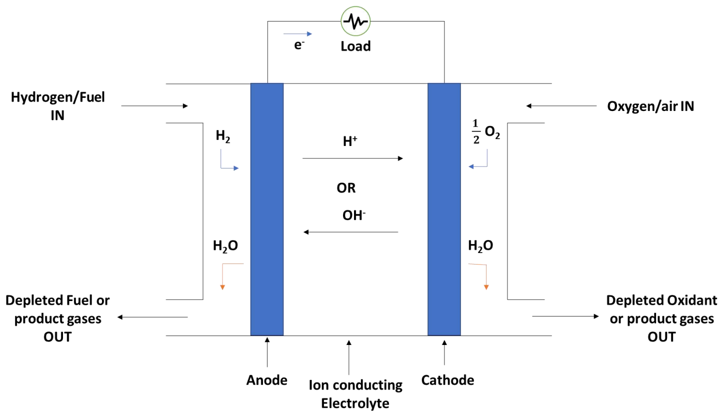

Figure 1. General scheme of a fuel cell.

The classification of fuel cell can be made on the basis of working temperatures, electrolyte types, their working areas and fuel types. Commercially, Fuel cells can be categorized based on the type of electrolyte used. These types include Proton Exchange Membrane Fuel Cells (PEMFC), Alkaline Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), Direct Methanol Fuel Cells (DMFC), and Solid Oxide Fuel Cells (SOFC) [17].

1.1. Proton exchange membrane fuel cell

PEMFCs are a popular type of fuel cell that uses a solid polymer membrane as the electrolyte. This membrane must be highly conductive to protons to ensure efficient operation [18].

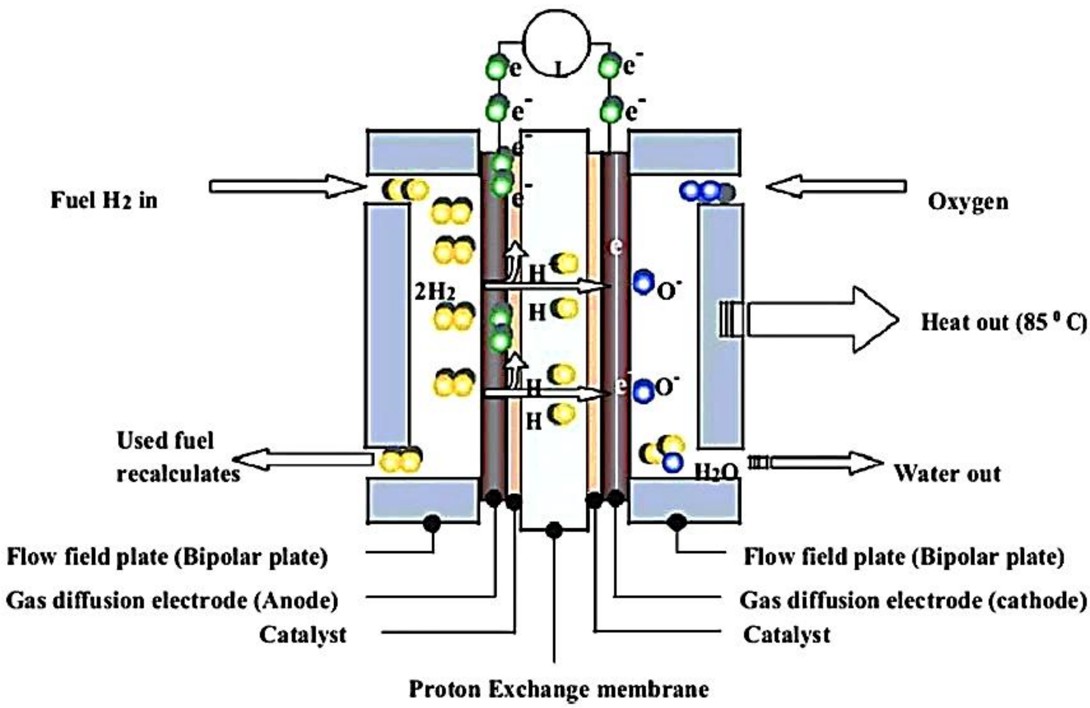

Figure 2. Polymer electrolyte membrane fuel cell [27].

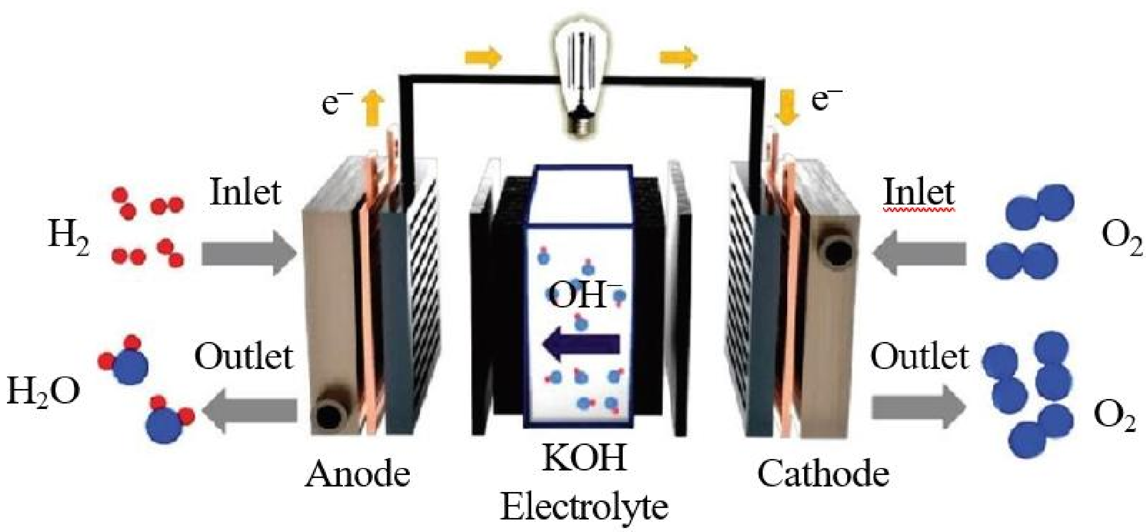

Figure 3. Schematic diagram of Alkaline fuel cell [35].

