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A Case Study on Fuel Cell Technologies: Classification, Working Mechanisms, and Applications

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Abstract:
Fuel cells are electro-chemical devices that directly convert the chemical energy of a fuel into electrical energy. They are regarded as one of the vital alternatives for conventional energy sources due to their high efficiency, low emission and potential in sustainable energy development. This study discusses the case of Fuel cells including definitions, types, working principle, merits and applications. The background of energy and environment in the world, the function of hydrogen as energy carrier and the history of development of fuel-cell technology are also discussed. During operation, fuel (typically hydrogen) is fed to the anode, and oxygen or air to the cathode. The reactions generated force the electrons to pass through an external circuit where electricity is generated, while water and heat are generated as by-products. It is not like in the conventional power generation, which uses combustion, which limits the efficiency of heat engines and is subject to emissions of harmful pollutants. These fuel cells can generate power continuously as long as fuel is provided, and have high energy-conversion efficiency, operate quietly and with less air pollution. They are employed in transportation, stationary power generation, backup power systems, portable electronics and space applications. Fuel cells can be used in small or large applications, from the few watts for portable power to the several megawatts for power plants. For widespread use, however, costs at the outset, the storage of hydrogen, the supply of hydrogen fuel, durability, and the supply of clean hydrogen must be resolved. This study focuses on the importance of fuel-cell technology in the modern era of energy systems and the ability of fuel cells in minimizing fossil fuel dependency. It also underscores the contribution of fuel cells in the integration of renewable energy and the creation of cleaner transportation and power generation technologies. The study demonstrates that with affordable manufacturing processes and appropriate infrastructure, fuel cells are a technology with significant potential for contributing to a more efficient, reliable and environmentally friendly energy future.

Keywords: Fuel Cells, Renewable Energy, Electrochemical Reaction, Clean Energy, Sustainability.

1. Introduction

1.1 Fuel Cells at a Glance

A fuel cell is an electrochemical device in which the chemical energy of a fuel, typically hydrogen, is directly converted to electricity. If pure hydrogen is used the by-products are only water and heat. Since the fuel is not combusted, a fuel cell does not incur the large losses experienced by conventional heat engines, and can run as long

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as fuel and oxidant are added. All these characteristics make the fuel cell one of the best prospective technologies for clean and efficient generation of power in the twenty-first century[1].

Fuel cells have already been applied in various applications. They have powered passenger cars, buses and trucks, provided backup power to telecommunication towers and data centres, powered buildings through CHP, and been flown on manned space missions for over 50 years. They can be scaled from a few watts in a portable system to several megawatts in a power plant, by varying the number and size of the cells in a stack[2].

The systematic analysis of fuel cell technology is presented in this case study. The later part of the book talks about various types of fuel cells, their working and how they work, advantages and applications. This introduction sets the scene for them. It details the need for Fuel Cells, the integration of hydrogen and renewable energy, the evolution of Fuel Cell technology over almost 200 years and what problems lie ahead of further adoption.

1.2 Energy and Environmental Background

The world's need for energy has been steadily increasing since the Industrial Revolution, as a result of population growth, urbanization and an increase in living standards, and the majority of this energy demand is still being supplied through combustion of coal, petroleum and natural gas. These fuels are limited in supply, unevenly distributed and subject to geopolitical tensions in price. In a country with rapid development like India, where the crude oil import rate is high, energy security becomes a national concern[3].

Also, the conversion of fossil fuel to useful work is inefficient. The chemical energy of the fuel in a thermal power plant is first converted into heat, this heat is used to convert water into steam, this steam is used in a turbine, and this turbine is used in a generator. Each step suffers losses and the efficiency is typically between 30 and 40 percent. In the case of a petrol car, only one in three of the car's fuel is transferred to the wheels. These limits are fundamental restrictions on thermodynamics of the heat engines, and they cannot be surmounted by improved engineering solutions alone. Any method that doesn't involve the heat engine really has the potential to save fuel[4].

