

# Development of Fuel Cell Technology and Applications: A Review

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**Abstract:** Fuel cell technology is considered one of the most important solutions for clean energy, characterized by its high efficiency, minimal pollution, and adaptability across various sectors such as transportation, stationary energy, and portable electronics. Over the past two decades, significant progress has been made in materials science, system design, and cost optimization, enhancing the feasibility of commercialization. This paper follows the development of various types of fuel cells, including Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), Direct Methanol Fuel Cells (DMFC), Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cells (MCFC), and Alkaline Fuel Cells (AFC), highlighting key innovations and market launches. The review emphasizes significant technical challenges, particularly concerning durability, catalyst degradation, and hydrogen infrastructure systems. Additionally, it outlines the existing state of fuel cell technology and proposes a strategy for integrating fuel cells into global low-carbon energy systems. From a decarbonization perspective, incorporating fuel cells into energy systems is crucial, as they not only provide high efficiency but also operate without emitting harmful pollutants. The article reviews advancements in fuel cell technology from 2020 to 2024, comparing performance metrics

with market applications and obstacles to market entry. Assessments of over 80 peer-reviewed studies indicate that PEMFCs are achieving 0.85 A/cm<sup>2</sup> at 0.6V, while SOFCs are reaching 60% electrical efficiency in combined heat and power (CHP) applications. Currently, most deployments, comprising 62% of market share, are in the transportation sector; however, significant challenges remain in material stability and hydrogen infrastructure. Progress in fuel cell technology hinges on the integration of anion-exchange membranes, platinum-group-metal-free catalysts, and advanced manufacturing capabilities.

**Keywords:** Fuel cells, PEMFC, SOFC, DMFC, AFC, PAFC, MCFC, Clean energy, Applications.

## Introduction

The fuel cell functions as an electrochemical appliance that converts the chemical energy of a fuel, such as hydrogen, and an oxidant into electrical energy, producing only water as a byproduct. Achieving global net-zero carbon targets by 2050 significantly depends on advanced clean energy technologies, with fuel cells expected to play a vital role. Fuel cells are categorized based on the type of electrolyte used, including Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), Alkaline Fuel Cells (AFC), and Direct Methanol Fuel Cells (DMFC). Each type operates at varying temperatures and has distinct efficiencies and applications. Over the past decade, government policies, technological advancements, and the development of a hydrogen economy have accelerated the commercialization of fuel cells. PEMFCs are particularly favored in transportation due to their rapid start-up times and high power density, whereas SOFCs are more appropriate

for stationary and industrial uses owing to their efficiency at high temperatures and versatility with fuels. Recent innovations include the development of non-platinum group metal catalysts, enhancements in membrane durability, and the integration of renewable-fuel cell hybrid systems. The growing market presence of fuel cells is exemplified by applications like the Toyota Mirai and Hyundai NEXO, as well as stationary power solutions implemented in Japan and Germany. Despite this progress, challenges remain, including the need for cost reduction, material degradation, and the establishment of hydrogen infrastructure, which are critical barriers to further development. This review encompasses current research and applications from 2020 to 2024 and anticipates future advancements in fuel cell technology.