PEMFCs are emerging as a promising alternative to traditional internal combustion engines in the transportation sector, offering a cleaner and more sustainable solution [19]. The electrodes are separated by using proton exchange membrane to keep them isolated from reactions of the gases and electrical conduction inside the cell [20-22]. Figure 2 shows the key components: electrodes, catalyst, a semi-permeable membrane, and bipolar plates. This system typically operates at temperatures below 80°C [23]. The electrodes, constructed from carbon paper, are coated with a hydrophobic polymer and platinum particles [24]. Platinum acts as a catalyst, facilitating the electrochemical reactions within the fuel cell. [20, 25, 26]. Eq. 3 and eq. 4 shows the electrochemical reactions that occur at anode and cathode;

At Anode :

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (3)$$

At Cathode :

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (4)$$

PEMFC catalysts primarily rely on platinum. To enhance performance and longevity, these platinum catalysts often undergo pretreatment processes such as heat treatment. This treatment can increase particle size and the use of highly graphitized carbon sup-ports can help minimize degradation rates. These strategies contribute to increased lifespan and improved electrical conductivity [28]. The high cost, low durability, hydrogen storage, Pure hydrogen requires expensive fuel infrastructure for transport and on-site fuel processors that use liquid fuel require startup time. These issues limit the global commercialization of this technique [21, 29, 30]. The PEMFC innovation providers available for maritime vehicle have been individuated and grouped, zeroing in consideration on the frameworks 'qualities regarding size, productivity, power thick-ness, voltage, ebb and flow runs, and anticipated lifetime. The gravimetric and volumetric thickness of the accessible frameworks available have been looked at, as this is a significant component for an effective establishment plan for transport applications that PEMFC had acquired an exceptional interest in sea applications [31, 32]. The most popular solution, PEMFC, is used in 73% of all projects and is often fed with pure hydrogen (61% of all projects). Recently, PEMFCs have also been tested for propulsion in battery-powered hybrid systems. From a safety perspective, low temperature fuel cells, such as PEMFC, have greater potential for use aboard ships; however, additional rules are required for hydrogen storage [28].

1.2. Alkaline Fuel Cells

AFCs are named after their alkaline electrolyte, typically potassium hydroxide (KOH). These fuel cells utilize nickel at the anode and silver at the cathode. During the electrochemical process, hydroxyl ions (OH^-) migrate through the electrolyte from the cathode to the anode [29]. Additional components, such as humidifiers, compressors, blowers, and heat exchangers, are often integrated into AFC systems to optimize performance and efficiency [30].

Alkaline electrolytes, such as potassium hydroxide (KOH) and sodium hydroxide (NaOH), are highly sensitive to carbon dioxide (CO_2). This sensitivity limits their applications to fuels and oxidants that are free of CO_2, such as reformed fuels or pure oxygen [31, 32]. When exposed to CO_2, whether from air or steam, these electrolytes react to form large metal carbonate crystals. These crystals can clog the pores of the gas diffusion layer on the electrodes, significantly reducing the fuel cell's performance and ultimately leading to its failure. The working temperature is generally below 100°C which has a significant advantage that cell has the capability to use more abundant, inexpensive, and non-platinum catalysts [17, 33, 34]. Humidified hydrogen gas is fed into the anode compartment of an alkaline fuel cell. This gas diffuses through the Gas Diffusion Layer (GDL) and reaches the catalyst layer, where it reacts with hydroxide ions (OH^-) coming from cathode through electrolyte and produces water as byproduct on anode side and electrons pass through the external circuit as shown in Figure 3. Overall reaction at anode is shown in the eq.5.

$$H_2 + 2OH \rightarrow 2H_2O + 2e^- \quad (5)$$

The purified air/oxygen is supplied to the cathode together with water through a humidified oxygen source in which oxygen gas dissolved in water and reduced to produce hydroxide ions as shown in eq. 6 [33]. The direct 4-electron pathway is ideal oxygen reduction reaction (ORR) given in the following equation:

$$O^{-2} + 2H_2O + 4e^- \rightarrow 4OH^- \quad (6)$$

Alkaline fuel cell utilizing the concepts of the electrochemistry, laws of thermodynamic and system review through the development of a 10kW alkaline fuel cell that can be used for one-day in space [36].

1.3. Phosphoric acid fuel cells

PAFCs utilize phosphoric acid as the electrolyte. The electrodes, often made of carbon paper, are coated with a catalyst layer containing platinum, iron, or cobalt particles embedded in a polytetrafluoroethylene (PTFE) matrix. These electrodes are designed to be hydrophobic, separating the gas chambers from the electrolyte compartment. PAFCs typically operate at around 200°C and atmospheric pressure, achieving an electrical efficiency of approximately 40% [27, 37]. A major challenge facing PAFCs is their limited lifespan, primarily due to corrosion issues at elevated temperatures [21]. However, phosphoric acid's complete dissociation at these temperatures makes it an excellent ionic conductor, enhancing the cell's overall performance [38]. Current research efforts are focused on improving the long-term stability and durability of PAFCs [39]. Figure 4 shows the electrochemical reactions inside a PAFC. Reactions at anode and cathode are shown in eq.7 and eq. 8 respectively ;

At Anode

$$H_2 \rightarrow 2H^+ + 2e \quad (7)$$

At Cathode :

$$O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (8)$$

The main two problems of phosphoric acid cell are leakage and conductivity which can be controlled by using combination of two membranes and enveloping it with PTFE films. Yoon and Yang used SiC (silicon carbide) bonded PTFE to hold electrolyte with its minimal leakage [40, 41]. The most widely used applications of PAFCs can be made reviewing two areas such as improved materials particularly carbon supports and improved cathode catalysts, and postmortem analysis of cells. Sebastián et al. Observed that Platinum supported on carbon was used to reduce the loadings of the electrodes and as catalyst supports in both low temperature as well as high temperature fuel cells by about an order of magnitude [42].

1.4. Solid oxide fuel cells

SOFCs are unique in their use of a solid ceramic electrolyte. This electrolyte, along with the anode and cathode, forms a layered structure. SOFCs can operate at extremely high temperatures, often reaching 1000°C, making them particularly well-suited for stationary power generation applications [43, 44].