When they burn, they produce carbon dioxide, the primary greenhouse gas responsible for climate change caused by human activity, that contributes to increased temperature, melting ice, sea level rise and increasing extreme weather events. It also produces oxides of nitrogen and sulphur, carbon monoxide, unburnt hydrocarbons and fine particulate matter which contribute to smog, acidity, heart and respiratory diseases. This pollution is a significant source in urban areas by road transport. The goal of the Paris Agreement and many countries have a net-zero target of global warming of well below 2 degrees Celsius. They require renewable energy, greater efficiency, electrification, new approaches to energy storage and delivery and fuel cells are a critical component here.

1.3 Hydrogen and Renewable Energy

The potential for solar and wind energy is vast, their emissions are negligible and they have become much cheaper in the last ten years. Their production, however is not consistent. The sun does not always shine and the wind does not always blow steadily, thus there are times when supply is not equal to demand. While large-scale deployment of renewables requires storage, battery storage is a challenge to implement for long-term energy storage or for heavy transportation, shipping and industry. Chemical energy carriers are able to store energy with high density, transport it over long distances and store it for months. Hydrogen is considered one of the most attractive of them[5].

Hydrogen storage and transport are a technical challenge. The highest concentration of hydrogen is in the form of a strongly compressed gas, at pressures of 350 to 700 bar, or in the form of a liquid, which is also stored under pressure, at approximately minus 253 degrees Celsius.

What is necessary is then a device that will efficiently and cleanly convert the hydrogen back into electricity, and that's where the fuel cell comes in. Green hydrogen and fuel cells are one of the most clean energy supply methods that can be used for energy transport to vehicles, buildings and industry, and form the basis of the envisioned hydrogen economy.

1.4 The Fuel Cell: Basic Concept

A fuel cell is composed of three parts: an anode, a cathode and an electrolyte sandwiched between them. A fuel (typically hydrogen) is fed into the anode and an oxidant (typically oxygen from air) is fed into the cathode. The electrolyte allows the ions to move but not the electrons or the reactants. The electrons thus have to pass through an external circuit and this current of electrons is what is useful as an electric current. The ions, electrons and oxygen

unite to create water at the cathode. The working and principle of operation explains the detailed reactions of each type of cell[6].

A fuel cell and a heat engine do not have the combustion step as the major difference. This conversion is electrochemical, and not thermal, which means that its efficiency is not restricted by the Carnot efficiency. The efficiencies of practical fuel cells are around 40 to 60 percent, and by also using the waste heat from the fuel cells in a combined heat and power system, overall efficiencies can be over 80 percent. There are no moving parts in the cell which results in low vibration and quiet operation.

The average voltage that a single cell can provide is around 0.6 volts to 0.8 volts in practice. Many cells are connected in series to form a stack and the stack is integrated with ancillary components (air supply, humidifiers, cooling, power electronics and controls) to create a fuel cell system for useful voltage and power output.

There are similarities between fuel cells and batteries, since both generate electricity through an electrochemical process. A battery "contains" its components inside the battery itself and ceases to function when the components are depleted. Reactants are fed to a fuel cell from the outside, so as long as fuel is provided, a fuel cell continues to generate electricity, and it can be refuelled in a few minutes. Its energy capacity is based on the size of the fuel tank, NOT the size of the cell..

1.5 Main Components of a Fuel Cell Stack

In practice a fuel cell is more than three layers. The membrane electrode assembly or MEA is the core of a low-temperature cell, made up of the electrolyte membrane and a thin layer of catalyst at both ends. Catalyst layers are the place the electrochemical reactions occur. They consist of finely divided particles of platinum or platinum alloy on a carbon support as reactions are slow at the low temperatures that are used and require the presence of a catalyst. There is a gas diffusion layer of porous carbon paper or cloth located on both the inside and outside of each catalyst layer. It evenly disperses the reactant gases over the electrode, conducts electrons to and from the catalyst, and assists in the removal of the product water[7].

Cells are separated and connected by bipolar plates, which are usually made of graphite composites or coated metals. These plates have fuel and air channels which spread fuel and air over the surface of the cell, carry current from one cell to another and in many designs also carry the coolant. Gases are sealed by gaskets and the entire assembly is held together with uniform pressure from the end plates, ensuring a low contact resistance. High-temperature cells use ceramic or metallic materials that can withstand high temperatures, and require specialized sealing and thermal management systems for high-temperature operations, typically in the hundreds of degrees Celsius[8].