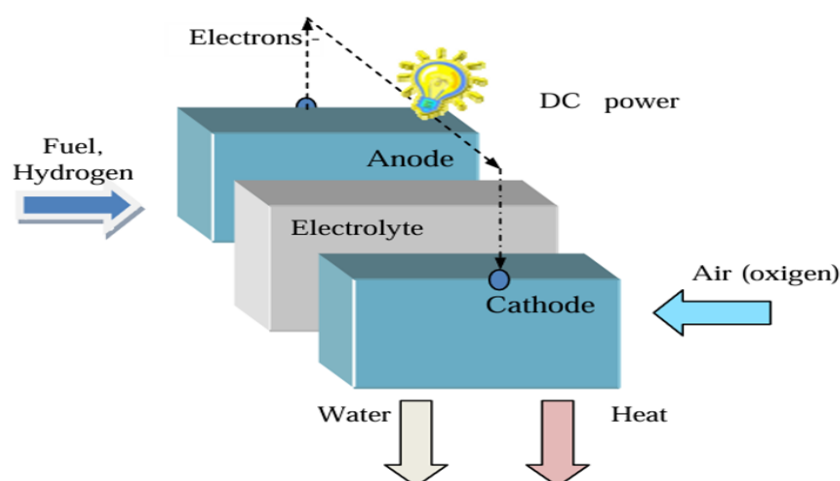
### The Structure of Fuel Cells

In a typical fuel cell, the cathode (positive electrode), where electrochemical processes produce electrical current, receives continuous oxygen and gaseous fuel from the anode (negative electrode) (Fig. 1). The following electrochemical reactions take place in an acid electrolyte fuel cell:

The anodic process produces  $\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$ .

The cathodic process involves  $1/2\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$ .

The complete reaction between  $\text{H}_2$  and  $1/2\text{O}_2$  produces  $\text{H}_2\text{O}$  and heat which is an exothermic process with  $H=-286 \text{ kJ mol}^{-1}$ . The fuel cell operates as a power conversion system with battery-like features yet maintains distinct operational characteristics. The battery functions as an energy storage system because its available energy originates from chemical reactants contained within its structure. The battery stops generating electric energy after the stored biochemical substances are depleted (i.e., a spent battery). The reactants in the secondary battery (fuel cell) receive a continuous supply from external sources. The fuel cell operates as an energy conversion system that can produce electricity indefinitely as long as it receives fuel and an oxidizing agent at its electrodes. Fuel cells have practical operating limitations due to component degradation which includes corrosion and malfunction.



**Figure. 1**

## Advantages and Disadvantages of Fuel Cells

The advantages and disadvantages of fuel cells, in addition to traditional fossil fuel generators, offer many benefits:

1. Advanced thermal, volumetric, and weight effectiveness.
2. Lower chemical, acoustic, and current radiation.
3. Variety of components and flexibility in location.
4. Low maintenance.
5. Flexibility in fuel type (fuel cell-dependent).
6. No production of pollutants.

## Fuel Cells Technologies

Today's market offers a variety of fuel cell technologies. Each of which is distinguished by its energy conversion efficiency ratio, operating temperature range, fuel type, and catalyst type. The following are the primary technologies on the market (Table 1):

1. Proton Exchange Membrane Fuel Cells (PEMFC)
2. Direct Methanol Fuel Cells (DMFC)
3. Alkaline Fuel Cells (AFC)
4. Phosphoric Acid Fuel Cells (PAFC)
5. Molten Carbonate Fuel Cells (MCFC)
6. Solid Oxide Fuel Cells (SOFC)

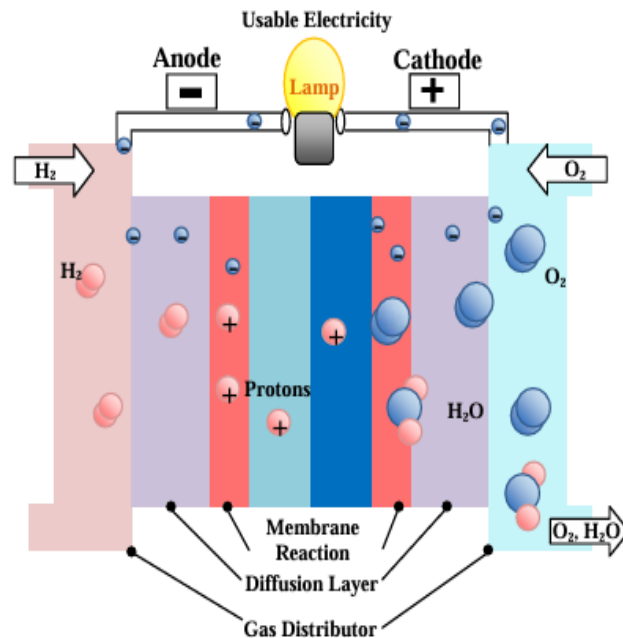
**Table 1: Fuel Cell Types & Characteristics**