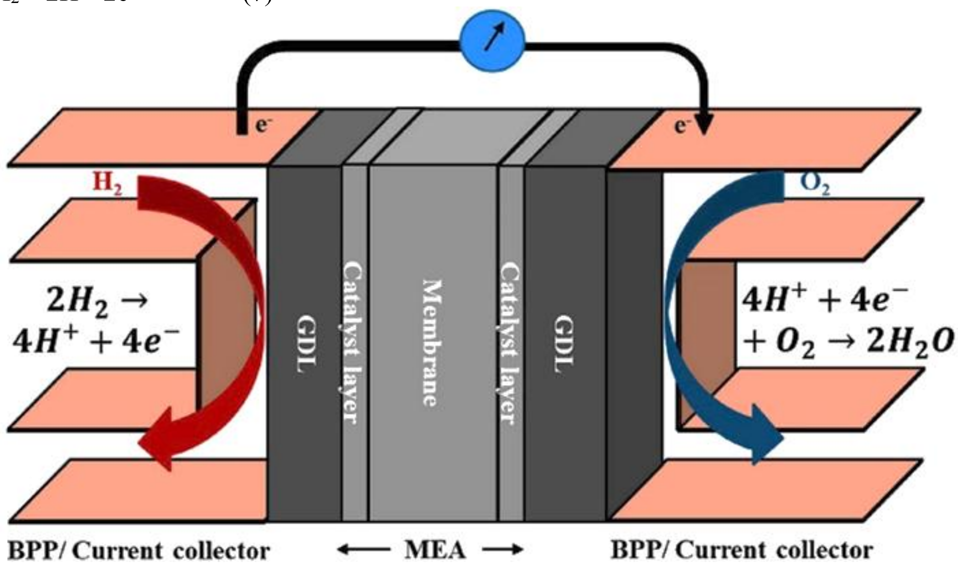

Figure 4. Schematic diagram of Phosphoric acid fuel cell [28].

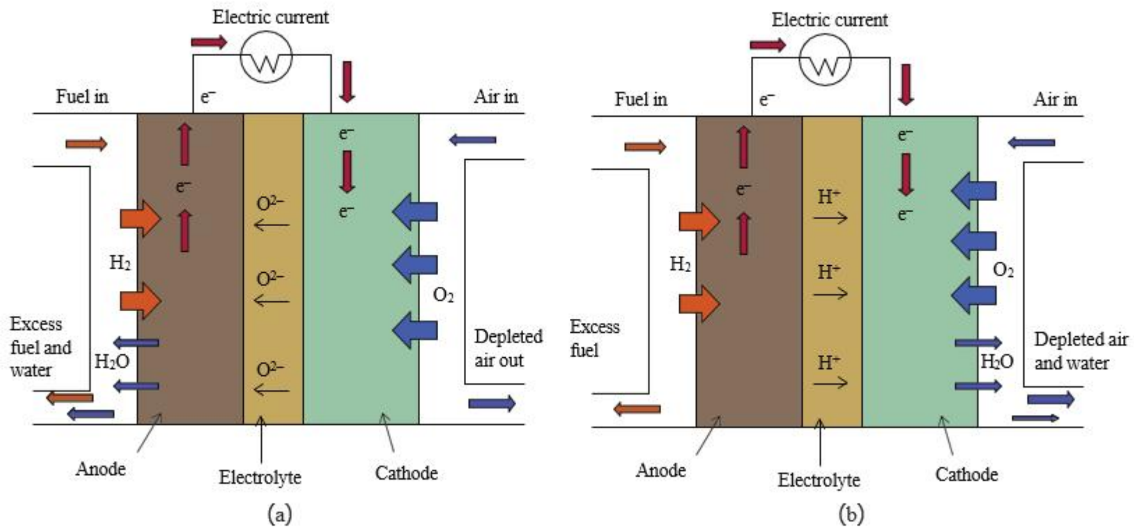

Figure 5. Solid oxide fuel cell, (A) oxygen ion-conducting (SOFC–O^{2-}), (B) proton-conducting (SOFC–H^+) [35].

Figure 5(a) shows after electrochemical reduction oxygen ions migrate from the cathode to the anode through the electrolyte. At the anode, these ions react with hydrogen gas, resulting in the production of water. This electrochemical process at cathode and anode can be represented by eq. 9 and eq. 10 respectively [45].

At Cathode:

$$O_2 + 4e^- \rightarrow 2O^{-2} \qquad (9)$$

At Anode:

$$2H_2 + 2O^{-2} \rightarrow 2H_2O + 4e^- \qquad (10)$$

Solid oxide fuel cells employ two different kinds of electrolytes: proton-conducting (SOFC–H^+) and oxygen ion-conducting (SOFC–O^{2-}). As the hydrogen molecules from the anode react with the SOFC–H^+ electrolyte, as demonstrated in Figure 5(b), steam is created at the cathode side of the process. According to Li et al., SOFC-H^+ provides a low operating temperature to increase the cell's lifespan [46-48].

Mojaver and colleagues observed the energy efficiency of an SOFC–O^{2-} based system, is higher, which is 60.20% compared to SOFC–H^+ with 54.06% and the power produced by SOFC–O^{2-} is 18 kW greater than SOFC–H^+ [49].

1.5. Direct methanol fuel cells

DMFCs generates electricity by oxidizing methanol, a small organic molecule, in an aqueous solution. Figure 6 shows that in this electrochemical process CO_2 gas, e^- and H^+ produces at anode shows in eq.11 while at cathode reduction of O_2 occurs and H_2O as byproduct were formed as shown in eq. 12 [50-53]. Overall reaction shows in eq. 13. DMFCs employ relatively inexpensive and durable electrocatalysts for both the methanol oxidation reaction (MOR) at the anode and ORR at the cathode. However, the slow kinetics of these reactions, particularly the MOR, pose significant challenges to the overall performance and efficiency of DMFCs [54, 55]. The reaction involves following steps;

At Anode;

$$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \qquad (11)$$

At Cathode;

$$\frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O \qquad (12)$$

Overall reaction is

$$CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2 + 2H_2O \qquad (13)$$

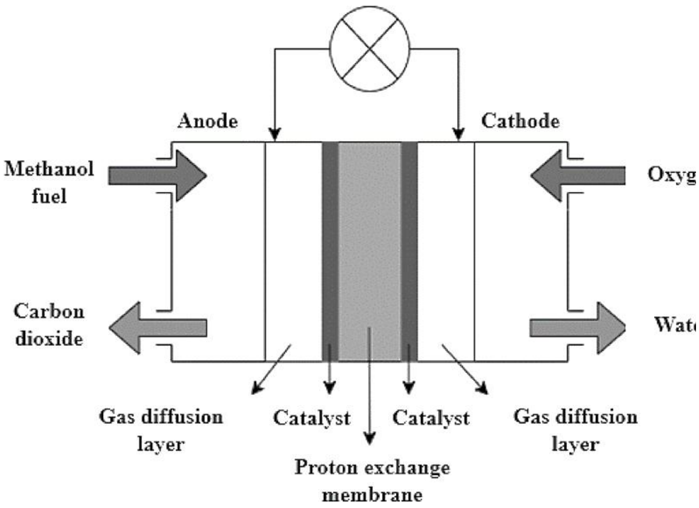

Figure 6. Schematic diagram of Direct Methanol Fuel Cell [55].

