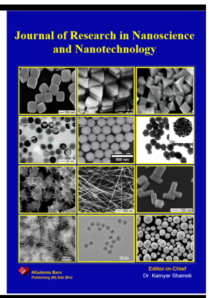
Penerbit Akademia Baru

Journal of Research in Nanoscience and Nanotechnology

Journal homepage:
http://akademiabaru.com/submit/index.php/jrnn/index
ISSN: 2773-6180



Fuel Cells and Their Role in Sustainable Energy Transition: A Review

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https://doi.org/10.37934/jrnn.16.1.3859

ABSTRACT

Fuel cells are innovative clean energy technologies that generate electricity through an electrochemical reaction, rather than conventional combustion, offering higher efficiency and significantly lower environmental impact. Among various types, hydrogen fuel cells stand out as particularly promising due to their ability to produce only water as a by-product, making them ideal for sustainable energy systems. This review paper provides an overview of the fundamental operating principles of fuel cells, along with a detailed examination of the major types, including Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs), and Alkaline Fuel Cells (AFCs). Their applications across diverse sectors such as transportation (e.g., hydrogen-powered vehicles), stationary power generation, and portable electronic devices are also discussed. Furthermore, the paper explores recent advancements aimed at enhancing performance, reducing costs, and improving durability through innovations in catalyst materials, membrane technologies, and system integration. Despite these advancements, fuel cells continue to face several challenges, including high production costs, limited hydrogen infrastructure, and concerns regarding fuel storage and safety. The review highlights the importance of continued research and development, as well as strong policy support and investment, to address these barriers and promote large-scale adoption. In conclusion, with strategic advancements and integration with renewable energy sources, particularly through green hydrogen production, fuel cells have the potential to play a transformative role in achieving global decarbonization and sustainable energy goals.

Keywords:
Fuel cells, electrochemical reaction, sustainable energy

Received: 15 July 2025 Revised: 30 July 2025 Accepted: 21 August 2025 Published: 25 August 2025

1. Introduction

Fuel cells are advanced electrochemical devices that directly convert the chemical energy of a fuel. Most commonly, hydrogen is converted into electrical energy without combustion. This is achieved through redox reactions that occur within the cell, typically involving hydrogen as the fuel and oxygen as the oxidant. The fundamental advantage of fuel cells lies in their ability to bypass the thermodynamic limitations of traditional heat engines, such as those governed by the Carnot cycle[1]. As a result, they can achieve significantly higher efficiencies, often ranging from 40% to 60%, with even higher efficiencies possible in combined heat and power (CHP) systems. A typical fuel cell consists of three primary components: an anode, a cathode, and an electrolyte that facilitates the movement of ions while blocking electrons. At the anode, hydrogen gas is split into protons and electrons with the help of a catalyst[2]. The protons move through the electrolyte to the cathode, while the electrons flow through an external circuit, generating electricity. At the cathode, the protons, electrons, and oxygen from the air recombine to form water, which is the primary by-product. This process is clean, quiet, and efficient, offering substantial environmental benefits compared to fossil fuel combustion [3].

Fuel cells are classified based on the type of electrolyte used and their operating temperatures. Common types include Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs), Alkaline Fuel Cells (AFCs), Phosphoric Acid Fuel Cells (PAFCs), and Molten Carbonate Fuel Cells (MCFCs). Each type has its advantages and limitations in terms of efficiency, durability, operating temperature, and application suitability. The key attributes of fuel cells, such as low greenhouse gas emissions, scalability, modular design, and high-power density, make them suitable for a wide range of applications [4]. These range from small-scale portable electronics and backup power systems to large-scale stationary power plants and transportation, including cars, buses, trucks, trains, and even maritime vessels. Notably, hydrogen-powered fuel cell vehicles (FCVs) are emerging as an alternative to battery electric vehicles, offering longer driving ranges and shorter refueling times. Despite their potential, fuel cells face several challenges that hinder their widespread adoption [5]. These include the high cost of catalyst materials (especially platinum), issues related to hydrogen production, storage, and distribution, as well as durability and performance degradation over time. However, ongoing research and technological advancements are gradually overcoming these barriers, making fuel cells an increasingly viable component of the global sustainable energy transition. With the world's growing focus on decarbonization and clean energy, fuel cells represent a pivotal technology in the transition to a low-carbon economy. Their integration into renewable energy systems, such as solar and wind, enhances energy storage and grid stability, further amplifying their importance in future energy systems [6].

2. Types and Applications of Fuel Cells

Fuel cells are a versatile and promising clean energy technology that come in several types, each tailored for specific applications based on their operating temperature, electrolyte type, efficiency, fuel tolerance, and scalability.[7] The most common fuel cell types include Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs), Molten Carbonate Fuel Cells (MCFCs), Alkaline Fuel Cells (AFCs), Phosphoric Acid Fuel Cells (PAFCs), and Direct Methanol Fuel

Cells (DMFCs). This section provides an in-depth overview of the primary fuel cell types and their respective applications [8].

3. Proton Exchange Membrane Fuel Cells (PEMFCs)

PEMFCs are among the most widely researched and commercially deployed types of fuel cells. They operate at relatively low temperatures (around 60–80°C), making them ideal for applications that require quick start-up and shut-down cycles. PEMFCs use a solid polymer electrolyte membrane that conducts protons (H^+) from the anode to the cathode. Hydrogen gas is supplied to the anode, where it is catalytically split into protons and electrons [9]. The protons pass through the proton exchange membrane (PEM), while the electrons are forced to travel through an external circuit, generating a flow of electricity. At the cathode, oxygen gas reacts with the protons and electrons to form water (H_2O) as the only byproduct, making PEMFCs a clean and efficient power source [10].

Figure 1 shows a schematic representation of a single PEMFC, illustrating its major components and the internal electrochemical processes. Hydrogen (H_2) is introduced at the anode, where it undergoes oxidation, releasing protons and electrons. The gas diffusion layer (GDL) ensures even distribution of gases and helps conduct electrons to the external circuit. The PEM, placed between the electrodes, selectively allows protons to migrate toward the cathode [11]. The electrons, traveling through the external load, create usable electric power, as depicted by the glowing light bulb in the diagram. On the cathode side, oxygen (O_2) is introduced and combines with the incoming protons and electrons to produce water. The half-cell reactions are as follows: at the anode, 2H2→4H++4e−2H_2 \rightarrow 4H^+ + 4e^-2H2→4H++4e−; and at the cathode, O2+4H++4e−→2H2OO_2 + 4H^+ + 4e^- \rightarrow 2H_2OO2+4H++4e−→2H2O. This figure effectively demonstrates the core working principle of PEMFCs, highlighting the flow of charge carriers and the clean conversion of chemical energy into electrical energy [12].

