

# The Role of Fuel Cell Technology in Modern and Future Aviation

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**Abstract.** The aviation sector ranks among the fastest-growing contributors to carbon dioxide emissions, making the decarbonization of air transport an urgent global imperative for sustainable development. Regarding propulsion options, while conventional gas turbines are constrained by greenhouse gas emissions, while battery-electric propulsion systems are criticized regarding its energy density and charging speed. Fuel cells replace combustion with electrochemical reactions to convert chemical energy into electrical energy, gradually emerging as an ideal alternative solution characterized by high efficiency, rapid refueling, and near-zero emissions. This article examines the suitability and comparative advantages of fuel cell technology for electric aviation applications by analyzing the operational mechanisms of different fuel cell types. It also identifies the challenges facing fuel cell development and highlights key areas for future innovation. Research findings indicate that proton exchange membrane fuel cells (PEMFCs) offer high power density and rapid transient response characteristics, making them highly suitable for small regional aircraft. In contrast, solid oxide fuel cells (SOFCs) demonstrate superior fuel flexibility and steady-state efficiency, rendering them ideal for hybrid or long-range flight applications. These discoveries underscore the significance of fuel cell propulsion systems in extending flight endurance, increasing flight frequency, and advancing aviation decarbonization.

**Keywords:** Fuel cells; Electric aviation; Decarbonization.

## 1. Introduction

A fuel cell is an electrochemical device that directly converts chemical energy into electrical energy without combustion. Unlike batteries, it does not store energy but can operate continuously by relying on a fuel supply (typically hydrogen) [1]. Fuel cells offer advantages such as high efficiency, low carbon dioxide emissions, and low noise levels, making them suitable for diverse applications including aerospace, transportation, and portable power sources. The development history of fuel cells can be traced back to 1838 when sir William Groove proposed the principle of fuel cells. In 1889, Langer and Mond began experimenting with coal and natural gas applications under the concept of the “fuel cell.” In 1939, Bacon assembled the first fuel cell [2]. The integration of fuel cells into the electric aviation sector originated with NASA's Apollo program and space shuttle missions, which utilized alkaline fuel cells (AFC) as sources of electricity and water [3]. This initiative established the use of fuel cells in the aerospace field. Subsequently, the United States, Europe, and Japan successively conducted fuel cell unmanned aerial vehicle (FC-UAV) experiments, discovering that hydrogen fuel cells could significantly extend endurance. In 2016, the German Aerospace Center (DLR) unveiled the first hydrogen fuel cell passenger aircraft prototype, the “HY4” [4]. Marked by projects like ZeroAvia and Airbus's ZEROe, fuel cell aircraft have now entered the commercial exploration phase.

Currently, fuel cells are categorized into several types depending on electrolyte composition and operating conditions, such as proton exchange membrane fuel cells, direct methanol fuel cells, solid oxide fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and alkaline fuel cells.

Despite these advances, fuel cells still face a series of challenges: the durability of electrode assemblies remain severely tested, the price of platinum, which is the primary component of catalysts, is too high, and there still exists a series of technical challenges in the production, storage, and

transportation of hydrogen itself. [1, 2]. Overall, these factors constrain the further commercialization of fuel cells. Recent review studies indicate growing interest in applying fuel cell technologies to new domains, including aerospace and aviation [3]. This surge stems from their high efficiency and low emissions, coupled with the environmental drawbacks of traditional fossil fuels. Meanwhile, the development of electric aircraft remains constrained by battery energy density limitations [4]. Consequently, fuel cells are gaining increasing prominence in aviation applications.

A limitation of current research is that most analyses fail to correlate the fundamental principles of fuel cells with actual aircraft mission parameters. This paper focuses on elucidating the operational mechanisms of proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC), emphasizing their electrochemical and thermal performance in relation to critical aviation requirements. Through a multi-faceted comparative approach, it clarifies the advantages and disadvantages of fuel cell applications in aerospace, identifies specific scenarios for different fuel cell types (e.g., PEMFC for short-range aircraft or drones), and proposes potential solutions to current challenges faced by fuel cell technology.