Platinum is used as the cathode catalyst, while a platinum-ruthenium alloy (1:1 ratio) is employed at the anode [56]. One significant challenge in DMFCs is the "crossover effect," where methanol molecules permeate from the anode to the cathode, reacting with the platinum-based cathode catalyst. This leads to a mixed potential and reduces overall cell performance and fuel efficiency [57]. At the anode, methanol is oxidized to carbon dioxide, with carbon monoxide as an intermediate. This intermediate strongly adsorbs to the platinum catalyst surface, hindering the reaction rate. While platinum-based catalysts, both pure and alloyed, exhibit the highest activity for the MOR and ORR, respectively. The crossover effect and catalyst poisoning remain major obstacles to widespread DMFC adoption [45–46]. Despite these challenges, DMFCs hold promise as a power source for portable devices due to their low operating temperature, high energy conversion efficiency, and low pollutant emissions [58]. DMFCs address a promising wellspring of energy that is promptly pertinent to present day life and can establish a superior climate for humanity. The battery-powered battery is the significant wellspring of force for most lithium-based, e.g., lithium or lithium-polymer. There is a hindrance in involving a battery-powered battery as a power source as the battery needs an outer electrical power source to charge, and this is an impediment to the versatility of the gadget since it must be utilized with a current electrical source and has restricted battery limit. In far off regions where there is no electric power framework, running a gadget on versatile batteries is tricky. A significant issue in regards to electrical power plants is that a considerable lot of them utilize petroleum derivative to produce power. In 2000, around 6.2 billion tons of carbon was transmitted into the air as CO_2, of which roughly 40% was radiated during the creation of power [59-62].

2. Applications of fuel cells

2.1. PEMFCs applications

PEMFCs are popular fuel cells due to their lightweight design, high efficiency over 60%, low operating temperature, zero greenhouse gas emissions, and suitability for various applications [63, 64]. PEMs are divided into low-temperature types for commercial use and high-temperature types for industrial applications, with key uses in transportation and portable power, needing careful design for space, weight, and power demands as shown in Figure 7 [65].

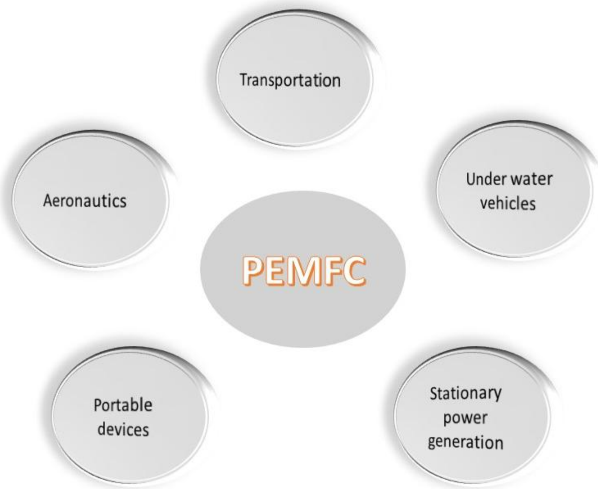

Figure 7. PEMFCs key applications.

2.1.1. Transportation applications

PEM fuel cells are key for transportation because of their zero emissions and efficiency, leading car manufacturers to improve the technology and tackle cost and durability issues [66-68]. Despite progress, more work is needed to lower costs and enhance durability [69-71]. Fuel cell hybrid electric vehicles (FCHEVs) are gaining attention for combining PEM fuel cells with batteries and other energy sources, with Japan aiming for 800,000 fuel cell vehicles by 2030. GM Authority partnered with the US Army to create the Chevrolet Colorado ZH2, featuring a 94-kW fuel cell system. The ZH2 can supply soldiers with 2 gallons of water per hour through its electrochemical reactions [72-74]. Small-scale PEMFCs are being used as an alternative energy source for electric propulsion in low-power vehicles, including UAVs and underwater applications [75]. Another expanding market includes powertrains for various vehicles like cars, buses, forklifts, boats, and small aircraft [76, 77]. Unmanned aerial vehicles (UAVs) need propulsion systems that offer high energy, long flight time, and strong power [78]. UAVs powered by small-scale PEMFCs are quieter and have less thermal signature, making them suitable for military use, and recent research has led to many lightweight, safe, and flexible multirotor models [79]. Honeywell acquired Ballard Unmanned Systems in 2020 and launched a UAV fuel cell system with three times the battery runtime and five times the reliability of small engines [80]. To achieve the needed voltage and power, multiple low-output single cells are connected in series to create a PEMFC stack [81, 82]. PEMFCs in UAVs use bipolar plates for cell separation and require systems for managing water, gas, and power, while four main hydrogen storage methods—compressed, liquid, cryogenic, and metal hydride—are crucial for enhancing flight endurance [83]. The endurance of a PEMFC system relies on the total energy of its reactants [84]. The PEMFC system is ideal for long-endurance UAV missions over 1.49 hours, while Li-ion batteries are better for shorter flights; however, metal hydride hydrogen storage lags behind Li-ion batteries, despite offering higher energy density [85].

2.1.2. Underwater vehicles

Miniature submarines and autonomous underwater vehicles (AUVs) are increasingly used in military and commercial sectors, relying mainly on Li-ion batteries, which face issues like low energy density and long charging times [75, 86]. Small-scale PEMFCs provide a more efficient and longer-lasting power source for small underwater vehicles compared to costly and polluting primary cells [86-88].

2.1.3. Stationary applications

Small-scale stationary power generation provides independent energy to nearby users and benefits from small-scale PEMFCs, which offer fast startup, zero emissions, high efficiency, and low noise, making them suitable for applications like UPS and residential cogeneration [89, 90]. UPS systems powered by small-scale PEMFCs are gaining popularity for their zero emissions, low maintenance costs, and adaptability, unlike conventional UPSs that produce harmful emissions and face energy storage limitations. A key requirement for UPS systems, especially in telecom, is the ability to start up within milliseconds during a power outage [91, 92].

2.1.4. Portable applications

Portable applications usually need about 5–500 W of power, with some special uses requiring up to several kilowatts [93]. The portable PEMFC market mainly focuses on off-grid power supplies and military applications, especially for outdoor use and emergencies. Portable PEMFCs are increasingly used in military applications for soldiers due to their low noise and heat, along with benefits like long-lasting power and quick recharging. PEM fuel cells are ideal for portable electronics and aircraft, providing continuous power and high energy capacity, attracting interest from Boeing and Airbus [94, 95].

