Chapter 6

Fuel Cell and Applications

Kemal Ermiş[1]

Abstract

Electrical energy is clean and the most convenient for use. Today, hydroelectric, thermal, and nuclear systems produce electricity. Electricity production using fossil-based power is rapidly decreasing due to global warnings and excessive pollution of our atmosphere. New technologies are evolving that can reduce carbon emissions significantly; one of them is fuel cell. Studies on fuel cell applications are intensifying and many application developments in engineering will continue to be seen in the 21st century.

Fuel Cell is a power generation element that converts the chemical energy of a fuel (hydrogen) and oxidizer (air) into energy that can be used directly in the form of electricity and heat. In this study, fuel cell types with various names according to various criteria are explained, fuel cell usage areas are specified and applications in the world are mentioned. Application examples of fuel cells used in power stations, distributed energy production, and vehicle applications are given. The environmental effects, one of the most important advantages of fuel cells, are explained and compared with other conventional power generation systems. Although fuel cells have many advantages, the most important obstacle to commercialization is their cost. Development studies and significant increases in power density show that the commercial use of fuel cells will increase rapidly and significantly in the 21st century.

1. Introduction

Currently, the world's main source of energy is the burning of fossil fuels and the by-products of this combustion (e.g. SO_x, NO_x, CO_2, and fine particles) seriously pollute the air, soil, and water [1, 2]. In recent years, due to the negative effects of fossil fuels on the world such as the greenhouse effect and global warming, there has been an increasing interest in new alternative energy sources and exergy analysis to use these resources

1 Prof. Dr., Sakarya University of Applied Science, Faculty of Technology, Dept. of Mechanical Engineering, ermis@subu.edu.tr, http://orcid.org/0000-0003-3110-2731

https://doi.org/10.58830/ozgur.pub250.c1205

more efficiently. Reducing or even eliminating these effects as much as possible will make our world livable. For this reason, fuel cell systems, which are the new alternative energy systems with almost zero harmful emissions, have been developed instead of fossil fuel-based systems. The fuel cell electrochemically converts chemical energy into electrical energy. However, such a system that can continue to produce electricity when fuel is continuously fed from outside can be considered a conventional power generation system. Although the fuel cell operating principle was discovered in 1889, it was not used in power generation until the space programs in the 1960s. A fuel cell, which can obtain direct current electricity and heat at various temperatures depending on the cell type, is an electrochemical device that has no moving parts, is highly efficient, silent, and does not harm nature. The primary advantage of a fuel cell is that it immediately converts the chemical energy of fuels into electrical energy. Because the by-products are only water and heat, there are no carbon emissions and as generation continues to shift away from coal and towards natural gas, fuel cells will not only dramatically reduce CO_2 emissions but also combine with power plants burning a less carbon-intensive fuel. As a result, fuel cells are substantially more efficient than other energy conversion devices that require numerous conversion steps. The direct energy conversion in fuel cells occurs at triple-phase boundaries, so-called TPBs where fuels, electrodes, and electrolytes meet simultaneously [3].

Table 1 gives comparative NOx emission characteristics of competing technologies. Legal restrictions imposed to reduce NOx emissions increase the prices of competing system technologies and provide an advantage for fuel cells.

Table 1. Comparison of NOx emission characteristics

Technology	**Uncontrollable emissions**	**Controllable emissions**	**Control technology**
Internal combustion engine	2370 ppm @ 15% O_2	474 ppm @ 15% O_2 95 ppm @ 15% O_2	Lead Burning SCR catalyst System
Gas Turbine	120 ppm @ 15% O_2	45 ppm @ 15% O_2 20 ppm @ 15% O_2 7.5 ppm @ 15% O_2	Steam Injection Lead Burning SCR System
Fuel Cell	5 ppm @ 15% O_2	5 ppm @ 15% O_2	None

Comparing fuel cells with general batteries; Batteries are rechargeable, intermittent power can be obtained, they are closed systems, generally solid, and have high power density. Fuel cells can be refueled, can provide continuous power, are open systems, generally use gas/liquid fuel, have a high energy density, and can produce power from Micro Watts to Mega Watts.

Application examples of fuel cells used in power stations, distributed energy production, mobile applications, and vehicle applications are given. Developmental work and significant increases in power density indicate that the commercial use of fuel cells will increase significantly throughout the 21st century.