## 2. How Fuel Cells Work

### 2.1. Working mechanism

The main components of a fuel cell system are the anode, cathode, electrolyte, and external circuit (load). Fuel ( $H_2$ ) enters the anode and is decomposed under the action of a platinum catalyst.  $H^+$  migrates through the electrolyte to the cathode, while electrons flow through the external circuit toward the cathode, generating an electric current [5]. At the cathode, oxygen combines with protons and electrons. The electrolyte facilitates proton passage [6]. Through the process, electricity and heat are generated. The specific chemical reactions are shown as follows.



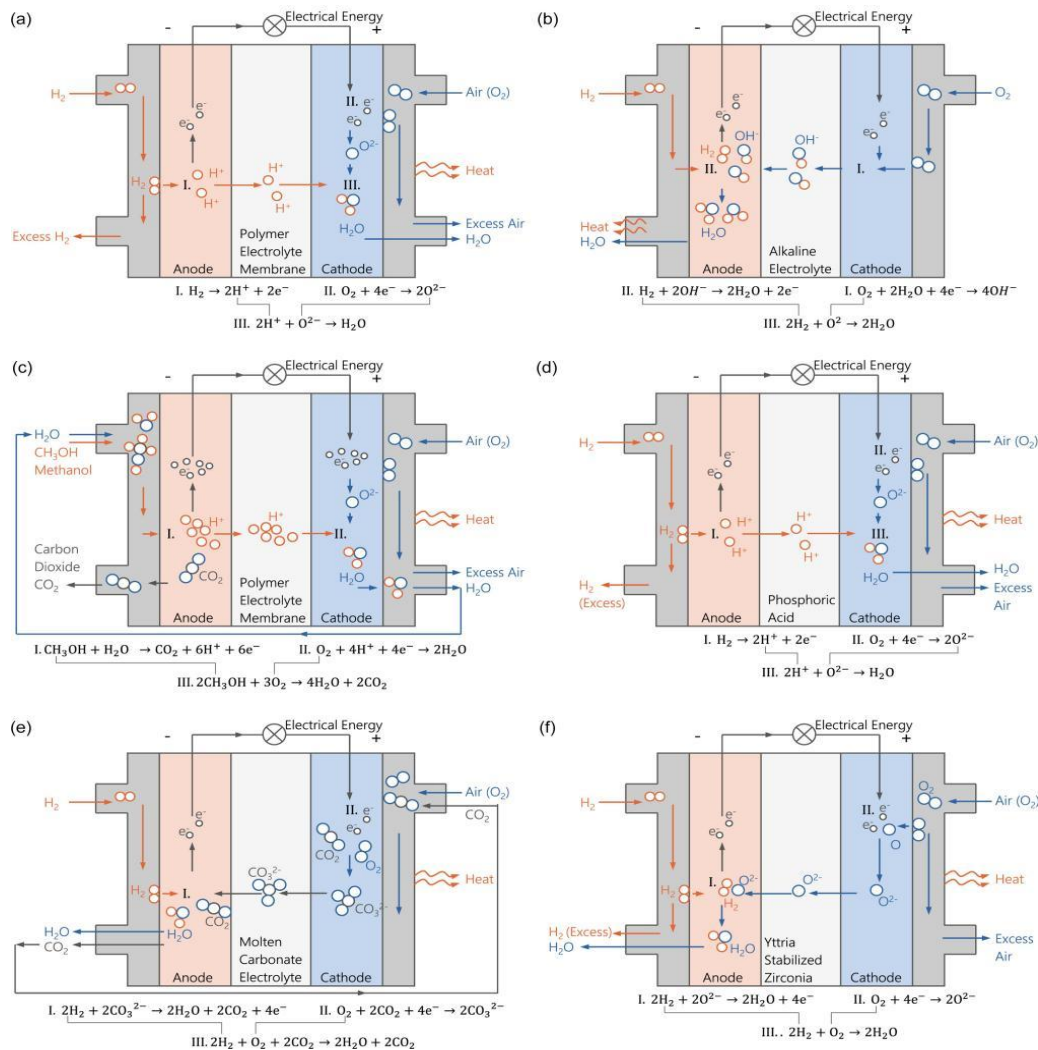
### 2.2. Unique Energy Conversion

Throughout the process, chemical energy is directly converted into electrical energy via electrochemical reactions, by passing the Carnot efficiency limit of thermal engines and achieving a theoretical efficiency exceeding 60% [7]. The byproducts of the reaction are primarily water and a small amount of heat, meeting low-emission requirements. If the hydrogen required for the reaction is produced from renewable energy sources such as solar or wind power, it achieves true zero emissions [6]. As long as hydrogen and oxygen are continuously supplied, electrical energy can be continuously output, enabling uninterrupted operation for extended periods [6, 7].

### 2.3. Categories of fuel cells

Figure 1a illustrates the operating principle of a proton exchange membrane fuel cell (PEMFC). At the anode, hydrogen molecules are dissociated into protons and electrons. Protons are transported through the polymer electrolyte membrane, while electrons flow through the load and generate electrical energy. Oxygen reacts with incoming protons and electrons at the cathode, releasing heat while forming water. Figure 1b illustrates an alkaline fuel cell (AFC). Within the alkaline electrolyte, hydroxide ions ( $OH^-$ ) serve as charge carriers. It combines hydrogen gas at the anode and is regenerated during the reaction between oxygen and water at the cathode. Figure 1c depicts a direct methanol fuel cell (DMFC), which uses a liquid methanol-water mixture as fuel. In the oxidation reaction of the anode, methanol is converted into carbon dioxide, and at the same time, the generated