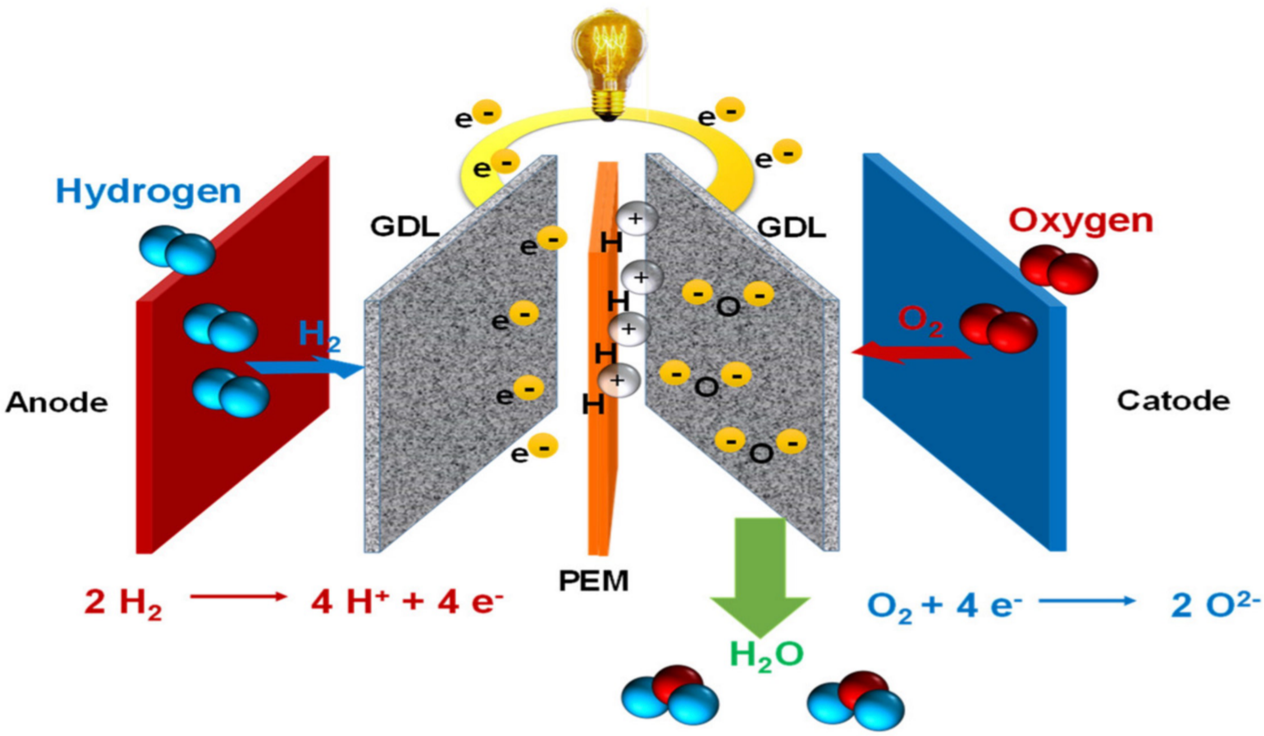

Fig. 1. Schematic diagram of a single PEMFC showing key components[13]

4. PEMFCs: Uses and Future Challenges

Proton Exchange Membrane Fuel Cells (PEMFCs) are widely used due to their compact design, high efficiency, and rapid startup. In transportation, the power fuel cell vehicles (FCVs), including cars, buses, trucks, and trains, providing a clean alternative to internal combustion engines. Their lightweight and portable nature also makes them suitable for backup power, military operations, laptops, and handheld devices. Furthermore, PEMFCs are applied in residential and commercial combined heat and power (CHP) systems, delivering both electricity and heat to improve overall energy efficiency. Despite their advantages, PEMFCs face key challenges for future adoption. These include the high cost of platinum catalysts, sensitivity to fuel impurities, and the requirement for pure hydrogen, along with effective water management systems [14].

5. Solid Oxide Fuel Cells (SOFCs)

Solid Oxide Fuel Cells (SOFCs) are high-temperature electrochemical devices that efficiently convert chemical energy from fuels directly into electrical energy. Operating typically between 600°C and 1000°C, SOFCs offer significant advantages, including high fuel flexibility, long-term stability, and tolerance to impurities[15]. Unlike low-temperature fuel cells like PEMFCs, which require pure hydrogen, SOFCs can utilize a range of fuels such as hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and their mixtures. As illustrated in the diagram, fuel gases (H_2, CO) are introduced into the anode chamber through the fuel inlet. Here, the fuel spreads across the anode surface and reacts with oxygen ions (O^{2-}) that are transported from the cathode side. This oxidation reaction releases electrons (e^-), which cannot pass through the solid electrolyte and thus travel through an external circuit, generating electrical energy [16]. The resulting products, such as water (H_2O), carbon dioxide (CO_2), and unreacted fuel, exit via the fuel outlet.

Simultaneously, oxygen (O_2) from the air enters the cathode chamber through the air inlet. At the cathode, oxygen molecules gain electrons from the external circuit and are reduced to form oxide ions (O^{2-}). These ions move across the solid electrolyte to the anode side, where they participate in the oxidation of the fuel. The electrolyte, a dense ceramic material, is crucial as it selectively conducts ions while blocking electrons, ensuring continuous electrochemical reactions [17]. This flow of electrons through the external circuit is what produces useful electricity. Meanwhile, the excess air exits through the air outlet. Overall, the SOFC system, as depicted in the figure, demonstrates an elegant process of fuel-to-power conversion with high efficiency and low emissions, making it a vital technology in the shift toward cleaner and more sustainable energy systems.

In the operation of the fuel cell, oxygen from the surrounding air first enters the cathode, where it undergoes a reduction reaction to form oxygen ions, as shown in Fig. 2. These negatively charged ions then migrate through the electrolyte, which acts as a selective barrier allowing only the desired ions to pass. Upon reaching the anode, the oxygen ions react chemically with the supplied fuel, often hydrogen or another suitable fuel source [18]. This reaction releases electrons, which flow through an external circuit to produce electricity, while also generating water as a byproduct and releasing heat that can be utilized or dissipated depending on the application. This continuous process enables the fuel cell to provide a steady supply of clean energy as long as fuel and oxygen are available.