Type	PEMFC	SOFC	MCFC	AFC	DMFC
Efficiency	40-60%	50-70%	45-55%	60-70%	30-40%
Temp (°C)	60-80	600-1000	600-700	90-100	60-120
Power Range	1W-100kW	1kW-100MW	300kW-10MW	1-100kW	<1kW
Applications	Vehicles, drones	CHP, power plants	Industrial power	Space, submarines	Portable devices
Advantages	Quick startup, compact	Fuel flexibility, high eff.	Carbon capture ready	High purity performance	Liquid fuel operation

### 1. Polymeric Electrolyte Membrane Fuel Cells (PEMFC)

PEMFCs, or proton exchange membrane fuel cells, are extremely effective and eco-friendly energy conversion technologies that are crucial to the energy economy of the future. By oxidizing hydrogen and reducing oxygen on an appropriate catalyst, fuel cells enable the conversion of fuel's chemical energy into electrical power with only heat and water as byproducts. The proton exchange membrane, which separates the fuel (H<sub>2</sub>) from the oxidizing agents (air or oxygen), is made of a substance that allows hydrogen ions to move across the membrane layer. PEMFCs

run at temperatures between 60°C and 80°C. Additionally, these cells have a low operating temperature, which causes them to start rapidly (i.e., have a low warm-up time). This reduces the amount of time that system components must operate, allowing the cell to run for longer periods of time.



**Figure 2.** structure of a PEMFC

## PEMFC Applications

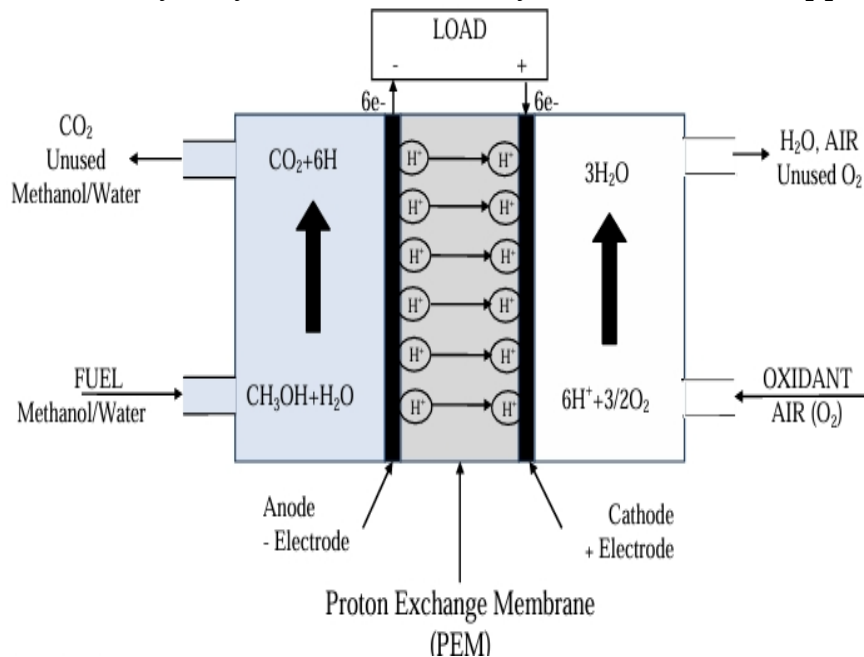
PEM fuel cells operate at power outputs ranging from a insufficient watts to hundreds of kilowatts. This technology enables applications in any case where electricity needs to be produced locally. Testing of PEMFC fuel cells has begun in various applications including cars, buses, public vehicles, bicycles, and aerospace/military fields (such as shuttles and submarines). PEMFC fuel cell testing continues for discrete generation of power in houses, establishments, and facilities because of their modular design and flexibility in power supply capabilities. PEMFC fuel cells utilized in various needs require different configurations that adapt to their characteristics to meet the needs of diverse operating environments. This document reviews the three main atmospheres for PEM fuel cell applications which include: -

- a. Transport (up to 70 kW);
- b. Stationary power applications (up to 500 kW);
- c. Portable power applications (up to a few kilowatts)

## 2. Direct Methanol Fuel Cells (DMFC)

The ion-exchange polymer membrane is the core of straight methanol fuel cells. What is currently utilized in membranes is Nafion, just as in proton argument membrane fuel cells (PEMFCs). These sites play the role of proton exchange sites because they possess strongly ionic properties. This arrangement is similar in