1.6 Historical Development of Fuel Cells

Fuel cells have sometimes been considered as "the technology of the future," but they have evolved since the early nineteen hundreds. The fuel cell effect was discovered by the German-Swiss chemist Christian Friedrich Schönbein in 1838, and in 1839 Sir William Robert Grove, a Welsh scientist built its first functioning model, which he called a gas voltaic battery. Grove used dilute sulphuric acid and supplied it with hydrogen and oxygen and demonstrated that an electric current could be generated.

In the 1930s the English engineer Francis Thomas Bacon started producing alkaline fuel cells that used nickel electrodes and a potassium hydroxide electrolyte, rather than platinum, and in 1959 he presented a system of some 5 kilowatts. At the very same time the space race demanded a small, light, power efficient and drinkable water and power source. Fuel cells based on the work of Bacon were used on the Gemini missions (1960s) and the Space Shuttle orbiters (and the Apollo spacecraft).

Research into alternative energy sources was stimulated by the oil crises of the 1970s. The platinum loading and the cost of proton exchange membrane fuel cells was decreased through development of new membrane materials, especially perfluoro sulfonic acid polymers, and catalyst design. During the 1980s and 1990s, fuel cell buses, cars and stationary power plants were demonstrated by North American, European and Japanese companies and laboratories. Phosphoric acid fuel cells were the first to be commercialized for stationary power and molten carbonate and solid oxide fuel cells were developed to serve larger high-temperature applications.

Fuel cells are now moving into early commercialization in the 21st century. Several manufacturers are selling hydrogen fuel cell cars; fuel cell buses and trucks are operating in many cities; fuel cell systems are used for backup

power for telecom towers and data centres, for powering forklifts in warehouses, and as combined heat and power for residential applications (CHP) in countries like Japan and South Korea. Fuel cells are also being developed for electric trains, ships and aircraft. Strategies and financial support have been announced by many governments to hasten the growth of hydrogen production and applications including the National Green Hydrogen Mission by the Government of India.

1.7 Fuel Cells and Hydrogen in the Indian Context

India is one of the top energy consumers and has adopted a target to attain a net zero emission by 2070. Much of its energy supply relies on coal and imported oil and gas, and cleaner and more secure supplies are a national priority. Production of hydrogen is also being considered as a route to decarbonise hard-to-electrify sectors like steel, fertilisers, refining and heavy road transport, and the country has good solar and wind resources, making production of green hydrogen attractive[9].

The National Green Hydrogen Mission was started in 2023 to establish a large-scale green hydrogen production capacity and to develop demand in industry and transport. Hydrogen fuel cell buses and trucks, hydrogen refuelling stations and research projects on hydrogen fuel cell materials are being started at national laboratories and institutes. Fuel cells are also a good fit for backup power applications in telecom towers, where power outages are still occurring at a regular interval in a country.

1.8 Present Status and Challenges

However, there are technical and economic challenges that prevent fuel cells from being widely adopted. The first is cost. The cost of platinum-group catalysts has to date been the limiting factor for the use of low-temperature fuel cells, and even at current production levels membranes, bipolar plates and other components are cost-prone. High-temperature cells do not require precious metals, but require expensive materials capable of operating at high temperatures.

Thirdly, hydrogen is flammable in a wide range of concentrations. It has a rapid rate of dispersion in the air, and can be safely handled with appropriate codes, standards, training and public awareness, if designed properly. Over the coming years, provision of additional research in materials, electrochemistry, system design and manufacturing is likely to overcome these challenges[10].

1.9 Scope and Organisation of the Case Study

Fuel cells is an interdisciplinary field involving chemistry, thermodynamics, materials and electrical engineering, so that they are interesting for students, researchers, engineers, and policy makers. The aim of this case study is to give a clear and organised account of the technology.

The study first introduces the main types of fuel cells and compares the properties of its electrolytes, operation temperatures, fuels, and typical applications.The study begins with an introduction of the main types of fuel cells, their electrolytes, their operating temperature ranges, fuels and typical applications. Then it describes the working and principle of operation with all its electrode reaction, ion and electron movement and factors which determine the performance of the cell. Then it addresses the benefits and the major applications in the areas of transportation, stationary power, portable power, space and defence. The study concludes with a summary of the key findings and the prospect for the technology going forward.