2.2.5. Aeronautic applications

PEMFCs are ideal for aviation due to their quiet operation, useful byproducts, solid electrolyte, and no moving parts[96-100]. Fuel cells operate quietly, reducing airport noise and protecting personnel's hearing, while also generating water and using heat for hot water and ice prevention in cold conditions [97, 98]. PEMFCs on board can recharge batteries, generate electricity and heat, produce drinkable water, replace Ram Air Turbines, and supply deoxygenated air for safety [101, 102]. A key goal of "more electric" aircraft is to replace gas turbine-powered auxiliary power units (APUs) with PEMFC-powered

APUs [102, 103]. PEMFC-powered APUs generate electricity for ground operations, reducing the load on the main engine and jet fuel consumption [95]. PEMFCs are recognized as secondary power sources for aircraft, often used in combination with batteries, as they cannot meet the entire power demand [104-107]. PEMFCs can generate chemicals like ethanol and hydrogen peroxide with electricity, but they may indirectly pollute during hydrogen production, a problem that nanoparticles can help solve [108].

2.1.6. Green hydrogen-based power generation

PEMFC-based green hydrogen power generation. Green hydrogen, a long-term renewable energy source, can be stored in the salt cavern and used as an emergency energy supply. Several green power plants located in specific locations throughout Bangladesh can produce a sizable portion of the country's electricity. To lessen reliance on fossil fuels, a long-term energy strategy that incorporates hydrogen and renewable energy sources is being prioritized (General Economics Division, 2020). Building a green hydrogen-based power plant now will help the nation become more sustainable and facilitate the transition to green energy. To rule out the possibilities, no investigation has been conducted. This work's goals are to examine the viability and efficiency of proton-based green hydrogen power generation.[109]. Based on technical specifications of the designed configuration, including available commercial devices of the power generation system according to the recent technology ready level (TRL), the green hydrogen production and power generation performances of 45 MW hydrogen gas turbine power plants and PEM fuel cell based 45 MW power plants, as well as their related parametric analyses, were examined. According to estimates, renewable energy could generate The entire power generating configuration is constructed by combining, integrating, and adjusting the hydrogen gas turbine and PEMFC to match the 45 MW power plant consumption[110]. To produce electricity, a proton exchange membrane electrolyzer (PEME), a producer of clean hydrogen gas, is “complementary” to a Proton Exchange Membrane Fuel Cell (PEMFC) [111, 112]. These can be consolidated in a Discrete Reversible Proton Trade Layer Power device (DRPEMFC) organization, where a PEME and a PEMFC are free Components of the construction with renewables like windmills or sunlight-based chargers Turbines. The EL (electro-lyzer mode), a Unitized Regenerative Proton Trade Film Energy component (URPEMFC) technique acts like an electrolyte arrangement since it isolates fluid into hydrogen and oxygen using electric power [113]. Subsequently, there is an immense worldwide requirement for hydrogen, yet there is an assembling is-sue. While petroleum products can be utilized to create hydrogen, doing so at the same time results in air contamination and an Earth-wide temperature boost. The essential objective of the researcher is to supportive of duce hydrogen in a harmless to the ecosystem way. This outline centers around the photograph layer power module as the fundamental method and the expected future bearings for creating perfect and unadulterated hydrogen. During the time spent hydrogen age, the expense of an impetus and its plan is costly and convoluted. On the off chance that some new impetus is imagined to supplant the high costly impetus, for example, platinum and iridium, we can lessen the expense of hydrogen age [114].

Storing the necessary amount of hydrogen with traditional methods is challenging, but nanotechnology, specifically carbon nanotubes, offers a solution [103, 115]. PEMFCs are clean and efficient, and the use of nanotechnology improves their cost, durability, and performance, while alkaline fuel cells (AFCs) offer advantages like using various catalysts and reducing corrosion, positioning them as a viable alternative to PEMFCs [116-118].

2.2. Applications of AFCs

Alkaline fuel cells have diverse applications in different fields from stationary to portable devices as shown in Figure 8.

2.2.1. Space application

AFCs originally used by NASA for space missions to generate electricity and water, are now being adapted for portable power applications and can produce 10 kW for one-day space trips, as well as power equipment like forklifts and welding machines. Alkaline fuel cells are efficient and adaptable, requiring life cycle assessments; in spacecraft, the water produced is used for drinking, while cooling systems use fluids like glycol or fluorinated hydrocarbons [119].

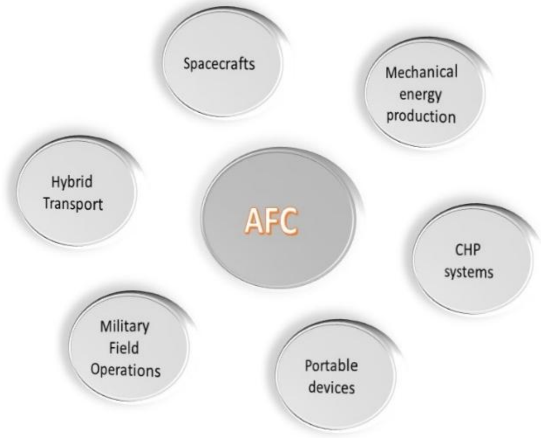

Figure 8. AFCs key applications.

2.2.2. Mechanical energy production

AFC exhaust heat can be turned into electricity with a Stirling engine, boosting system performance [120]. A Stirling engine converts heat into mechanical energy and then into electricity using a generator [121]. Researchers analyzes a 2.4 kW Alkaline Fuel Cell's performance to optimize fuel flow for remote power supply, highlighting the benefits of membrane less AFC technology [122]. AFCs offer high efficiency and easy control, suitable for both small and large applications, and are less expensive than PEMFCs but require pure hydrogen and oxygen as fuel and oxidant [123]. AFCs benefit from a relatively high efficiency of up to 60% in specific applications [124]. The outstanding performance of AFCs is related to the rate at which electrochemical reactions occur in the cell. In space applications, they have also achieved efficiencies of more than 60%. Also, alkaline FCs may produce an electrical output ranging from 5 to 150 kW [125]. One significant difficulty for AFCs is their sensitivity to carbon dioxide poisoning (CO_2). In fact, even a minor quantity of CO_2 in the air can significantly impact performance and durability owing to carbonate production [126]. AFCs are often utilized for stationary power generation applications that are more feasible for higher temperatures and larger sizes than PEMFCs (which are preferred for transportation). Also, the membrane durability of AFCs is lower than that of PEMFCs due to the liquid electrolyte, but AFCs have a lower cost (lower catalyst costs as non-precious metals can be used).