protons pass through the exchange membrane, while electrons enter the external circuit. They combine oxygen at the cathode to form water. Figure 1d presents a phosphoric acid fuel cell (PAFC). It uses concentrated phosphoric acid as the electrolyte, and the reaction process is roughly similar to that of PEMFC. Figure 1e exhibits a molten carbonate fuel cell (MCFC). Its electrolyte conducts carbonate ions ( $\text{CO}_3^{2-}$ ).  $\text{CO}_3^{2-}$  reacts with hydrogen at the anode to produce  $\text{CO}_2$ . It then combines with oxygen at the cathode to form new  $\text{CO}_3^{2-}$ . Figure 1f illustrates a solid oxide fuel cell (SOFC). Oxygen ions ( $\text{O}^{2-}$ ) are transported from the cathode to the anode through a stable zirconate electrolyte. Finally, they react with hydrogen to form water and release electrons. The electrons are accepted by oxygen at the cathode, and new  $\text{O}^{2-}$  is released.



**Fig 1.** Electrochemical operation of six primary fuel cell  
 (a) PEMFC (b) AFC (c) DMFC (d) PAFC (e) MCFC (f) SOFC [7].

Table 1 lists specific values for the six fuel cell types, including operating temperature, efficiency, and power density [1]. They differ in operating temperature, the type of ions transported, and the fuel used. In AFC, hydroxide ions migrate through an alkaline aqueous electrolyte, achieving high efficiency but requiring an oxidant stream free of carbon dioxide [7]. PEMFC and HT-PEMFC represent low-temperature and high-temperature proton exchange membrane fuel cells, respectively [7]. The low-temperature variant offers high power density and rapid response characteristics, while the high-temperature version exhibits greater tolerance to carbon dioxide and superior thermal integration capabilities. PAFC utilizes liquid phosphoric acid as the electrolyte, enabling operation at moderate temperatures but sacrificing power density for enhanced durability [8]. SOFC and MCFC operate at high temperatures by transporting oxygen ions or carbonate ions, respectively. They enable internal reforming of hydrocarbons and achieve exceptionally high steady-state efficiencies, though they exhibit slower startup times and present greater material challenges.