2. Fuel Cells

2.1 Types of Fuel Cells

Fuel cells are classified mainly by the electrolyte they use. The electrolyte decides the ion that carries charge, the operating temperature, the fuels that can be used and the suitable applications. Six major types are discussed below.

2.1.1 Proton Exchange Membrane Fuel Cell (PEMFC)

The electrolyte for a PEMFC is a solid polymer and the typical operating temperature is less than 120°C. The low operating temperature enables quick start up, high power density and response time to load changes. Fuel cell electric vehicles, buses, material handling equipment and backup power applications are all powered by PEMFCs. They have drawbacks such as the high cost of platinum catalysts, fuel impurity sensitivity and careful water and thermal management.

2.1.2 Alkaline Fuel Cell (AFC)

An alkaline electrolyte is typically a solution of potassium hydroxide, used in an AFC to transport ions between the electrodes. It can be used to generate high electrical efficiency, and is known and used extensively in the aircraft power systems industry. But the carbon dioxide reacts with the electrolyte and this adversely affects the performance, which is why the fuel and oxidant used must be very pure. This requirement makes it unsuitable for general purpose applications.

2.1.3 Phosphoric Acid Fuel Cell (PAFC)

A typical PAFC has an electrolyte of concentrated phosphoric acid and runs at around 150-200°C. It is designed for stationary electrical generation, commercial buildings and combined heat and power (CHP) systems where it can be utilized for its waste heat. The drawbacks are its relatively slow start-up and the cost of the catalyst and moderate electrical efficiency.

2.1.4 Solid Oxide Fuel Cell (SOFC)

The electrolyte of an SOFC is solid ceramic material, usually stabilised zirconia, and works within a broad operating temperature range of approximately 500–1,000°C, depending on the type of SOFC. It is high electrical efficient, has high fuel flexibility and good integration with gas turbines or heat-recovery systems. SOFCs are suitable for stationary & distributed power generation but thermal stress, material compatibility and degradation during repeated heating & cooling is a challenge.

2.1.5 Direct Methanol Fuel Cell (DMFC)

A DMFC is similar to PEMFC but it is fueled with liquid methanol rather than requiring an external source of hydrogen. The DMFC is desirable for uses in low power applications such as portable electronics, as methanol is relatively convenient to transport and store. It is hampered by the fact that methanol can cross the membrane, by the cost of the catalyst and by its comparatively low power density; work is in progress on developing a more selective membrane, improved catalysts and durability.

2.1.6 Comparison of the Types

Table 1 compares the six types. The values are approximate and vary with the electrolyte composition, cell design and operating conditions.

Table 1: Comparison of fuel cell types

Type	**Electrolyte**	**Charge carrier**	**Temperature**	**Electrical efficiency**	**Main applications**	**Main limitation**
PEMFC	Polymer membrane	H^+	below 120°C	40–60%	Vehicles, backup power	Catalyst cost, impurities
AFC	KOH solution	OH^-	below 100°C	50–60%	Space, special power	CO_2 sensitivity
PAFC	Phosphoric acid	H^+	150–200°C	40–45%	Stationary power, CHP	Slow start-up
MCFC	Molten carbonate	CO_3^{2-}	600–700°C	45–60%	Industrial, utility power	Corrosion, degradation
DMFC	Polymer membrane	H^+	below 130°C	20–30%	Portable power	Methanol crossover

No single type is best for every application. The choice depends on the operating conditions, fuel availability, cost and system requirements.

2.2 Working and Principle of Operation

2.2.0 General Working Principle

In a fuel cell, the chemical energy of a fuel is converted directly to electrical energy by electrochemical reaction instead of combustion as in thermal power plants. A fuel cell can be divided into three main components:

- Anode: The fuel is oxidised here, electrons are released.
- The oxidant (typically oxygen from air) is reduced at the cathode consuming electrons.
- Electrolyte: Only ions can pass between the electrodes, not electrons.

Electrons are unable to flow through the electrolyte, and so must travel through an external circuit, generating the desired electric current. Ions travel through the electrolyte and make the circuit. With hydrogen as the fuel, the products are electricity, heat and water. The electrolyte determines the nature of the fuel cell as it determines the operating temperature, mobile ion, electrode reactions, and what materials can be used. The charge is therefore the same for each of the six types, with the exception that the charge may reside on either the Nitrogen or the Oxygen, and move in either direction; it is summarised in Table 2.