PEMFCs: the cathode faces the anode, and both layers consist of a three-layer structure, one catalyst layer, one diffusion layer, and the third support layer. Fig (3)



### DMFC Characteristics and Applications

(DMFCs) are a kind of fuel cell that has been developed to be smaller in size, as they inject fuel directly into the air and operate at low temperatures. Moreover, due to their nearly similar characteristics resulting from their composition, DMFCs also belong to soft technology and are environmentally compatible. These cells have the additional advantage of operating on methanol, which is easier to supply and yield than hydrogen, and does not pose an explosion risk like hydrogen does. Given their compact size, low operating temperature, and high fuel tolerance, DMFCs are an attractive power source for portable devices and power generators. (20).

### 3. Alkaline Fuel Cells (AFC)

The first alkaline fuel cells and how they were utilized: Alkaline fuel cells are considered the first kind of fuel cells utilized in missions, chronologically. The aerospace industry has developed many other technologies, in addition to silicon MMICs, due to the extensive service temperature requirements involved. However, the focus here was on developing a power source to feed spacecraft. There are multiple types of alkaline fuel cells that vary in operational temperature ranges, although the technology can generally operate within a temperature range from 30°C to 250°C (even down to -20°C for alkaline fuel cells used in space applications). KOH (potassium hydroxide solution) is the electrolyte for alkaline fuel cells, which are supplied with hydrogen. Because CO<sub>2</sub> (300 parts per million) in the air carbonates the electrolyte, the oxidant must be 100% oxygen and not air. Each cell produces an output voltage between 0.5 and 0.9 volts (Fig 4).

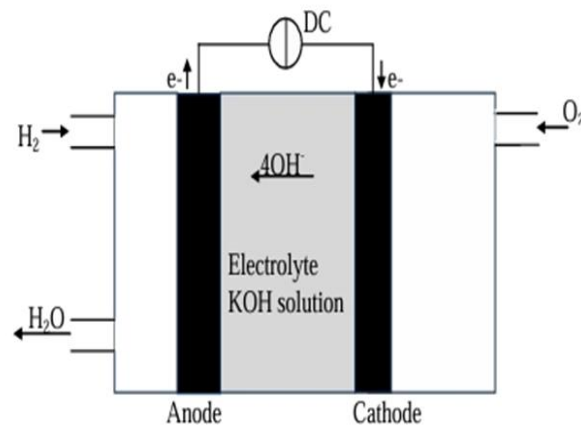


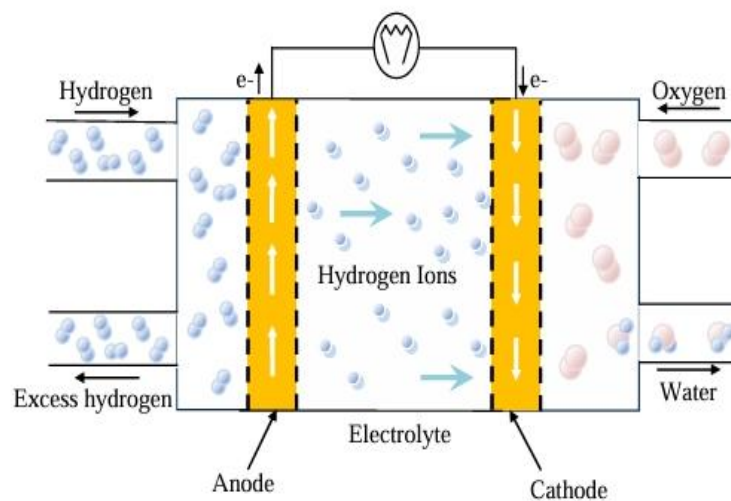
Figure 4. Structure of an AFC

### Alkaline Fuel Cell Applications and Characteristics

- a. To sum up, alkaline fuel cells have several advantages:
- b. A wide range of operating temperatures.
- c. High ease of cell structure.
- d. Fast start-up.
- e. Simple material construction leads to affordable cost
- f. The ability to achieve electrical efficiency of up to 65% (which is a high rate for cold fuel cells).
- g. A lifespan ranging from 10,000 to 15,000 hours attributed to the well matching cell fabrication (however, lifespans of up to 40,000 hours are needed for the full commercialization of fuel cell knowledge). Alkaline fuel cells are therefore more affordable and effective than PEM fuel cells. Electrolyte poisoning by carbon dioxide is the reason alkaline fuel cells aren't taking the lead in the fuel cell industry (19).