**Table 1.** Specific values for the six fuel cell types [1, 7, 8]

<b>Fuel Cell Type</b>	<b>Operating Temp. (°C)</b>	<b>Electrical Efficiency (%)</b>	<b>Power Density (W/kg)</b>
PEMFC (Low-temp.)	60–100	40–50 %	Up to ~1000 W/kg (peak, stack only)
HT-PEMFC	120–180	45–55 %	Higher than LT-PEMFC. ~1000 W/kg possible
AFC	60–90	40–55 %	Moderate, less reported
PAFC	150–200	37–42 %	~400–800 W/kg estimated
MCFC	600–700	60–70 %	~300–600 W/kg (large scale)
SOFC	700–1000	~60 %	<100 W/kg (stack)

Direct methanol fuel cells (DMFCs) are not depicted in the figure because, despite also utilizing polymer electrolytes, they operate by electrooxidizing liquid methanol directly at the anode rather than using gaseous hydrogen or internally reformed fuels. This results in fundamentally different kinetic processes, power densities, and water management compared to the six typical systems shown, which primarily fuel hydrogen or reformed fuels. Consequently, DMFCs are generally regarded as a subcategory of low-temperature proton exchange membrane technology for portable electronics, rather than a mainstream category for transportation or aviation applications.

### 3. Fuel Cells for Aviation

#### 3.1. Comparison of Fuel Cells, Conventional Fuel Systems, and Batteries in Aviation

The table below shows that while traditional internal combustion engines offer significant advantages in energy density and benefit from a global infrastructure, their high emissions and noise levels clearly fail to meet modern aviation's environmental requirements. Batteries provide low emissions and rapid response times but remain constrained by limited range and insufficient energy density. Fuel cells combine the clean emissions and low noise characteristics of batteries with higher energy density and rapid refueling capabilities—properties critical for medium-to-long-range electric aviation. Thus, fuel cells emerge as a promising compromise technology, enabling zero-emission flight with greater range than pure battery systems.

**Table 2.** Comparison of fuel cells and other propulsion systems [1, 5, 8, 9].

<b>Feature/System</b>	<b>Fuel Cell</b>	<b>Internal Combustion Engine</b>	<b>Battery</b>
Energy Conversion Efficiency	40–60%	20–35%	70–90% (only as storage)
Emissions	main product is water	CO <sub>2</sub> , NO <sub>x</sub> , SO <sub>x</sub>	Zero at point of use; possible CO <sub>2</sub> during charging depending on grid
Fuel Source	H <sub>2</sub> , natural gas, methanol	Fossil fuels	Grid electricity (dependent on source)
Noise	Low	High(combustion, mechanical friction)	Low
Response	Fast start-up, good dynamic response	Slow start, sluggish transients	Fast response, but endurance limited
Endurance	High (fast refuelling)	High (high energy density)	Limited by battery capacity
Renewable Integration	Compatible with wind/solar via hydrogen production	Dependent on fossil fuels	Grid stability dependent
Maintenance Cost	Low (few moving parts)	High	Low
Lifetime	Long (can reach tens of thousands of hours)	Medium (mechanical wear)	Capacity fade over time, limited lifespan

### 3.2. Key Requirements for Electric Aviation and Fuel Cell Compatibility

Electric aviation imposes demands on the performance and safety of propulsion systems. Propulsion units must possess high energy density to support takeoff, climb, and extended range, while maintaining overall mass efficiency [10]. They require rapid dynamic response for in-flight thrust control, and fast charging capability is essential for sustaining continuous operation in electric aviation. The system must also demonstrate robust environmental adaptability, maintaining reliable performance under high-altitude low-pressure conditions, low humidity, and extreme temperature fluctuations. Long service life and durability, coupled with economic viability, are equally critical to ensuring competitiveness against conventional propulsion systems [11].