Table 2: Electrolyte, mobile ion and ion direction of the six fuel cell types

Type	**Electrolyte**	**Mobile ion**	**Ion direction**	**Temperature**
PEMFC	Polymer membrane	H^+	Anode → Cathode	below 120°C
AFC	KOH solution	OH^-	Cathode → Anode	below 100°C
PAFC	Phosphoric acid	H^+	Anode → Cathode	150–200°C
MCFC	Molten carbonate	CO_3^{2-}	Cathode → Anode	600–700°C
SOFC	Ceramic (zirconia)	O^{2-}	Cathode → Anode	500–1,000°C
DMFC	Polymer membrane	H^+	Anode → Cathode	below 130°C

2.2.1 PEMFC

Electrolyte	Solid polymer (proton-conducting) membrane
Operating temperature	Below 120°C
Charge carrier	Protons (H^+), moving from anode to cathode
Catalyst	Platinum-based catalyst on both electrodes
Fuel and oxidant	Hydrogen and oxygen (air)

How it works

The solid polymer membrane only conducts protons through it and prevents gas crossover and the conduction of electrons. The free electrons are not able to pass through the membrane, and are forced to travel through an external circuit to the cathode, where they provide electric power to the load. O2 of the air is fed to the cathode, where it reacts with the protons and electrons to produce water. A little water and heat escape from the cell. This should be controlled in order to prevent the electrodes from flooding while maintaining the membrane in a state of hydration.

The low temperature gives rapid start-up, high power density and good response to load changes, which is why the PEMFC is the preferred type for vehicles.

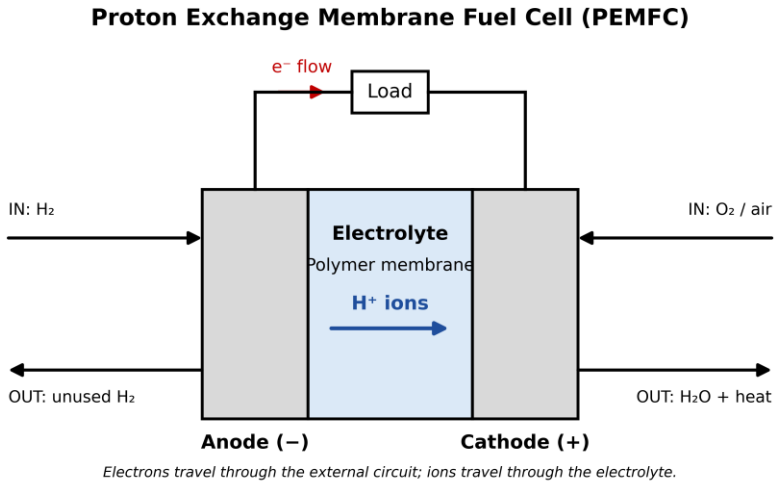


Figure 1: Schematic of the PEMFC showing reactant flow, electron flow and ion movement

2.2.2 AFC

Electrolyte	Alkaline solution, traditionally aqueous potassium hydroxide (KOH)
Operating temperature	Below 100°C (conventional systems)
Charge carrier	Hydroxide ions (OH^-), moving from cathode to anode
Catalyst	Platinum or non-precious metals, depending on design

How it works

At the cathode, oxygen and water take up the electrons that come from the external circuit and produce the hydroxide ions (OH^-). In the case of the hydroxide ion, the direction of movement in the KOH electrolyte is towards the anode, rather than towards the proton in a PEMFC. Hydrogen at the anode combines with the hydroxide to form water and electrons. These electrons move around the outer circuit down to the cathode and provide electrical energy. Water forms at the anode and needs to be taken away to maintain the stable concentration of the electrolyte. Carbon dioxide reacts with the alkaline electrolyte and degrades performance, so the fuel and oxidant must be very pure. This suits the AFC to controlled environments such as space missions.