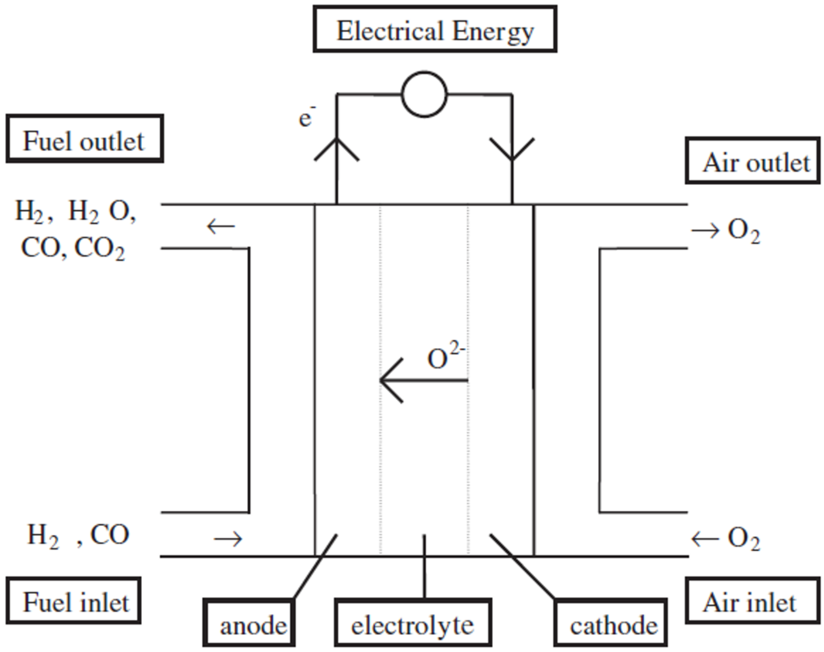

Fig. 2. Working principle of an SOFC [19].

6. SOFCs: Uses and Future Challenges

Solid oxide fuel cells (SOFCs) serve a wide range of energy applications, making them a versatile and efficient technology. In stationary power generation, they are highly valued for their exceptional efficiency, fuel flexibility, and long operational life, making them ideal for large-scale and distributed electricity production. In industrial combined heat and power (CHP) systems, the high-temperature exhaust from SOFCs can be effectively recovered and utilized for heating or other thermal processes, maximizing overall energy utilization. Furthermore, their ability to operate independently of the main electricity grid makes them an excellent choice for supplying dependable power to remote areas, off-grid facilities, and critical infrastructure where uninterrupted energy is essential [20]. Solid oxide fuel cells (SOFCs) provide a range of significant advantages that make them attractive for both industrial and commercial applications. They deliver exceptionally high electrical efficiency, often above 60%, and when integrated into combined heat and power (CHP) systems, their overall energy efficiency can rise even further by utilizing the waste heat for heating or other processes. Their remarkable fuel flexibility allows them to operate on a variety of fuels, including hydrogen, natural gas, biogas, and other hydrocarbons, enabling easier integration with existing energy infrastructure and diverse energy sources [21]. Unlike many other fuel cell technologies, SOFCs do not rely on costly precious metal catalysts, such as platinum, which not only reduces production costs but also enhances long-term sustainability and resource availability. This combination of efficiency, versatility, and cost-effectiveness positions SOFCs as a promising solution for clean and reliable energy generation. Despite their many benefits, solid oxide fuel cells (SOFCs) also face certain challenges that can limit their widespread adoption. One notable drawback is their long start-up time, which is a result of the very high operating temperatures often between 600°C and 1,000°C needed for efficient operation. These extreme temperatures also contribute to gradual material degradation, as components such as the electrolyte, electrodes, and seals can deteriorate over prolonged use, potentially reducing system lifespan and performance. Additionally, managing the intense heat generated during operation requires complex thermal management systems to ensure uniform temperature distribution and to prevent thermal stresses that could damage the cell structure. These factors make the design, maintenance, and operation of SOFC systems more demanding compared to lower-temperature fuel cell technologies.

7. Molten Carbonate Fuel Cells (MCFCs)

Molten Carbonate Fuel Cells (MCFCs) are high-temperature fuel cells that operate between 600°C and 700°C, using a molten mixture of carbonate salts, typically lithium, sodium, or potassium carbonates, as the electrolyte. These salts, supported in a porous ceramic matrix, conduct carbonate ions (CO_3^{2-}) from the cathode to the anode during operation [22]. The elevated temperature not only enables efficient electrochemical reactions but also allows the use of a wide variety of fuels, including hydrogen, natural gas, biogas, and coal-derived gases, since hydrocarbons can be reformed internally within the cell. MCFCs are well-suited for utility-scale power plants and industrial facilities, delivering steady, large-scale power output and often integrated into combined heat and power (CHP) systems to maximize efficiency, reaching up to 60% for electricity alone and even higher when waste heat is utilized. Their advantages include high efficiency, fuel flexibility, and low emissions, but challenges remain, such as long start-up times, material degradation from the corrosive molten salts, and the need for robust thermal management.

In a Molten Carbonate Fuel Cell (MCFC), the movement of carbonate ions (CO_3^{2-}) through the molten carbonate electrolyte is the key to generating electricity. At the cathode, oxygen from the air and carbon dioxide, often recycled from the anode exhaust, combine with electrons from the external circuit to form carbonate ions. These ions migrate through the electrolyte toward the anode, where they react with the fuel, which can be hydrogen or hydrocarbons such as methane. In the case of hydrogen, the reaction produces water, carbon dioxide and releases electrons; with hydrocarbons, the reaction additionally reforms the fuel internally. The released electrons then flow through the external circuit, producing electrical power. The carbon dioxide generated at the anode is partly recycled to the cathode, enabling continuous operation [23]. This process allows MCFCs to operate efficiently at high temperatures, with the carbonate ions acting as the charge carriers that link the electrochemical reactions at both electrodes.

8. MCFCs: Uses and Future Challenges

Molten Carbonate Fuel Cells (MCFCs) are particularly well-suited for large stationary power plants, especially when integrated into combined cycle systems that use both fuel cells and gas turbines to maximize overall efficiency. Their unique ability to use carbon dioxide at the cathode makes them compatible with carbon capture and sequestration technologies, as CO_2 from industrial exhaust or other sources can be fed directly into the cell, where it participates in the electrochemical process rather than being released into the atmosphere [24]. Additionally, because MCFCs operate at high temperatures, they produce significant amounts of usable heat, making them ideal for industrial heat recovery in energy-intensive sectors such as refineries, chemical plants, and manufacturing facilities, where the waste heat can be harnessed for steam generation or other thermal processes, further improving overall system efficiency. Molten Carbonate Fuel Cells (MCFCs) offer several key advantages that make them attractive for large-scale and industrial energy applications. They operate with high electrical efficiency, which can be further increased when integrated into combined heat and power (CHP) systems. Their fuel flexibility is another major strength, as they can run not only on pure hydrogen but also on more readily available fuels such as natural gas, biogas, and other hydrocarbon-based sources, thanks to their ability to internally reform these fuels at high operating temperatures. Additionally, MCFCs have the unique capability to capture and utilize carbon dioxide as part of their electrochemical process at the cathode, allowing them to be integrated with carbon capture systems to reduce greenhouse gas emissions while still producing clean, reliable electricity. Molten Carbonate Fuel Cells (MCFCs) face several challenges that limit their widespread adoption. The molten carbonate electrolyte is highly corrosive, which can gradually degrade cell components such as electrodes, current collectors, and sealing materials, leading to increased maintenance and replacement costs [25]. Their high operating temperatures require precise thermal management to prevent thermal stress and damage, while also ensuring stable chemical conditions to maintain performance and avoid unwanted side reactions. Furthermore, compared to lower-temperature fuel cells like PEMFCs, MCFCs generally have shorter operational lifespans, as prolonged exposure to high heat and corrosive conditions accelerates material wear, reducing overall durability and reliability over time [26].