**Table 3.** Comparison of fuel cell Types for electric aviation [7, 8].

Type	Key Advantages	Main Drawbacks / Risks
PEMFC	High power density Rapid response Lightweight Fast refueling	Water management Impurity sensitivity Heat rejection
HT-PEMFC	High temperature CO tolerance Wide thermal window	Lower power density Durability validation
SOFC	High efficiency Fuel flexibility Cruise advantage	Slow start-up Thermal stress Heavy insulation
AFC	Low temperature High efficiency Reduced Pt loading	CO <sub>2</sub> sensitivity Complex purification
PAFC	Durability Moderate CO tolerance	Low power density Heavy High operating temperature
MCFC	High efficiency Multi-fuel	Heavy Vibration-sensitive Worst transient

Based on the evaluation of the table content, PEMFCs are most suitable for small and regional commuter aircraft. Their fuel cell stacks can achieve specific power outputs of up to several hundred kilowatts per kilogram, combining high power density with instantaneous response capabilities [7]. Demonstrations of PEMFC systems exceeding 200 kilowatts have shown that startup and shutdown can be completed within minutes, proving their dynamic performance surpasses that of conventional turbines. HT-PEMFCs, operating at 120–180 °C, further alleviate water management challenges through dry-film operation while enhancing tolerance to carbon monoxide impurities. This broadens the operational temperature range and reduces thermal fluctuation risks associated with altitude variations.

In contrast, while SOFCs suffer from slow startups and high thermal retention requirements, they exhibit distinct advantages during steady-state cruise phases. Operating at 600-800 °C, SOFCs routinely achieve electrical efficiencies exceeding 60%. Their ability to reform fuels like liquefied natural gas (LNG) or methanol provides significant logistical flexibility for long-endurance or medium-to-large aircraft platforms [7, 8].

Other fuel cell types remain limited in primary aviation propulsion. Alkaline fuel cells (AFC) offer high efficiency and rapid response but require CO<sub>2</sub>-free oxidant streams due to extreme sensitivity to carbon dioxide contamination [8]. Their complex purification processes are difficult to integrate into aviation applications. PAFCs and MCFCs offer durability and fuel adaptability advantages, respectively. However, their low power density, heavy system weight, and requirement for high-temperature operation make integration into weight-sensitive aircraft systems challenging.

Consequently, these technologies find more practical applications in auxiliary power units or stationary equipment rather than as primary propulsion sources.

#### **4. Challenges and Potential Innovation of Fuel Cells**

Although fuel cells are widely regarded as a core technology for achieving low emissions and high efficiency in aviation, they still face several challenges and require improvements in certain areas before large-scale deployment. This section summarizes recent reports and projects to present the most significant challenges currently facing fuel cells in the field of electric aviation, along with the corresponding technological solutions under development.

##### **4.1. Cost and Key Materials**

One persistent challenge is the high cost of platinum group metals used as catalysts. As noted by Kazura et al., significantly reducing platinum group metal content determines the cost of achieving the required power for regional aircraft [7]. Two potential solutions currently exist: one involves reducing platinum usage through catalyst structure optimization. SINTEF developed an ultra-thin PEM membrane (reduced from the conventional  $\sim 15\ \mu\text{m}$  to  $\sim 10\ \mu\text{m}$ ) and optimized platinum loading within the catalyst layer. This innovative thin-film catalyst maintains nearly identical performance to standard membrane types while reducing total platinum content by approximately 62.5%, significantly lowering catalyst costs and enhancing material sustainability. Another approach involves identifying non-precious metal alternatives to platinum or platinum alloys. Nanocarbon materials such as carbon nanotubes and graphene can serve as catalyst supports or be modified through doping with heteroatoms like nitrogen or sulfur to function as direct catalysts [12]. The advantages of these platinum-free (or extremely low-platinum) catalysts include low cost, good electrical conductivity, and improved corrosion resistance and CO tolerance [12, 13]. However, carbon materials exhibit inherently lower catalytic activity than Pt for hydrogen oxidation reactions, and their stability under high potentials and strongly oxidizing conditions remains a challenge.