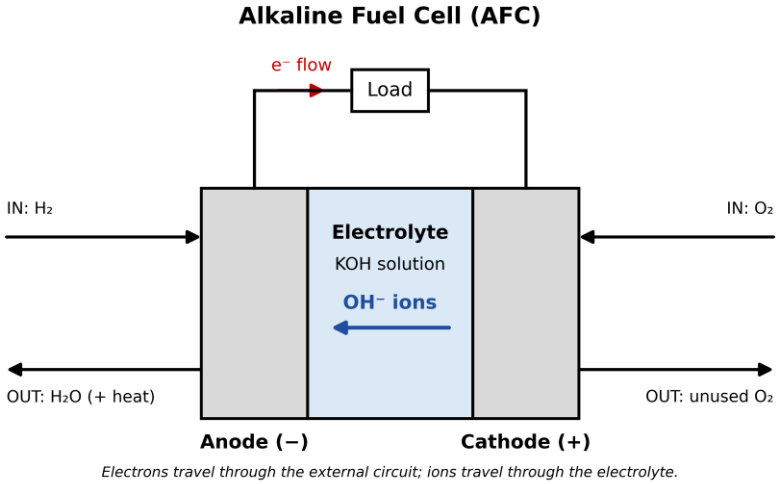


Figure 2: Schematic of the AFC showing reactant flow, electron flow and ion movement

2.2.3 PAFC

Electrolyte	Concentrated phosphoric acid held in a matrix
Operating temperature	About 150–200°C
Charge carrier	Protons (H^+), moving from anode to cathode
Catalyst	Platinum-based catalyst
Fuel and oxidant	Hydrogen (for example from a reformer) and air

How it works

The oxidation of hydrogen occurs at the anode producing protons and electrons, similar to that in a PEMFC. A. Protons travel to the cathode with the electrolyte being a liquid phosphoric acid. The electrons travel around the external circuit and provide electric power. At the cathode, oxygen molecules, protons and electrons result in the formation of water. The waste heat from the cell is useful quality and can be utilized for CHP heating applications since the cell is operated at 150-200°C.

The PAFC is well suited to stationary generation and commercial buildings, but it starts slowly and its electrical efficiency is moderate.

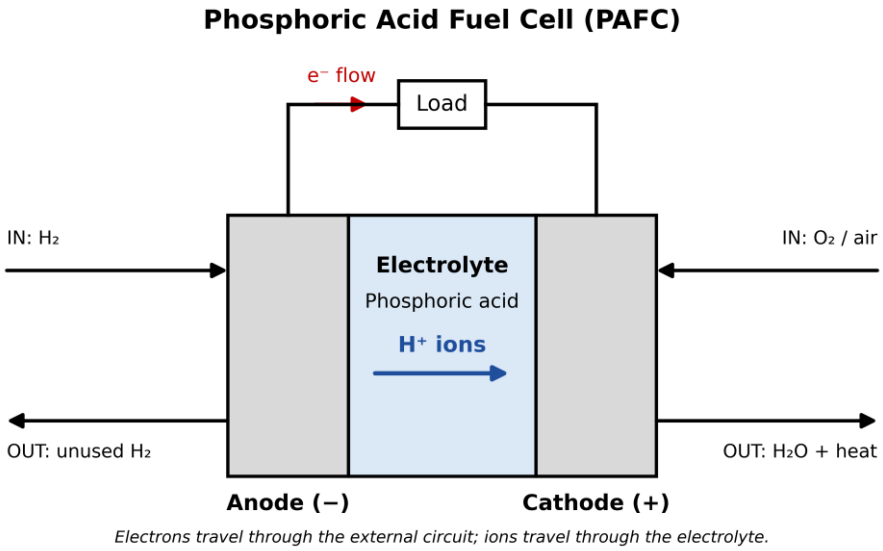


Figure 3: Schematic of the PAFC showing reactant flow, electron flow and ion movement

2.2.4 MCFC

Electrolyte	Molten carbonate salts
Operating temperature	About 600–700°C
Charge carrier	Carbonate ions (CO_3^{2-}), moving from cathode to anode
Catalyst	Non-precious metal (for example nickel-based) electrodes
Fuel and oxidant	Hydrogen or hydrocarbon fuels (reformed internally) and air with CO_2

How it works

Oxygen is fed to the cathode and it reacts with electrons to produce carbonate ions (CO_3^{2-}). The carbonate ions move through the molten carbonate electrolyte towards the anode. At the anode hydrogen combines with the carbonate ions to form water, carbon dioxide and electrons. The electrons move around the external circuit to the cathode. The CO_2 emitted at the anode is then usually recycled to the cathode and overall, the CO_2 is not used. Inside the cell, it is possible to reform suitable hydrocarbon fuels (for example methane, CH_4 with H_2O to reform CO and $3H_2$) at 600–700°C, providing direct supply of hydrogen.