2. Fuel Cell Working Principle

In a fuel cell, fuel is constantly fed to the anode, that is, the negative electrode and air or pure oxygen is constantly fed to the cathode, that is, the positive electrode. Electrochemical reactions occur at the electrodes to produce an electric current through the electrolyte, resulting in a complementary electric current operating on the load. A fuel cell is an energy conversion device in which fuel and oxidant are continuously fed. In principle, the fuel cell produces power as long as fuel is supplied. The fuel cell basic diagram is shown in Figure 1.

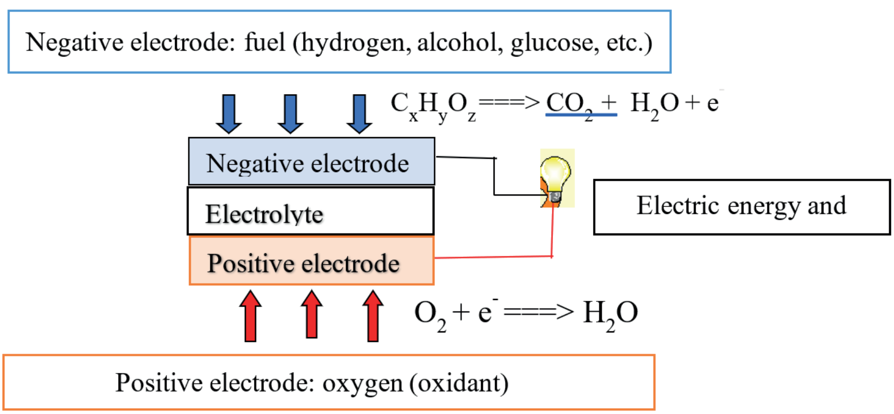

Figure 1. Fuel cell basic diagram

The fuel cell operating principle is the opposite of the electrolysis of water. In the electrolysis of water, an electric current is given to the water and it is separated into oxygen and hydrogen, which form water. In the fuel cell, when the oxygen and hydrogen in the air are brought together, water, electric current, and heat are produced. The basic design of a fuel cell system contains; a) Fuel source (Hydrogen, fuels containing hydrogen (from reformer) or bio-fuels)

b) Air or Oxygen

c) Electrolyte medium for transportation of protons

d) On one side of the electrolyte medium, a cathode serves as an electrode.

e) On the opposite side of the electrolyte medium, an anode serves as an electrode.

Fuel cells are often classed depending on the electrolytes used in the cell, which in turn determines the type of chemical reaction taking place inside the cell, the type of catalysts necessary, the temperature range for cell operation, the type of fuel required, and so on. The reaction formula for the fuel cell is as follows.

Hydrogen at the electrode (Anode):

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

Oxygen is at the electrode (Cathode):

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

Overall Reaction:

$H_2 + \frac{1}{2} 0_2 \rightarrow H_2O$ + Electrical Energy (3)

As seen in Figure 2, Proton-exchange membrane fuel cell components are combined with each other to form a single fuel cell. Single fuel cells can then be placed in a series to form a fuel cell stack. It can be used in a stacked system to power a vehicle or provide constant power to a building.

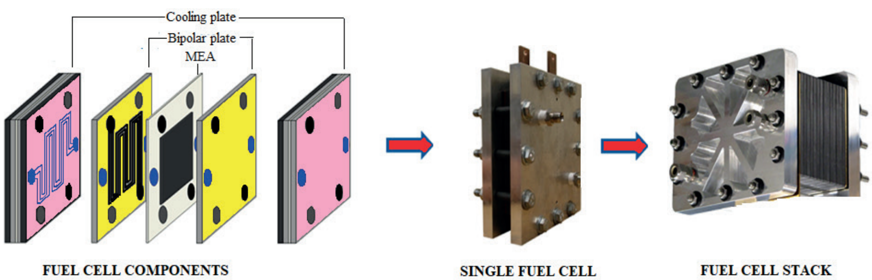

Figure 2. Proton-exchange membrane components

2. Fuel Cell Basic Thermodynamics and Chemistry

2.1. Theoretical Electrical Work of Fuel Cell

The enthalpy or high heating value (HHV) resulting from the combustion of one mole of hydrogen is 286 kJ/mole. If one mole of hydrogen is placed in a calorimetric container containing ½ mole O_2 and burned completely when ignited and then allowed to cool to room temperature (25 °C) at atmospheric pressure, only water will remain in the calorimetric container. The amount of heat released at the end of this process will be 286 kJ/mole as a high heating value (HHV).