#### 4. Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid fuel cells (PAFCs) were the first fuel cells to be sold, but AFC-type fuel cells were the first to be used in energy applications. They were being tested in the field by the 1970s after being developed in the middle of the 1960s. All indicators of this kind of cell's cost, performance, and stability have steadily improved in recent years. Phosphoric acid ( $\text{H}_3\text{PO}_4$ ) serves as the electrolyte in a PAFC, and because of its low ionic conductivity, the cell can function best at temperatures between 150 and 220 degrees Celsius. Consequently, PAFCs are no longer low-temperature, cold-start fuel cells. Hydrogen is the fuel that the cell always requires, although it need not be pure because of the large temperature range that exists inside these cells. Since any kind of fuel reforming technology that generates hydrogen in significant amounts can be used to feed the cell with reasonably impure hydrogen, this presents (21) (see Fig 5).



**Figure 5.** Phosphoric Acid Fuel Cell (PAFC)

### Phosphoric acid fuel cell characteristics and applications

PAFC fuel cell technology has the best reliable performance record among all fuel cell technologies, with more than 400 systems installed globally (most of which are units with electrical capacities ranging from 100 kW to 400 kW), although most have only been installed in the United States and Japan. In Japan, the number of installed PAFC stations exceeds 150, with sizes ranging from 50 to 500 kW and from 1 to 5 MW. The largest prototype PAFC station (with a capacity of 11 MW) has been operating since 1991 at the Tokyo Electric Power Company's thermal power station in Guay, which is also located in Japan. With information gathered from all these applications, PAFC is considered the most advanced technology in the market with the following characteristics:

- A lifetime exceeding 65,000 hours and an operating temperature ranging from 150 to 220 degrees Celsius.
- Maximum electrical efficiency reaching up to 40%, which increases using integrated heat systems to up to 60%.
- Partial immunity to carbon monoxide poisoning (not immune if they are present).

### 5. Molten Carbonate Fuel Cell (MCFC)

High-temperature fuel cell technology in the shape of molten carbonate fuel cells (MCFCs) is currently becoming increasingly popular as a means of producing electricity or as a supplement to other stationary power generation applications, e.g., for use in certain industrial buildings or coal-fired power plants. An alkaline carbonate salt is used as the electrolyte in MCFCs, which are high-temperature transport gas-operated fuel cells that can withstand temperatures of as much as 650 degrees Celsius. With waste heat recovery efficiency, MCFC efficiency can be

enhanced to 45% and reach as high as 60–70% in the long term. When running as fuel cells, MCFCs can run on gases like methane, natural gas, or gases from reformed coal because of their temperature. The temperature does make them face a line of problems, though, such as the quick weakening of the cell structure because of wear and mechanical problems and additional peeling throughout the electrochemical process because of evaporation within (22).