##### **4.2. Durability**

Another major challenge is ensuring a long operational lifespan under extreme conditions. In proton exchange membrane fuel cells, conventional perfluorosulfonic acid (PFSA) membranes degrade at high potential, generating free radicals that attack membranes like Nafion, leading to decreased proton conductivity. Cyclic start-stop operations or low-humidity, low-temperature environments exacerbate this degradation—conditions frequently encountered during high-altitude flights [7, 14, 15]. Nature Communications Materials 2025 describes an innovative modification where water-soluble fullerene derivatives and cerium ions are incorporated into Nafion membranes. This enhancement increased membrane durability by over tenfold during accelerated stress testing [14]. RSC CrystEngComm 2025 summarizes how  $\text{CeO}_{2-x}$  nanoparticles rapidly react with ROS (reactive oxygen species, including free radicals) via oxygen vacancies between  $\text{Ce}^{3+}$  and  $\text{Ce}^{4+}$  ions, thereby reducing degradation of membranes and catalytic layers [15].

##### **4.3. Fuel purity, storage, and infrastructure**

Hydrogen itself presents numerous challenges as a fuel. Proton exchange membrane fuel cells are highly sensitive to contamination from carbon monoxide and sulfur, while alkaline fuel cells are extremely vulnerable to carbon dioxide in ambient air. Maintaining high hydrogen purity in large quantities within airport environments or even during flight operations is no simple task [16]. Furthermore, hydrogen storage imposes significant weight and volume burdens. Storing compressed gas (350-700 bar) inevitably increases costs, and high-pressure cylinders require thick composite walls, adding to storage weight and space requirements [16]. Liquid hydrogen storage offers advantages in volumetric density but faces challenges such as cooling and thermal insulation losses. The stringent purity and storage requirements for hydrogen necessitate more sophisticated infrastructure. In response, the International Energy Agency and other organizations have proposed

phased planning approaches for airport hydrogen production, storage, and refueling systems, including standards for leak detection and crash safety.

## 5. Conclusion

This review analyzes the fundamental principles of major fuel cell types and evaluates their applicability in electric aviation. Findings indicate that PEMFCs offer superior power density and response speed, making them particularly suitable for small and regional aircraft. HT-PEMFCs complement PEMFCs by expanding thermal management ranges and enhancing CO tolerance. Meanwhile, SOFCs achieve the highest steady-state efficiency among fuel cells, making them more suitable for hybrid or long-range missions. Other fuel cell types such as PAFC, MCFC, and AFC are limited to ground-based auxiliary applications due to CO<sub>2</sub> sensitivity, low power density, or excessively high operating temperatures.

Beyond these direct conclusions, several overarching patterns emerge. First, fuel cell systems for aviation must simultaneously meet extremely stringent requirements for specific power, rapid response, and reliability under low-temperature, low-pressure conditions. Second, the primary barriers to widespread adoption—high catalyst costs, degradation of membranes and electrodes, and hydrogen production, storage, and refueling infrastructure—are interrelated and must be addressed at the system level rather than in isolation. Third, comparisons between Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC) indicate that no single technology can fulfill all mission requirements. Instead, selecting appropriate fuel cell types based on flight phases and integrating them with batteries or turbines for hybrid propulsion appears the more realistic short-term path for fuel cells in electric aviation. Based on these insights, several recommendations emerge. Cost and weight reduction can be achieved by minimizing platinum group metals through thin films, nanostructures, or non-precious metal catalysts. Introducing various radical scavengers can extend durability under cyclic aviation conditions. For hydrogen, coordinated development of airport-scale green hydrogen production, cryogenic or high-pressure storage, and safety standards is critical to ensuring supply, purity, and operational turnaround times. Finally, integrating fuel cell stack techno-economic modeling with aircraft mission analysis can guide the achievement of realistic performance targets and certification pathways. Overall, systematically addressing these challenges positions fuel cell propulsion as a compelling pathway toward aviation decarbonization and highly efficient flight.

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