9. Alkaline Fuel Cells (AFCs)

Alkaline Fuel Cells (AFCs) use an aqueous alkaline solution, typically potassium hydroxide (KOH), as the electrolyte to conduct hydroxide ions (OH^-) between the electrodes. They operate at relatively low temperatures, usually between 60°C and 90°C, which allows for quick start-up and stable operation. AFCs are known for their high electrical efficiency, often exceeding that of many other fuel cell types, particularly when using pure hydrogen and oxygen as reactants [27]. Their ability to deliver clean, reliable power made them a preferred choice in early space programs, such as the Apollo missions, where they not only generated electricity but also produced potable water as a useful by-product for astronauts.

10. AFCs: Uses and Future Challenges

Alkaline Fuel Cells (AFCs) have found notable applications in specialized fields due to their high efficiency and reliability. They were famously used by NASA in the Apollo and Space Shuttle programs, providing both electricity and drinking water for astronauts in space. Their lightweight design and ability to deliver efficient, clean power have also made them suitable for certain military applications, where portable and dependable energy sources are essential. Additionally, AFCs can serve as backup or remote power systems in specific settings; however, their commercial use is limited because they are highly sensitive to carbon dioxide, which can react with the alkaline electrolyte and reduce performance, making them less practical for operation in environments with normal air [28]. Alkaline Fuel Cells (AFCs) face some notable operational challenges, the most significant being their high sensitivity to carbon dioxide present in either the air supply or the fuel stream. CO_2 reacts with the alkaline electrolyte, forming carbonates that reduce its conductivity and overall performance, which is why AFCs require either pure oxygen or highly filtered air to function efficiently. Another challenge is complex water management, as water is both consumed and produced during the electrochemical process. Maintaining the right water balance is critical to prevent electrolyte dilution or drying, both of which can negatively impact the cell's efficiency and lifespan.

11. Phosphoric Acid Fuel Cells (PAFCs)

Phosphoric Acid Fuel Cells (PAFCs) use liquid phosphoric acid as the electrolyte, which conducts protons from the anode to the cathode during operation. They run at medium temperatures, typically between 150°C and 200°C, which allows them to tolerate certain fuel impurities, such as small amounts of carbon monoxide, better than low-temperature fuel cells. PAFCs are widely recognized as the first type of fuel cell to become commercially available, with early systems deployed for stationary power generation and combined heat and power (CHP) applications [29]. Their moderate operating temperature also enables efficient heat recovery for use in heating systems, making them practical for industrial, commercial, and large building installations.

12. PAFCs: Uses and Future Challenges

Phosphoric Acid Fuel Cells (PAFCs) are well-suited for commercial and institutional buildings, where they are often integrated into combined heat and power (CHP) systems to provide both electricity and useful heat from a single fuel source. This makes them particularly valuable in facilities with constant energy demands, as they can operate efficiently year-round. They are also widely used in hospitals and hotels, where reliable, low-noise power generation is essential, and the recovered heat can be utilized for space heating, hot water, or other thermal needs, improving overall energy efficiency while maintaining a quiet and dependable power supply. Phosphoric Acid Fuel Cells (PAFCs) have a reasonable tolerance to fuel impurities, meaning they can operate effectively even when the hydrogen fuel contains small amounts of contaminants such as carbon monoxide, which would quickly poison the catalysts in many other fuel cell types [30]. This makes them more flexible in terms of fuel processing and less demanding in purification requirements. Additionally, PAFCs have proven long-term operational performance, with decades of real-world use demonstrating their durability, reliability, and stable output over extended periods. This track record provides confidence for commercial and institutional users looking for a dependable power generation technology. Phosphoric Acid Fuel Cells (PAFCs) have moderate electrical efficiency, typically lower than that of high-temperature fuel cells like MCFCs or SOFCs, which means a larger portion of the fuel's energy is lost as heat rather than converted into electricity. While their efficiency can be improved in combined heat and power (CHP) applications, they are less competitive when only electricity generation is considered. Another drawback is their long warm-up time due to their medium operating temperature range of 150–200°C; it can take a significant amount of time for the system to reach optimal operating conditions, making them less suitable for applications that require rapid start-up or frequent cycling.

13. Direct Methanol Fuel Cells (DMFCs)

Direct Methanol Fuel Cells (DMFCs) use methanol (CH_3OH) directly as the fuel, mixed with water, which is fed to the anode where it undergoes electrochemical oxidation to produce electricity. This approach eliminates the need for an external fuel reformer, simplifying the system compared to fuel cells that require hydrogen derived from other fuels [31]. DMFCs operate at low temperatures, typically between 60°C and 130°C, which allows for compact designs and quicker start-up times. Their ability to use liquid methanol, a high-energy-density fuel that is easy to transport and store, makes them attractive for portable, small-scale, and off-grid power applications.

14. DMFCs: Uses and Future Challenges

Direct Methanol Fuel Cells (DMFCs) are particularly useful in consumer electronics such as laptops, mobile devices, and battery chargers, where their ability to provide continuous power from easily replaceable methanol cartridges can extend device operation far beyond traditional batteries. They are also valuable for military and remote field applications, offering a lightweight, portable energy source that is easy to refuel without the need for complex infrastructure. Since methanol is a liquid at ambient conditions, it can be stored, transported, and handled more easily than compressed hydrogen, making DMFCs practical for situations where reliability, portability, and quick fuel replenishment are essential. Direct Methanol Fuel Cells (DMFCs) generally have lower efficiency compared to other fuel cell types, meaning a smaller portion of the fuel's chemical energy is converted into electricity, with more lost as heat. A significant challenge affecting their performance is methanol crossover, a phenomenon where methanol molecules pass through the electrolyte membrane from the anode to the cathode without fully reacting [32]. This not only wastes fuel but also reduces the cell's voltage and overall efficiency, as it interferes with the cathode reaction and generates unwanted heat. Over time, methanol crossover can also lead to durability issues, making it a key area of improvement for DMFC technology.