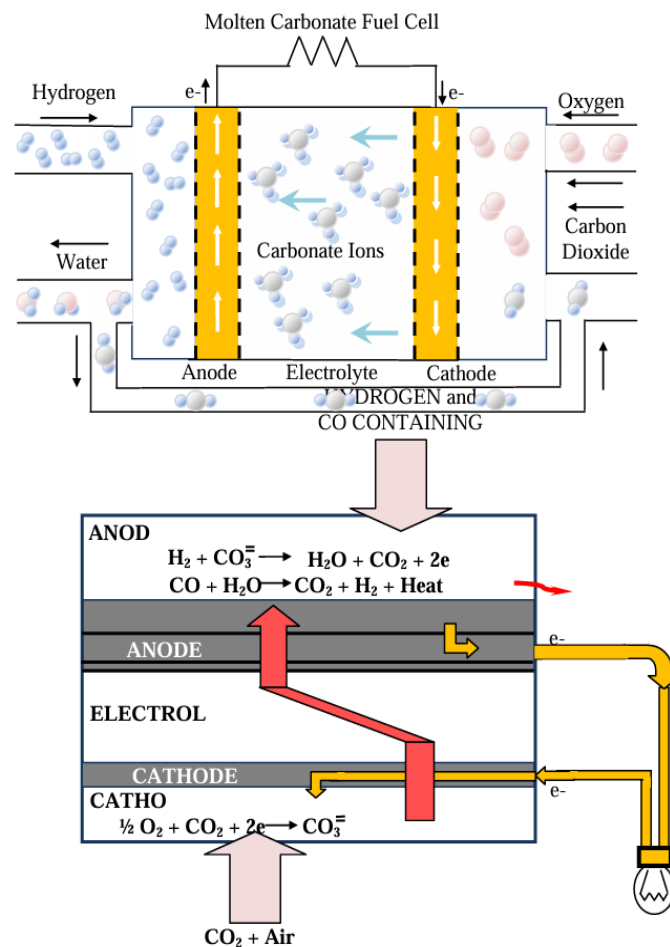


Figure 6. MCFC structure

### Characteristics and Applications of Molten Carbonate Fuel Cell

At present, large molten carbonate fuel cells (MCFC) have emerged in several countries, e.g. the United States, Japan, South Korea, and Germany. The applications to be demonstrated will range in power generation from 125 kilowatts to 1 megawatt. This technology has the following strengths: - The efficiency of ceramic alkaline fuel cells can reach up to 45%, producing large amounts of high heat and steam, and if applied with a combined cycle system, the efficiency of ceramic alkaline fuel cells can be increased to more than 50%-60%. - Ceramic alkaline fuel cells canister usage a variety of hydrogen-rich fuels such as natural gas or coal gases, and an external reactor is not required if fuel reforming is

done inside the cell. These characteristics help significantly reduce the cost of power generation. - The ability to use low-cost and industrial resources such as stainless steel and nickel blends leads to a significant decrease in the costs of building the cells.

## 6. Solid Oxide Fuel Cell (SOFC)

Other extraordinary temperature fuel cell technologies, developed for stationary power requests at scales ranging from residential to mw, include Solid Oxide Fuel Cells (SOFC). The SOFC operates at the temperature of 800 °C to 1000 °C. Due to high functioning temperatures and fuel improving process taking place directly inside the cell, various fuels with hydrogen (such as coal gas, biogas, propane, natural gas, hydrogen) can be applied. SOFCs have high energy conversion efficiency, approaching 60%, durable long term degradation behavior, and high thermal efficiency. This is because there is a very high quality of waste heat which can be used under pressure, leading to an integrated heat system from gas turbines, where sheer efficiency can in theory push electrical yield to 80%. The high temperature also brings another benefit that the air could start electrochemical reaction without considering noble metals used as catalyst. This significantly reduces sustainable costs. (23).