2.2.3. Combined heat and power (CHP) systems

AFCs struggle to find effective catalysts for hydrogen oxidation due to higher over potential in alkaline environments [127, 128]. Fuel cells can operate at various temperatures and are a cleaner alternative to fossil fuels, emitting low or zero pollutants while efficiently using fuels like hydrogen, natural gas, and methanol, with lower maintenance costs. AFCs are combined with thermoelectric components to increase energy efficiency and recover heat, providing more environmentally friendly energy generation options. AFCs work with systems to reuse waste heat, which lowers environmental impact and also provide clean and efficient energy solutions to support life systems in space exploration AFCs in domestic CHP systems lower emissions and energy costs, by producing heat and electricity effectively [129]. Recent research focuses on the development of improved catalysts for AFCs, such as zinc/cobalt mixtures. These developments lower the cost of fuel cells while increasing their durability and efficiency [130].

2.2.4. Portable applications

Lightweight and durable AFCs power portable devices like electronics supply effective, mobile energy sources for electronics and other equipment. AFCs in hydrogen-powered cars offer environmentally friendly transportation that is more economical and energy-efficient. Fuel cell technology is advanced by the use of novel anion exchange membranes, which give AFCs a longer lifespan and improved performance. New AFC designs with solid electrolytes enhance durability and performance, by preventing it to contaminate with CO_2 [131]. Fuel cell technology is advanced by the use of novel anion exchange membranes, which give AFCs a longer lifespan and improved performance. AFCs promote the global adoption of renewable energy sources, by assisting in the environmentally friendly production of hydrogen [132]. AFCs are increasingly used in microgrids to supply clean, localized electricity for both urban and rural areas. In areas with unstable grid connections, these fuel cells improve energy independence and provide a steady supply. AFCs are used in vital industries including IT and healthcare. In the event of a power outage, as a reliable backup power [124]. Portable devices like remote field systems and outdoor electronics use lightweight, compact AFCs to provide dependable energy in difficult circumstances [130].

2.2.5. Military field operations

In military applications, AFCs alleviate the logistical challenges associated with conventional power sources by offering soldiers and equipment in the field portable, quiet, and effective power systems sources, its renewable energy generation guarantees that vital services continue to Sustainable electricity is being provided by integrating AFCs into decentralized home energy systems function. Sustainable electricity is being provided by integrating AFCs into decentralized home energy systems [124].

2.2.6 Transportation applications

AFCs are becoming a more environmentally friendly option for hydrogen-powered cars in the transportation industry. They are a good substitute for traditional fuels since they are economical, efficient, and help to lower emissions [130].

2.3. Applications of PAFCs

PAFCs are mainly used as stationary uninterrupted auxiliary or hybrid power source ranging from homes to industries as shows in Figure 9

2.3.1. Stationary application

PAFCs are the first successful fuel cells, tolerant to CO and capable of using fuels like methanol and natural gas. According to Wu et al., 2018, they are mainly used in stationary applications and improve efficiency by 3% when combined with heat recovery systems.

2.3.2. Combined heating, cooling, and power (CHCP) systems

Systems that offer buildings with continuous heating, cooling, and electricity employ PAFCs. These systems are very effective and economical because they make use of the heat produced by the fuel cells [133, 134]. PAFCs can be combined with heat-driven refrigerators, using the heat they produce to maintain a cold reservoir. The cell's high-temperature exhaust can heat the reactants, increasing overall efficiency by 6% [135]. An absorption refrigerator linked to a PAFC system can enhance efficiency by 3% by using waste heat to lower grid electricity demand [21, 136-138].

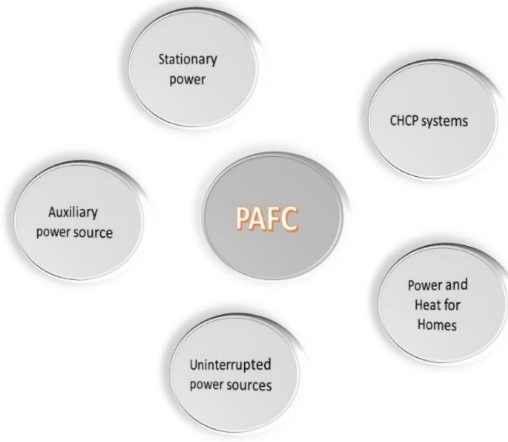

Figure 9. PAFCs key applications.

2.3.3. Power and heat for homes

PAFCs are also used in residential setups, like a 400-kW system that reformulates natural gas into hydrogen for the PAFC stack [139, 140]. Heat from the PAFC stack was used for heating water and space in apartments, reducing boiler fuel needs and CO_2 emissions [141, 142]. In Germany, PAFC systems have operated over 46,500 hours for residential heating and public baths, while also providing power in chemical industries and hospitals, where waste heat supports air conditioning, generating over 6 million kWh by 2002. Phosphoric acid fuel cells remain the most widely used type in commercial products [116].

2.3.4. Transportation applications

When compared to conventional diesel engines, hydrogen-powered buses that employ PAFCs emit fewer greenhouse gases. They can work quietly and effectively while enhancing the quality of the air, which makes them particularly helpful in urban areas [143]

2.3.5. Uninterrupted power sources

Military troops deploy portable PAFCs to generate electricity. In distant locations without access to conventional power sources, these fuel cells are perfect for field usage since they are quiet, strong, and effective. For data centers that need constant power, PAFCs are a reliable option. They last longer and are less harmful to the environment than conventional backup generators. This guarantees that servers remain operational even in the event of a power interruption [144, 145].

2.3.6. Auxiliary power source

Diesel generators are replaced with PAFCs to supply ships with main or auxiliary power. They are an excellent option for environmentally friendly maritime operations as they lower marine pollutants and increase fuel economy [146]. PAFCs are used by industries to convert waste heat into thermal energy or useable power. By turning otherwise lost energy into useful use, this increases factory energy efficiency and lowers operating costs [144]. Smaller, localized power systems, frequently in isolated locations, employ PAFCs. They promote renewable energy sources like solar and wind and offer clean, reliable electricity, lowering reliance on bigger, centralized power systems [147].

2.4. Application of SOFCs

SOFCs are the most efficient (fuel input to electricity output) fuel cell electricity generators currently being developed world-wide. SOFC is an energy conversion device that converts the chemical energy of the fuel gas directly into electricity and therefore very high electrical efficiency can be achieved. SOFC uses an oxide-ion conducting ceramic material as the electrolyte [148]. So, SOFCs are widely used in different applications ranging from stationary power sources to portable and transport devices as shown in Figure 10.

2.4.1. Stationary energy systems

SOFCs are extensively used in stationary energy systems to produce power in an environmentally responsible and highly efficient way. They are ideal for both urban and rural power demands since they can use a range of fuels and produce little emissions [49, 149].