Fuel cells vary in operating conditions, fuel types, and applications. PEMFCs are compact, quick-start systems for transport and portable uses, but face catalyst cost and water issues. SOFCs and MCFCs operate at high temperatures, offering high efficiency and fuel flexibility for large-scale or industrial power, though they suffer from start-up delays and material degradation. AFCs are efficient and low-cost for space and backup uses but are CO_2-sensitive. PAFCs are durable and low-emission for stationary applications like buildings and hospitals, with moderate efficiency [33]. DMFCs suit portable electronics due to easy methanol handling but have low efficiency and fuel crossover challenges, as Table 1.

Table 1
Comparison of Major Fuel Cell Types

Fuel Cell Type	Electrolyte	Operating Temp	Fuel Used	Applications	Key Advantages	Major Challenges
PEMFC	Proton Exchange Membrane	60–80°C	Pure hydrogen	Vehicles, backup power, portable use	Fast start-up, compact	Catalyst cost, water management
SOFC	Solid oxide (ceramic)	700–1000°C	Hydrogen, natural gas	Stationary power, industrial systems	High efficiency, fuel flexibility	High temp, long start-up
MCFC	Molten carbonate salt	600–700°C	H_2, CO, hydrocarbons	Utility-scale generation, CHP	Carbon capture, fuel flexibility	Corrosion, component degradation

AFC	Aqueous KOH (alkaline)	60–90°C	Hydrogen	Space missions, backup systems	High efficiency, low cost	CO_2 sensitivity
PAFC	Phosphoric acid	150–200°C	Hydrogen	Buildings, hospitals, CHP	Durable, low emissions	Moderate efficiency
DMFC	Polymer membrane (methanol)	60–130°C	Methanol	Portable electronics, field devices	Easy fuel handling	Low efficiency, methanol crossover

15. Role of Fuel Cells in the Sustainable Energy Transition

As the global community seeks cleaner, more efficient energy systems to combat climate change, reduce dependency on fossil fuels, and ensure long-term energy security, fuel cells are increasingly being recognized as a critical enabling technology [34]. Their unique ability to generate electricity cleanly and efficiently through electrochemical processes rather than combustion positions them as a pillar of the low-carbon energy infrastructure. This section explores how fuel cells contribute to sustainable energy systems through carbon reduction, support for the hydrogen economy, and energy efficiency improvements across sectors.

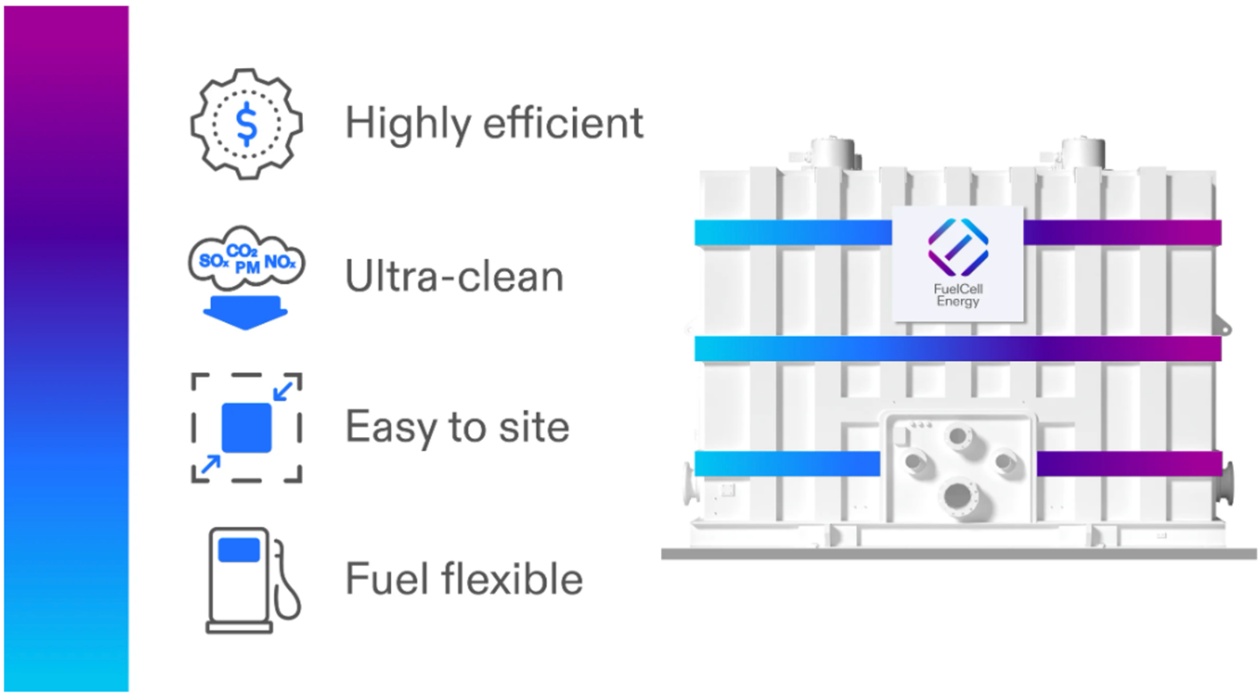

Fig. 3. Role of Fuel Cells in the Sustainable Energy Transition

16. Reducing Carbon Emissions

One of the most significant contributions of fuel cells is their potential to reduce greenhouse gas emissions, particularly when hydrogen is derived from renewable sources (green hydrogen). In Proton Exchange Membrane Fuel Cells (PEMFCs), the primary by-product of the reaction between hydrogen and oxygen is water vapor—making these systems completely free of carbon emissions during operation. This contrasts sharply with internal combustion engines and coal or gas power plants that emit carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur dioxide (SO_2), and particulate matter [35]. For example, a hydrogen-powered fuel cell vehicle emits zero tailpipe emissions, whereas even the cleanest combustion-based vehicles still emit CO_2. Similarly, stationary fuel cell systems using clean hydrogen can power homes, offices, and data centers with virtually no environmental footprint.

While some fuel cells, such as Direct Methanol Fuel Cells (DMFCs) or Molten Carbonate Fuel Cells (MCFCs), produce CO_2 as a by-product, they do so more cleanly and efficiently than traditional combustion systems. Furthermore, MCFCs can be integrated with carbon capture technologies, utilizing CO_2 from industrial processes at the cathode and reducing net emissions. Therefore, even carbon-emitting fuel cells can contribute positively when part of a broader decarbonization strategy [36].