The high temperature allows non-precious-metal catalysts and internal reforming, but it also causes corrosion, material degradation and long start-up times.

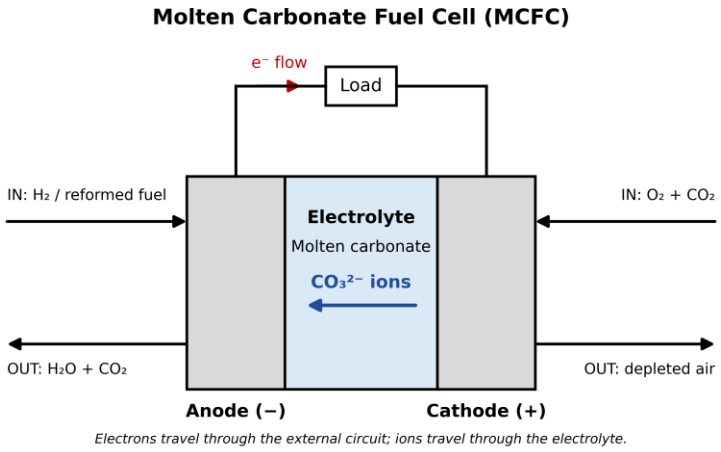


Figure 4: Schematic of the MCFC showing reactant flow, electron flow and ion movement

2.2.5 SOFC

Electrolyte	Solid ceramic electrolyte, commonly stabilised zirconia
Operating temperature	About 500–1,000°C (design dependent)
Charge carrier	Oxide ions (O^{2-}), moving from cathode to anode
Catalyst	Ceramic or cermet electrodes (no precious metals required)
Fuel and oxidant	Hydrogen, CO and hydrocarbon fuels; air
Anode reaction	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$ (and $CO + O^{2-} \rightarrow CO_2 + 2e^-$)
Cathode reaction	$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$
Overall reaction	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ + electricity + heat

How it works

1. Oxygen from air is reduced at the cathode: each oxygen atom picks up two electrons to become an oxide ion (O^{2-}).
2. At high temperature the solid ceramic electrolyte becomes conductive to oxide ions, which pass through it towards the anode. Electrons cannot pass through.
3. At the anode, the oxide ions react with the fuel (hydrogen, and also carbon monoxide) to form water and CO_2, releasing electrons.
4. The electrons return to the cathode through the external circuit, producing useful current.
5. The hot exhaust can be used for heat recovery or fed to a gas turbine, which raises the overall system efficiency.

The SOFC offers high electrical efficiency and fuel flexibility. Its challenges are thermal stress, material compatibility and degradation during repeated heating and cooling.

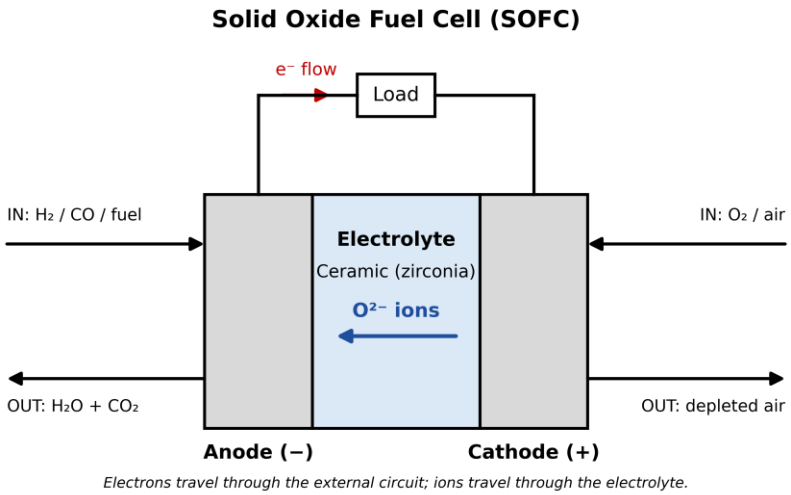


Figure 5: Schematic of the SOFC showing reactant flow, electron flow and ion movement