2.4.2. Industrial application

Various industries use low-quality, high-ash coal in fluidized bed gasification to power SOFCs, which are becoming increasingly valued SOFCs operate at high temperatures, allowing them to tolerate more carbon monoxide and reducing the need for extensive purification [150], thus promoting efficiency and supporting the shift toward a hydrogen economy [151]. SOFCs are not limited by the Carnot cycle, allowing them to generate energy electrochemically with high efficiency and low pollution, making them environmentally friendly [45, 152-154].

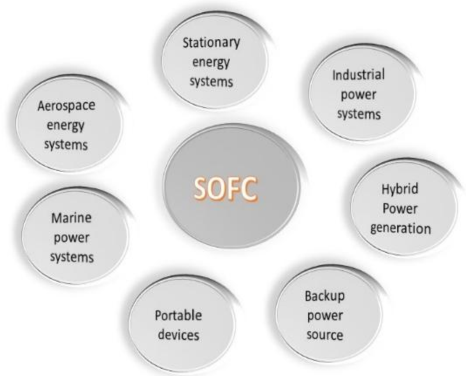

Figure 10. SOFCs key applications.

2.4.3. Hybrid power generation

SOFCs replaces traditional energy systems by producing low NO_x and SO_x emissions, being highly efficient and reliable, and operating quietly. Recent studies focus on SOFCs that operate at 650-800°C, allowing for greater material flexibility and reduced wear on components, while also enhancing overall system efficiency when combined with gas turbines [155]. SOFCs are highly efficient and suitable for heating, cooling, and power generation, with their waste heat enhancing cogeneration systems. Combining SOFCs with gas turbines can improve efficiency to about 60%. A novel power-to-gas method employs a reversible solid oxide cell to generate gases for storage as chemical energy. This system, akin to pumped hydro storage, includes methanation and separate underground storage for CO_2 and CH_4 [156]. Recent studies focusing on lowering the operating temperatures of SOFCs for use in vehicles, especially benefiting ships and aircraft due to improved efficiency [157].

2.4.5. Dependable backup power

Critical infrastructures like data centers and hospitals rely on SOFC systems as backup power sources. During power outages, their efficiency and rapid starting capabilities provide a continuous supply of energy [49, 149]. SOFCs are among the most efficient power generation technologies, offering flexibility in fuel choice, low CO_2 emissions, and long lifespans of 40,000 to 80,000 hours [149].

2.4.6. Portable Applications

Portable fuel cells can use methanol or ethanol, making them suitable for devices like laptops, mobile phones, power tools, and military equipment [158]. SOFCs use a solid electrolyte, eliminating common water management issues seen in other fuel cells, and can operate at high temperatures for better fuel tolerance and efficiency in co-generation systems [159, 160]. Compact SOFC designs are being used in portable applications, such military equipment and tiny electrical gadgets. They are a great option for portable energy because of their extended duration and lightweight design [149, 161].

2.4.7. Systems for Marine Power

Ship propulsion systems include SOFCs, frequently in conjunction with ammonia cracking technology. This application replaces conventional fuel-based engines, supporting the maritime industry's transition to zero-emission solutions [162-164].

2.4.8. Energy systems for homes

SOFC-based combined heat and power (CHP) systems in residential settings supply thermal energy for heating in addition to electricity. These solutions are very helpful for households who want to lower their energy expenses and carbon footprints [165-169]

2.4.9. Systems for Aerospace Energy

Because of their great energy density and dependability, SOFCs are used in aerospace applications where they can power spacecraft. Without frequent maintenance, they effectively supply energy in harsh environments [100, 157, 170, 171].

2.4. 10. Future trends of SOFs

Regardless of the complex benefits and incredible commitments of SOFC innovation, its utilization is as yet not far reaching true to form. The critical component for the fruitful commercialization of SOFCs is that they should be financially cutthroat (for example modest to produce) to supplant ordinary power age through petroleum derivatives. Nonetheless, at the present SOFCs require costly materials (for example intriguing earth or scant components) and cycles that limit their market exploit. The vitally restricting component for a practical commercialization is the high temperature expected by SOFCs during typical activity. The undeniable way to deal with diminish the working temperature from the regularly utilized 700°C-900 °C reach to 400°C-600 °C is definitely not a practical arrangement, as bringing down the working temperature likewise brings down the SOFCs execution. Established researchers and the business are resolved to find novel and modest terminal and electrolyte materials ready to keep up with their conductive and reactant properties even at diminished temperature accomplishing comparable or higher proficiency than regular high-temperature materials. These days, a determination of high performing material is as of now accessible [177]. Nonetheless, choosing the materials for the various parts framing the cell isn't direct, as their similarity with another must be thought of. As a matter of fact, at the high working temperatures required materials face warm burdens and science changes even at the connection points between cell's components, specifically terminal/electrolyte limit, like warm breaks, conglomeration, dissemination or inadvertent doping. The durability of SOFCs stays an extraordinary test particularly in the event of materials scaled from full scale to nano-scales, as the agglomeration of nanosized particles to form larger ones is among the primary reason of performance degradation [177][178].

2.5. Applications of DMFCs

The Direct Methanol Membrane was created at NASA's Jet Propulsion Laboratory and was first used in military and space missions. Now, companies like Ballard Power and Motorola are exploring its use for everyday gadgets. Motorola says their new fuel cell could allow a phone to stay charged for a month when not in use [172]. Direct methanol can be used as an alternative to hydrogen in PEMFCs. While it produces slightly less energy than pure hydrogen, it avoids the need to create hydrogen first, making it easier to store the fuel [173]. DMFC is a type of hydrogen fuel cell great for cars and portable electronics. Researchers are working hard to improve DMFCs by finding better materials and conditions to make them more efficient and durable. While they're getting closer to being practical, challenges with cost and long-term reliability still need to be addressed while some issues are in progress to be solved [174-178]. There is a great demand for portable power sources in the military, leading to a rise in the use of portable DMFCs and PEMFCs. These fuel cells are favored because they operate gently, have high energy and power densities, and are lighter than traditional batteries. Their compact size and ability to function in harsh conditions make them an alternative to batteries, especially in telecommunications and other electro power systems [179, 180]. Their key applications in different fields are shown in Figure 11.

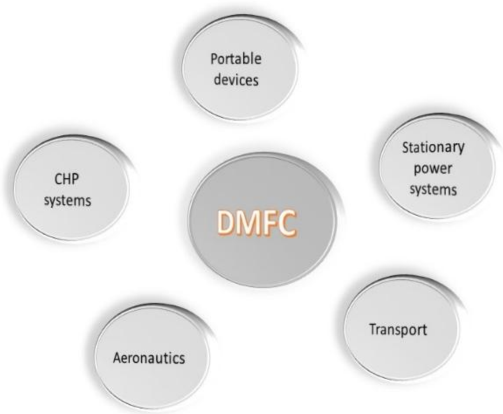

Figure 11. DMFCs key applications.