17. Supporting the Hydrogen Economy

Fuel cells are foundational to the development of the hydrogen economy—a vision where hydrogen serves as a clean, flexible, and abundant energy carrier. In this system, renewable energy (e.g., solar, wind, hydro) is used to produce hydrogen via water electrolysis. The hydrogen can then be stored, transported, and utilized in fuel cells to generate electricity on demand, enabling deep decarbonization across multiple sectors. Fuel cells make it possible to utilize green hydrogen in applications such as: Fuel cells enable the effective use of green hydrogen produced from renewable energy sources for a wide range of applications aimed at reducing carbon emissions [37]. In zero-emission transport, they can power vehicles such as cars, buses, trucks, trains, ships, and even future aircraft, producing only water as a by-product and helping to decarbonize the transportation sector. For off-grid and remote energy supply, fuel cells offer a reliable and clean alternative to diesel generators, making them ideal for isolated communities, disaster relief operations, and temporary installations. In industrial heat and power generation, they can provide both electricity and high-grade heat for manufacturing, chemical processing, and other energy-intensive activities, improving efficiency while reducing reliance on fossil fuels. Additionally, fuel cells can play a role **in** grid balancing and energy storage**,** using surplus renewable electricity to produce hydrogen, which can later be converted back into power during peak demand, thereby enhancing the stability and resilience of renewable-based energy systems. Their modular nature and rapid ramp-up capabilities allow them to complement intermittent renewable sources like solar and wind, ensuring stable power delivery without relying on fossil-fuel-based backup systems. Moreover, governments and industries worldwide are investing in hydrogen production, infrastructure, and storage solutions to support the scalability of fuel cell technology [38]. Countries such as Japan, Germany, South Korea, and Australia have launched national hydrogen strategies with fuel cells at their core.

18. Enhancing Energy Efficiency

Fuel cells stand out as one of the most promising clean energy technologies because they combine high efficiency, low environmental impact, and versatile applications**.** Unlike conventional combustion-based systems, which must first convert fuel into heat and then into mechanical and electrical energy, losing a significant portion of the original energy in the process, fuel cells directly transform chemical energy into electricity through electrochemical reactions. This avoids the inherent thermal conversion losses, enabling electrical efficiencies typically in the 40–60% range, and, when integrated into combined heat and power (CHP) systems, total efficiencies can reach 85–90% by utilizing the waste heat for space heating, hot water, or industrial processes [39]. This high efficiency translates into lower fuel consumption for the same amount of electricity, resulting in substantial cost savings over the system's lifetime. From an environmental perspective, fuel cells produce virtually zero emissions when powered by hydrogen, with only water and heat as by-products, and even when using other fuels like natural gas or biogas, pollutant levels remain far below those from combustion systems. They also help reduce greenhouse gas emissions and improve urban air quality by eliminating nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter. Economically, fuel cells offer longer operational lifespans and lower maintenance requirements because they have few moving parts, avoiding the mechanical wear and tear that plagues internal combustion engines. This makes them exceptionally reliable in applications where energy security is critical, such as hospitals, data centers, emergency response systems, and remote installations. Furthermore, their quiet operation and modular scalability make them well-suited for urban environments, residential areas, and off-grid sites. Looking ahead, fuel cells, especially when powered by green hydrogen produced from renewable energy, can play a pivotal role in the global energy transition, serving as both a decarbonization tool for transport, industry, and power generation, and a flexible energy storage solution to stabilize renewable-heavy grids. In this way, fuel cells offer not just an incremental improvement over traditional systems, but a fundamental shift toward a cleaner, more resilient, and more sustainable energy future.

19. Sector-Wise Contribution to Sustainability

Fuel cells are emerging as a transformative technology across multiple sectors, offering a clean, efficient, and versatile alternative to traditional power sources. In transportation, hydrogen-powered fuel cell electric vehicles (FCEVs) are redefining sustainable mobility by combining the zero-emission benefits of electric propulsion with the convenience and range traditionally associated with internal combustion engines. Capable of traveling up to 700 kilometres on a single refuelling and refuelling in under five minutes, FCEVs eliminate one of the biggest barriers to electric vehicle adoption, long charging timeswhile also avoiding the need for massive, heavy batteries. This makes them particularly well-suited for heavy-duty, long-haul, and high-utilization applications, including trucks, buses, trains, and even ships, where downtime must be minimized and range is critical. In the stationary power generation sector, fuel cells are replacing diesel generators and inefficient coal-based systems, especially in microgrids and decentralized setups where local generation improves resilience and reduces transmission losses [40]. Their quiet operation, minimal emissions, and modular scalability make them ideal for urban deployment, as they can provide reliable electricity without contributing to air or noise pollution. For portable and backup power, fuel cells are increasingly valued in military, remote, and emergency scenarios where lightweight, compact, and dependable energy sources are essential. They can extend mission times for soldiers, continuously power remote sensors and monitoring stations, and serve as backup systems for critical infrastructure such as telecom towers, hospitals, and data centres. By delivering clean power with high efficiency and rapid deployment capability, fuel cells are proving to be a key enabler of the energy transition, addressing the needs of mobility, power generation, and off-grid resilience in a way that supports both environmental sustainability and operational reliability.

20. Fuel Flexibility and Integration with Renewables

Most modern fuel cells, particularly high-temperature types like Solid Oxide Fuel Cells (SOFCs) and Molten Carbonate Fuel Cells (MCFCs), are highly versatile in their fuel compatibility, capable of running on a wide range of fuels beyond pure hydrogen, including natural gas, biogas, ammonia, ethanol, and methanol. This adaptability enables a phased transition toward full sustainability. In the short term, fuel cells can utilize existing fossil fuel infrastructure, significantly reducing emissions compared to conventional combustion systems. In the medium term, they can shift to low-carbon fuels such as biomethane and blue hydrogen, cutting greenhouse gases further while building hydrogen supply chains. In the long term, they can operate entirely on green hydrogen produced from renewable energy sources, achieving near-zero emissions. Fuel cells can also be integrated into hybrid renewable energy systems, enhancing both efficiency and reliability [41]. For example, during the day, solar photovoltaic (PV) panels generate electricity, and any excess power is used to electrolyze water to produce hydrogen. This stored hydrogen can then be fed into fuel cells to produce electricity at night or during cloudy periods, ensuring a continuous supply. Such configurations promote energy independence, reduce dependence on centralized grids, and provide resilience during power outages, making fuel cells a key enabler in the global transition toward clean, secure, and flexible energy systems.