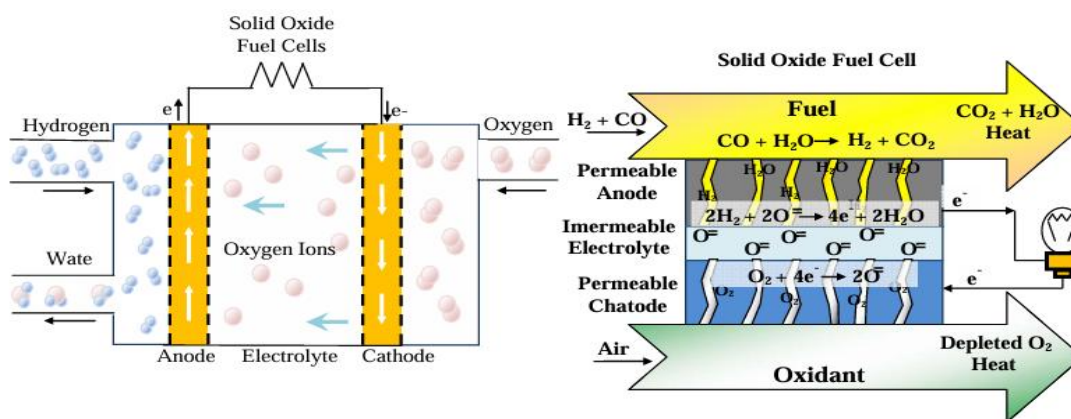


Figure 7. SOFC structure

## Solid Oxide Fuel Cells Characteristics and Applications

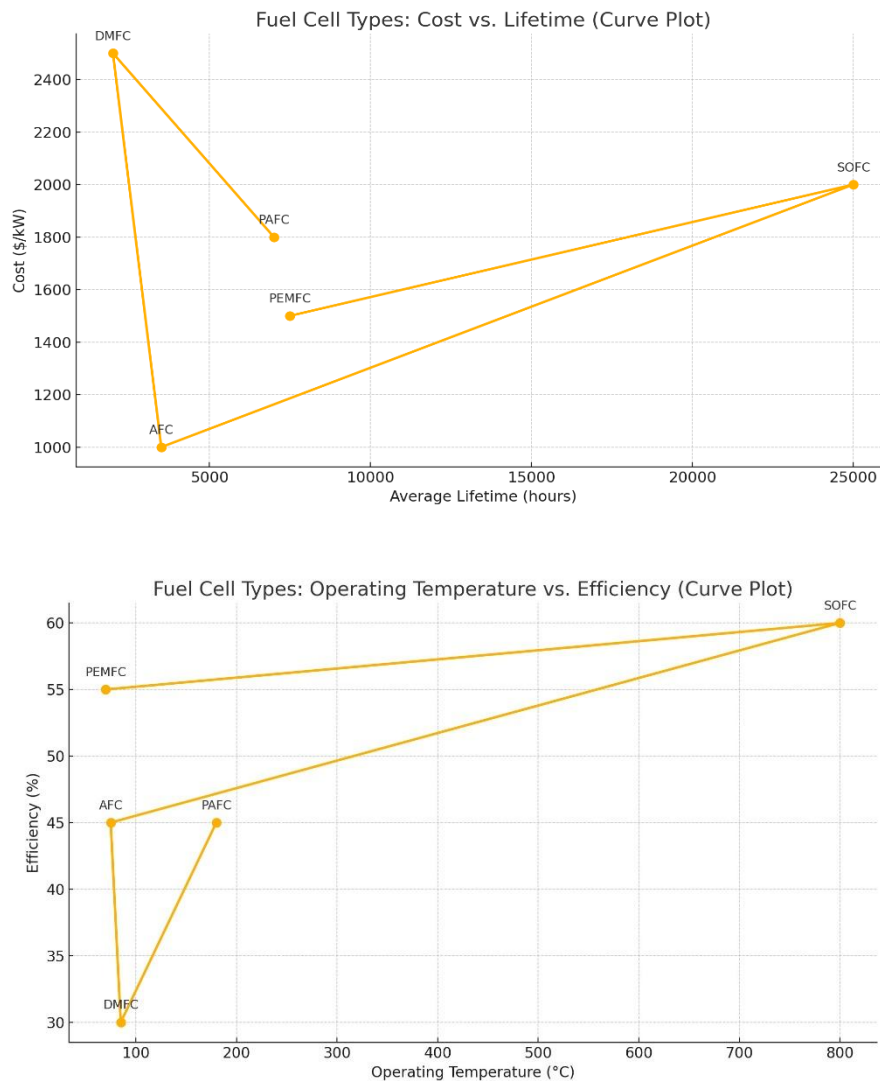
Solid oxide fuel cells (SOFCs) are a kind of stationary fuel cells categorized by high efficiency and high energy density. In comparison to other technologies, SOFCs benefit the following virtues:

- Highest electrical and current effectiveness (up to 80% in combined heat systems) among all fuel cells.
- Avoiding costly substances like catalysts.
- Can utilize various types of low-cost hydrocarbon fuels (natural gas, biogas, coal gas);

- d. Long operating life due to low chances of degradation of cell supplies.
- e. The simplified structure allows for fully automated procedures.
- f. Limited radiation of NO<sub>x</sub> and SO<sub>x</sub> when feeding the cell with hydrocarbon fuel. (24).