2.5.1. Portable applications

Study suggest DMFCs as a strong and promising solution for portable devices [181, 182]. This is because it operates at low temperatures, is highly efficient, and produces minimum pollutants. Liquid methanol fuel used in DMFCs is appealing because it's renewable, affordable, easy to store, and commonly available. DMFCs are expected to gain popularity for portable electronics due to their longer lifespans compared to lithium-ion batteries. Companies like Panasonic are developing compact generators that combine DMFCs with lithium-ion batteries for efficient outdoor power solutions [183]. While DMFCs aren't superior to lithium-ion batteries for all uses, they offer a compact alternative for devices like laptops. The graph suggests a target power density of 0.05 W cm−3, but current DMFCs only achieve about 0.01 W cm−3 [184]. Despite this, significant advancements are being made, making DMFCs appealing for portable electronics due to their high energy density and ease of methanol storage and transport. [185-187].

2.5.2. Stationary power applications

To provide electricity to isolated populations, DMFCs are incorporated into small-scale power producing units, particularly in off-grid areas. By serving as a backup or auxiliary power source, DMFCs assist microgrids in stabilizing their energy supply, particularly during periods of peak use [188, 189]. Important variables including temperature, concentration of fuel and water balance are tracked by sensors in DMFCs. By regulating fuel levels, guaranteeing steady operation, and identifying dangerous gases like CO, these sensors aid in improving efficiency [190]. To improve DMFCs efficiency, non-precious-metal catalysts is employed in the cathode. This strategy improved overall performance by optimizing methanol transport using anodic engineering. This development helps to make DMFCs more affordable and useful in the real world by increasing its efficiency [186].

2.5.3. Transportation applications

In electric cars, DMFCs function as auxiliary power units (APUs), supplying extra power for longer trips without the need for conventional gasoline. DMFCs are an environmentally beneficial substitute for conventional fossil fuel-powered boats in the propulsion of small maritime vessels. In the marine industry, DMFCs are being utilized more and more to power electric boats, which lower emissions while boosting energy efficiency and range [191].

Direct methanol energy unit innovation has been considered as the following enormous thing in the field of elective power sources and has given indications of possibilities to supplant regular batteries in application in compact electronic gadgets. Be that as it may, regardless of quite a long while of dynamic exploration, there actually exist a few disadvantages related with its essential activity, which are forestalling the broad utilization of this possibly encouraging innovation. Present audit shows the downsides and attempted to distinguish and fundamentally examine the different elements and boundaries related with difficulties in DMFC continuous client.

3. Future direction

The Direct Methanol Fuel Cell was first developed at NASA's Jet Propulsion Laboratory and used in military and space missions. Later, its potential for use in transportation and portable devices became clear. Companies like Ballard Power, Motorola, and others are working on its development. Motorola hopes to create a phone that can stay charged for a month on standby, with a commercial version expected in 3 to 5 years . Fuel cell has the potential to use in biomedical applications and implantable devices specially for pacemakers and sugar monitoring-based fuel cells that operated with microorganisms or enzymes [192]. DMFC has several advantages, there remains a critical issue to be overcome to commercialize DMFC as a real power source. The major technical issue is to increase the catalytic activities of the electrode catalyst [200]. In this present scenario, it's influential to design an electrode having elevated catalytic activity and efficiency. The suitable anode electro catalyst for DMFC is platinum (Pt). However, poisoning of Pt by carbon monoxide (CO), the major intermediate species produced by an indirect chemical reaction that occurred during methanol Oxidation requires less energy to form CO than carbon-dioxide (CO_2) [201, 202].

Hydrogen, while an ideal fuel, faces significant challenges in terms of storage. Current hydrogen storage technologies are bulky and heavy compared to liquid fuels. Advancements in materials science will play a crucial role in overcoming these limitations and developing more efficient fuel cell systems. Just as the introduction of PTFE enabled the development of Gas Diffusion Electrodes (GDEs) for aqueous-electrolyte fuel cells and ion-exchange membranes led to the creation of Proton Exchange Membrane Fuel Cells (PEMFCs), future innovations in materials will drive the design of improved and novel fuel cell types. Many industries utilize low-quality, high-ash coal in fluidized bed gasification processes to generate power for solid oxide fuel cells [157]. In many developing countries, rural areas lack access to electricity. Given the rapid advancement of technology, this gap needs to be addressed quickly. Fuel cells with cost-effective, clean, safe, and environmentally friendly solution will help to meet the need of sustainable and renewable energy resources. Investigating arising innovations and their likely ecological advantages, like green hydrogen creation techniques and high-level materials, presents an intriguing road for future examination. All in all, this study has contributed important experiences into the natural effect of hydrogen energy component advancements, accentuating the meaning of maintainable practices across their life cycle. The discoveries offer an establishment for informed independent direction, at last propelling the reception of perfect and economical energy arrangements on a worldwide scale.

4. Conclusion

Fuel cell technology represents a remarkable step forward in the pursuit of cleaner, more efficient energy solutions. These systems, which convert chemical energy directly into electricity while producing minimal emissions, offer immense potential across a range of applications. Their high efficiency, adaptability to different fuels, and suitability for use in stationary, portable, and transportation scenarios highlight their versatility and importance in modern energy systems. PEMFCs have emerged as a key player in revolutionizing transportation and portable power solutions due to their lightweight design and high efficiency. AFCs and PAFCs are making their mark in space missions, industrial operations, and even residential setups, demonstrating their wide-ranging utility. SOFCs, with their ability to operate at high temperatures, excel in stationary power and cogeneration, while DMFC) offer practical and efficient power for portable devices.

Despite their promise applications, challenges remain. Issues such as high costs, limited durability, hydrogen storage, and the need for advanced catalysts are significant barriers to the widespread adoption of fuel cell technology. However, ongoing research into materials, nanotechnology, and system design is paving the way for overcoming these obstacles. Fuel cells align perfectly with the global push for reducing greenhouse gas emissions, improving energy security, and transitioning to a hydrogen-based economy. With continuous advancements, they are set to play a pivotal role in shaping a sustainable energy future for the planet.

Authors contribution

Rehman, A.: conceptualization, Jamil, I.: formal analysis and methodology, Ahmad, F.: review and supervision, Waheed, H.: validation, Irfan, M.: writing, Nasir, H.: investigation, Nisar, H.A.: writing, Munawar, F.: visualization, Najaf, S.D.: investigation.

Conflicts of Interest

There are no conflicts of interest reported by the writers.

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Data Availability statement

The data presented in this study are available on request from the corresponding author.

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