20. Future Outlook and Global Policy Support

The future of fuel cells appears highly promising, propelled by a combination of technological progress, supportive policies, and collaborative efforts. Ongoing advancements are steadily reducing costs, improving durability, and enhancing performance, making fuel cells more commercially competitive across multiple sectors. Governments around the world are introducing policy incentives, including tax credits, subsidies, and stricter emissions regulations, that encourage adoption and help offset initial investment costs. At the same time, public-private partnerships are accelerating research, development, and large-scale demonstration projects, as well as building the necessary infrastructure for hydrogen production, storage, and distribution [42]. Global climate agreements and national decarbonization targets are further driving the shift toward low-carbon and zero-emission technologies, creating a favourable market environment for fuel cells. With their clean operation, high efficiency, and flexibility in applications ranging from transportation to stationary and portable power, fuel cells are poised to become a central pillar in achieving net-zero emissions goals and enabling a sustainable, resilient energy future.

Table 2
Contribution of Fuel Cells

Role/Area	Contribution of Fuel Cells	Examples/Notes
Carbon Emission Reduction	Zero-emission operation when using hydrogen; cleaner than combustion systems	PEMFCs emit only water; MCFCs enable CO_2 reuse.
Hydrogen Economy Support	Enable the use of green hydrogen in energy systems	Power-to-gas-to-power cycles, hydrogen refueling stations

Energy Efficiency	High electrical and total efficiency (>60% to >90% in CHP systems)	SOFCs, PAFCs in residential and industrial use
Transportation	Emission-free vehicles with long range and quick refueling	FCEVs (Toyota Mirai, Hyundai Nexo), fuel cell trains/buses
Stationary Power	Clean backup and primary power for critical infrastructure	Hospitals, telecom, military, off-grid systems
Portable Power	Lightweight, efficient energy for field operations and electronics	DMFCs in military gear, fuel cell chargers
Fuel Flexibility	Operation with hydrogen, natural gas, biogas, ammonia, etc.	Transitional path from fossil to renewable fuels
Renewable Integration	Store excess renewable energy as hydrogen and convert back via fuel cells	Solar + electrolysis + hydrogen + fuel cell = full cycle
Policy Alignment	Meets climate targets, emission regulations, and energy security objectives	EU Green Deal, US IRA, Japan's Hydrogen Roadmap

21. Challenges and Advancements in Fuel Cell Technology

Fuel cells are rapidly gaining traction as a promising clean energy technology capable of delivering high efficiency, zero-emission performance, and versatile applications across transportation, power generation, and portable energy systems. However, their widespread commercialization is still constrained by a range of technical, economic, and infrastructure-related challenges. These include high production costs, material durability issues, limited hydrogen production and distribution networks, and the need for more efficient fuel processing technologies [43]. Overcoming these barriers demands continued research, development, and innovation, supported by strategic investments from both public and private sectors. Recent advancements in catalyst materials, system design, and hybrid integration with renewable energy sources are showing significant potential in addressing these limitations. By tackling these challenges head-on, fuel cells can transition from niche applications to mainstream adoption, playing a major role in the global shift toward sustainable, low-carbon energy systems.

Fuel cells are gaining momentum as a clean energy solution, but their widespread adoption still faces technical, economic, and infrastructure-related barriers that must be addressed for large-scale commercialization. One of the most significant challenges is high system cost, particularly for Proton Exchange Membrane Fuel Cells (PEMFCs), which rely on scarce and expensive platinum-group metal (PGM) catalysts such as platinum (Pt) to accelerate electrochemical reactions. Additional cost drivers include the production and storage of high-purity hydrogen, the manufacture of specialized membranes and bipolar plates, complex thermal and water management systems, and advanced power electronics. While prices have been steadily declining due to improvements in materials and economies of scale, fuel cells still face tough competition from internal combustion engines and lithium-ion batteries, especially in the transportation sector. Durability is another key hurdle, as performance can degrade over time due to catalyst poisoning, membrane damage, thermal cycling stress in high-temperature systems like Solid Oxide Fuel Cells (SOFCs), and fuel impurities such as carbon monoxide and sulphur. For applications like automotive fleets and stationary power plants, systems must operate for thousands of hours with minimal efficiency loss to be viable. Equally important is the challenge of hydrogen production and infrastructure. At present, over 90% of hydrogen is produced via steam methane reforming (SMR), which emits large amounts of CO_2 unless paired with carbon capture and storage (CCS) to produce blue hydrogen. Clean alternatives such as green hydrogen, generated via electrolysis powered by renewables, remain costly and limited in scale, while hydrogen's low volumetric energy density necessitates high-pressure storage tanks, liquefaction, or chemical carriers like ammonia—all of which increase cost and complexity. Infrastructure gaps, including the limited availability of hydrogen refuelling stations and pipelines outside regions like East Asia and parts of Europe, hinder fuel cell electric vehicle (FCEV) deployment and consumer adoption.

To overcome these barriers, technological innovations and research advancements are accelerating. Development of non-precious metal catalysts (NPMCs) such as iron–nitrogen–carbon (Fe–N–C) compounds and transition metal oxides aim to reduce dependence on platinum, while next-generation advanced membranes are being engineered for better proton conductivity, thermal stability, chemical durability, and water management. In SOFCs, thin-film electrolytes are being designed to lower operating temperatures and improve start-up times. Hybrid and integrated systems such as fuel cell–battery vehicles, fuel cell–solar PV microgrids, and SOFC–gas turbine power plants are showing significant efficiency gains and flexibility. Additive manufacturing (3D printing) is enabling custom component designs, reducing waste, and improving microstructural control, while artificial intelligence is being applied to optimize operating conditions, predict degradation, and enable predictive maintenance, thereby extending service life and lowering operating costs.

Alongside these technical efforts, market and policy advancements are creating a more favourable environment for fuel cell deployment. Governments are offering subsidies, tax incentives, and funding for hydrogen infrastructure projects, examples include the U.S. Inflation Reduction Act and the EU Green Deal, while emissions regulations are pushing industries toward cleaner technologies. Public-private partnerships are supporting demonstration projects and pilot deployments, and the creation of international hydrogen corridors is helping standardize components and expand markets [44]. Globally, momentum is building as countries such as Japan, South Korea, Germany, China, and the U.S. roll out national hydrogen strategies that integrate fuel cells across multiple sectors. Japan's ENE-FARM project has installed thousands of residential fuel cell units, automakers like Hyundai and Toyota are leading in FCEV development, and companies such as Bloom Energy and Ceres Power are advancing SOFC solutions for industrial and grid-scale applications. Industry alliances like the Hydrogen Council are uniting stakeholders to scale up production, develop infrastructure, and tackle shared challenges. Together, these combined technological, policy, and market developments are paving the way for fuel cells to become a mainstream pillar of the global clean energy transition.