### Comparing the recital and applications of different fuel cell types

Here is the curve plot connecting the cost and lifetime data for different fuel cell types. Each point is labeled with the corresponding fuel cell type.



**Figure 8.**

Here is the curve plot showing the relationship between operating temperature and efficiency for various fuel cell types, with each point labeled.

### Future direction of fuel cell science and technology

In light of rising oil prices, the depletion of oil wells, the lack of new well discoveries, and the decline in hydrogen infrastructure, the development and application of fuel cell technology relieve this. Concerns about environmental pollution and the damage caused by

emissions from cars, thermal power stations, and oil refineries will accelerate the development process, unless users and manufacturers can see financial benefits if the costs of damage caused by pollution are lower. The hydrogen infrastructure refers to the existence of systems, rules, and other regulations established to support the production, transportation, and distribution of hydrogen, in addition to personal use of hydrogen and fueling vehicles, whether they are of type 1.5.4.3 or similar types of fuel (alcohols, esters, natural gases, naphtha, synthetic gases, including carbon-containing synthetic gases/materials, which are fed to fuel cells without prior reforming or to a fuel treatment station). For other sources, hydrogen and alcohol are obtained from renewable energy sources with potential value (wind energy, solar energy in water electrolysis, biomass gas, and fermentation). In the latter case, greenhouse gas emissions are low and insignificant. To the extent that one can hope for no emissions from vehicles and stationary power plants except for biomass gas. The former will prevent cities from being exposed to any pollution caused by cars (which is produced centrally), which is a byproduct of vehicles powered by internal combustion engines. It is worth noting that among all advanced options, hydrogen fuel cell vehicles and hybrid hydrogen vehicles are the least harmful to the environment. Considering that the pollution from hydrogen extracted from natural gas processing is equivalent to 1/8 of the costs of gasoline vehicles with internal combustion engines today, without CO<sub>2</sub> capture, and one-fifteenth of its costs if CO<sub>2</sub> capture technology is used. While current economies do not favor vehicles powered by proton exchange membrane fuel cells (PEMFC) and stationary power plants based on solid oxide fuel cells (SOFC) due to a lack of hydrogen infrastructure, it is expected that by the time crude oil prices rise, and we experience a shortage of new oil or gas reserves, fuel cell units will be more efficient, the operating costs of fuel cells will significantly decrease, and there will be a much better hydrogen infrastructure in place (regardless of the cost savings from reduced gas emissions) such that both fuel cell vehicles (FCV) and distributed power generation from fuel cells will be profitable. Bright dreamers estimate that by 2020, we will have 20% of the global fuel cell vehicles, 10% of home energy generation via fuel cells, and half of portable appliances operated via fuel cells.

## Conclusion

As evident from the previous chapters, there are various fuel cell technologies, each with its strengths and weaknesses. Each technology is applicable to specific application scenarios, and there are multiple issues hindering their broad marketing effectiveness. However, there are four technologies that have garnered significant attention due to their probable for specific applications and the development stage of the associated power plant types, which possess the best prospects for widespread marketing in the near future. These are solid oxide fuel cells (SOFCs), phosphoric acid fuel cells (PAFCs), direct methanol fuel cells (DMFCs) and polymer electrolyte membrane fuel cells (PEMFCs). In terms of all other applications, the first two technologies—distributed energy generation, mobile, and all applications pertaining to the mobility and automotive sectors—are undoubtedly the ones that most people around the world are concerned about. However, that is only possible

with a suitable hydrogen production and distribution network (as well as practical solutions for hydrogen storage safety). Out of all the technologies, the two and three might be the best suited for stationary energy applications. Actually, the three main advantages of this technology remain: adaptability, fuel cell longevity, and efficiency. This comparative article in fuel cell technologies: aims to be a good work instrument for all our (publications) and organic search researchers, and technicians interested on fuel cell topic: an important field that is an integrated part of diffusion of knowledge updated that has opened an era of new technologies from the laboratory research to the true industry.

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