2.3 Advantages of Fuel Cells

Fuel cells have several benefits over traditional power generation and over numerous other clean energy options:

- Low emissions. With hydrogen as the fuel, the only products are water and heat. The point-of-use carbon dioxide, sulphur oxide and particulate emissions are eliminated and high-temperature combustion is not a source of nitrogen oxides. Low noise and maintenance requirements. Since there are no moving parts, the cell operates quietly without vibration and is ideal for city, hospital and residential buildings.
- Continuous power. Energy can be generated in a fuel cell as long as fuel and oxidant are provided and the vehicle can be refuelled using hydrogen in a matter of minutes, rather than several hours.
- Modularity and scalability. Output can be a few watts for a portable device, or several Megawatts of a power plant, by combining cells into stacks, and stacks into systems.
- Fuel flexibility. Fuel cells may be based on hydrogen, natural gas, biogas, methanol or other hydrogen-rich fuels, thus providing flexibility to introduce fuel cell technology prior to the development of an infrastructure for hydrogen.
- Support for use of renewable energy and energy security. Surplus solar and wind energy can be captured and stored as hydrogen and fed back into the grid via fuel cells, thus lowering the need for imported fossil fuels.

2.4 Applications of Fuel Cells

Depending on operating temperature, fuel level and the power requirement, the various fuel cells are used for specific applications:

- Transportation. PEMFCs are used in cars, buses, trucks, forklifts and, in trials, trains, ships and aircraft. Fuel cells are particularly attractive for heavy, long-distance vehicles, where batteries weight down the vehicle and take a long time to recharge.
- Stationary power & CHP. Combined heat and power for houses is done using small PAFCs, MCFCs and SOFCs to provide electricity and useful heat in commercial, hospital, factory and utility buildings as well as electricity and useful heat in combined heat and power.
- Backup power. Fuel cells operate for long periods of time (compared to batteries) and are used for reliable emergency power on telecommunication towers, data centres and critical facilities.
- Portable power. DMFCs and small PEMFCs are used in portable electronics, chargers, sensors and remote equipment where high weight to power ratio and convenient refuelling are key factors. • Space and defence. Since the 1960s, alkaline and PEM fuel cells have provided power for crewed spacecraft, as well as the crew's drinking water, and fuel cells are used in submarines and quiet military power units.

- For industrial and utility applications. The high-temperature cells can be fueled by natural gas, biogas or industrial off-gases and can be combined with gas turbines, and fuel cells are also used to recover energy from the by-product hydrogen in chemical plants.

3. Conclusion

Fuel cells are potential energy conversion technology with great promise for supplying the world with increasing electricity demands in an efficient, reliable and environmentally friendly way. Fuel cells are different to traditional energy generation technologies in that instead of the energy in a fuel being converted into heat and used for energy, fuel cells use electrochemical reactions to directly produce electrical energy from the fuel. This case study covered the basic concepts, functions, key categories, benefits, drawbacks and applications of fuel cells. These major types vary in terms of their electrolyte, operating temperature, efficiency and application requirements, and are defined by their specific characteristics. Water is the main reaction product of a hydrogen fuel cell, so fuel cells are desirable when it is important to reduce local emissions. Fuel cells are considered for transportation, stationary power generation, back-up power, portable electronics and space applications. They can also be integrated with renewable energy systems like solar and wind energy, particularly for hydrogen production via renewable power and storage for subsequent use. However, there are still some obstacles that must be overcome before fuel cells are widespread. The high start-up costs, price of materials, hydrogen storage and transport challenges, availability of few refuelling stations and durability issues are still major obstacles. Moreover, the overall environmental impact will be different for hydrogen production based on different production methods, and therefore, low emission hydrogen production is crucial. Advancements in research and partnerships between researchers, industries, governments and energy developers are needed to further enhance efficiency, prolong operating life, lower costs, and design appropriate infrastructure. Overall, fuel cells offer a promising solution for a sustainable energy future and can help to decrease reliance on fossil fuels, avoiding the high costs of alternative energy sources.

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