Table 3
Challenges and Recent Advancements in Fuel Cell Technology

Challenge Area	Description	Recent Advancements
High Cost of Materials	Platinum-group metals (PGMs) raise system costs.	Development of non-precious metal catalysts (e.g., Fe–N–C, Co-based materials)
Durability and Degradation	Membrane thinning, catalyst poisoning, thermal stress	Advanced membranes, corrosion-resistant coatings, AI-based predictive maintenance

Hydrogen Production	Fossil-based hydrogen dominates production	Green hydrogen via electrolysis, photoelectrochemical water splitting
Hydrogen Storage & Distribution	Complex, costly infrastructure for H_2 compression, liquefaction, and pipelines	Solid-state storage (metal hydrides), chemical carriers (ammonia, LOHCs)
Lack of Refueling Infrastructure	A limited number of hydrogen stations globally	Government incentives and public-private partnerships are building H_2 stations.
Fuel Impurities	CO, sulfur affect catalyst performance	Development of fuel-tolerant catalysts and filtration systems
System Efficiency	Losses due to heat, water, and gas management	Hybrid systems (fuel cell + battery or turbine), better heat integration
Manufacturing Complexity	High-precision components increase cost and reduce scalability	Additive manufacturing (3D printing), roll-to-roll processes for membranes
Cold Start and Startup Time	Low-temperature PEMs suffer in freezing environments	Self-heating start-up systems, low-temperature SOFCs under development
Public Awareness and Market Readiness	Limited consumer knowledge, range anxiety in vehicles	Public education campaigns, successful pilot projects (e.g., hydrogen buses, homes)

22. Future Prospects of Fuel Cells

Fuel cells are emerging as a cornerstone in the global transition toward sustainable and clean energy systems. As energy demands grow and climate change accelerates, the urgency for efficient, low-carbon, and scalable energy solutions has never been higher. Fuel cells, which convert chemical energy directly into electricity with high efficiency and minimal emissions, offer a compelling alternative to conventional fossil fuel-based systems [45]. Their future development is driven by technological innovation, economic feasibility, supportive policies, and integration with other clean energy systems such as renewables and hydrogen infrastructure.

Recent developments in fuel cell technology are transforming the clean energy landscape by tackling long-standing challenges related to cost, durability, and efficiency. Advances in materials science are yielding new membranes, catalysts, and electrode materials, including non-precious metal catalysts like iron–nitrogen–carbon (Fe-N-C), which reduce reliance on costly platinum while maintaining high performance. Solid Oxide Fuel Cells (SOFCs) are being redesigned to operate at intermediate temperatures, improving their material stability and reducing start-up times, while Polymer Electrolyte Membrane Fuel Cells (PEMFCs) are benefiting from innovations that enhance proton conductivity, optimize water and thermal management, and reduce catalyst loading. Miniaturized and portable fuel cells are emerging for off-grid, defense, and consumer electronics applications, offering sustainable and lightweight alternatives to batteries. Alongside these hardware advances, artificial intelligence (AI) is becoming a powerful tool for optimizing fuel cell operation. AI and machine learning algorithms enable predictive maintenance, fault detection, and system control, while digital twins—virtual models of fuel cell systems—allow engineers to simulate and optimize designs before physical deployment, reducing both costs and risks. AI-driven energy management also supports intelligent integration with renewables, enabling fuel cells to store excess solar or wind energy as hydrogen and deploy it when needed. The expansion of a global hydrogen economy is tightly linked to fuel cell growth, with green hydrogen production from renewable-powered electrolysis emerging as a sustainable fuel pathway. Investments in hydrogen infrastructure, including production plants, pipelines, and storage, will enable large-scale commercialization and seasonal energy storage solutions to stabilize renewable-heavy grids. Fuel cells are gaining traction across multiple sectors: in transportation, Fuel Cell Electric Vehicles (FCEVs) offer long ranges, fast refueling, and suitability for heavy-duty transport; in stationary power, they provide reliable, grid-independent electricity for residential, commercial, and industrial applications; in industry, high-temperature fuel cells help decarbonize energy-intensive sectors like steel and cement; and in aerospace and defense, they offer silent, high-density power for sensitive operations. Market forecasts predict the global fuel cell sector will exceed USD 30 billion by 2030, driven by policy incentives, decarbonization mandates, and public–private R&D collaborations. Governments worldwide are promoting adoption through hydrogen strategies, subsidies, and infrastructure investment, such as the EU's large-scale green hydrogen rollout, Japan's "Hydrogen Society" roadmap, and the U.S. DOE's funding initiatives [46]. However, challenges remain, including limited refuelling infrastructure, the need for international safety and performance standards, and low public awareness. Overcoming these barriers will require coordinated action among governments, academia, and industry, ensuring that fuel cells fulfill their potential as a cornerstone of the clean energy transition.

Table 4
Future Prospects of Fuel Cells

Aspect	**Details**
Technological Advancements	Development of new catalysts (non-PGM), improved membranes, intermediate-temp SOFCs, and micro fuel cells.
AI Integration	Predictive maintenance, digital twins, performance optimization, intelligent energy management systems.
Hydrogen Economy	Green hydrogen production, storage, and distribution to power PEMFCs, enabling seasonal renewable energy storage.
Sectoral Applications	Transportation (FCEVs), stationary power, industrial processes, aerospace, and defense.
Market Outlook	The fuel cell market is expected to exceed $30 billion by 2030, with expanding adoption across various sectors.
Policy Support	National hydrogen strategies, research funding, and infrastructure investment (e.g., EU, US, Japan).
Challenges	High cost, limited infrastructure, standardization issues, and public perception.
Key Enablers	R&D funding, public-private partnerships, renewable energy integration, global cooperation on hydrogen and fuel cell standards.

23. Conclusion

Fuel cells have emerged as a pivotal technology in the global transition toward sustainable, low-carbon energy systems. By converting chemical energy directly into electricity through electrochemical reactions, they offer high efficiency, low emissions, and diverse applicability across transportation, stationary power generation, and portable energy systems. This review highlighted the operating principles, advantages, and limitations of major fuel cell types, PEMFCs, SOFCs, MCFCs, AFCs, PAFCs, and DMFCs, and examined their roles in decarbonization, energy efficiency enhancement, and integration with renewable energy sources. Despite their significant potential, fuel cells face persistent challenges, including high production costs, limited hydrogen infrastructure, material degradation, and fuel purity requirements. However, recent advancements in catalyst development, membrane technologies, hybrid system integration, and hydrogen production methods, particularly green hydrogen, are steadily addressing these barriers. Supportive global policies, infrastructure investments, and public–private collaborations further strengthen the pathway toward commercialization. Looking ahead, the combination of technological innovation, cost reduction, and strategic deployment in sectors where their unique advantages are most valuable positions fuel cells as a cornerstone of the clean energy transition. Their ability to complement intermittent renewable sources, enable the hydrogen economy, and deliver reliable, zero-emission power makes them an indispensable element in achieving net-zero targets and building a resilient, sustainable energy future.

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