$$H_2 + \frac{1}{2}\, 0_2 \rightarrow H_2O + 286 \text{ kJ/mole} \quad (4)$$

However, the theoretical value of 286 kJ/mole is generally not reached. Because, along with the water formed because of the burning of hydrogen with excessive amounts of oxygen, what remains is unburned oxygen or nitrogen mixed into the air in the form of vapor. Therefore, the resulting calorific value, called the lower heating value (LHV) of hydrogen combustion [4], is 241 kJ/mol. This value is smaller than the value calculated above. The HHV and LHV of hydrogen are used as a measure of the energy input in the fuel cell [5]. This is the maximum amount of thermal energy that can be extracted. In the chemical reaction, some entropy is produced because some parts of the HHV are not converted into useful work (Electricity). The fraction of the enthalpy reaction of HHV of hydrogen that can be converted into electricity in the fuel cell corresponds to Gibb's free energy (ΔG), and this relationship is represented by:

$$\Delta G = \Delta H - T\Delta S \quad (5)$$

Where ΔH is the total enthalpy of the reaction between the heat of formation of products and reactants, T is the temperature, and ΔS is the total entropy of the reaction between the entropies of products and reactants. The following relationships can help to explain ΔH and ΔS.

$$\Delta H = (H_f)_{H2O} - (H_f)_{H2} - \frac{1}{2}\,(H_f)_{O2} \quad (6)$$

$$\Delta S = (S_f)_{H2O} - (S_f)_{H2} - \frac{1}{2}\,(S_f)_{O2} \quad (7)$$

Where H_f and S_f values for reaction reactants and products. These values are shown in Table 2. at 25°C and ambient pressure.

Table 2. Enthalpies and entropies of formation of fuel cell reactants and products.

Reactants / Products	(H_f) kJ/mole	(S_f) kJ/mole K
Oxygen, O_2	0	0.20517
Hydrogen, H_2	0	0.13066
Water Vapors, H_2O	-241.98	0.18884
Water Liquid, H_2O	-286.02	0.06996

The amount of available energy is 286 kJ/mole that can be transformed into productive work-electricity is 237 kJ/mole and the remainder 48 kJ/mole is converted into heat at 25 °C [6].

2.2. Theoretical Potential of Fuel Cell

In a fuel cell, electrochemical processes occur simultaneously at the anode and cathode, which are placed on opposite sides of the membrane.

Generally, the electrical work can be defined as the product of charge and potential.

$$W_{el} = q\,E \tag{8}$$

Where W_{el} is the electrical work (J/mole), q is the charge (Coulomb/mole) and E is the potential (Volts).

The reactions in a fuel cell may consist of one step or several steps as shown in equations 1-3. These reactions accurately describe the reactions in a fuel cell. According to these reactions, the total charge transferred per mole of hydrogen consumed in a fuel cell can be expressed as follows;

$$q = n\,N\,q_{el} \tag{9}$$

Where q is the charge (Coulomb/mole), n is the number of electrons per H_2 molecule, N is the molecular number per mole (Avogadro's number = $6.023 * 10^{23}$ molecules per mole) and q_{el} is the charge on one electron ($1.602 * 10^{-19}$ C).

Combining Equations 8 and 9, the electrical work can be expressed as following Equation 10.

$$W_{el} = (n\,N\,q_{el})\,E \tag{10}$$

Multiplying Avogadro's number, N, with the charge of an electron (q_{el}) gives the Faraday constant (F = 96485 C/electron-mole) and can be expressed as follows;

$$F = (N_{avg} * q_{el}) = (96485\ \text{C /electron-mole}) \tag{11}$$

Electrical work (W_{el}) can be expressed by the following Equation by substituting it into the above Equation.

$$Wel = n\ F\ E \tag{12}$$

The maximum amount of electrical energy produced in a fuel cell corresponds to Gibb's free energy (ΔG).

$$Wel = -\Delta G \tag{13}$$

The relationship regarding the theoretical potential of a fuel cell can be found in Equations 12 and 13 as follows

$$n\ F\ E = -\Delta G \qquad \text{or } n\ F\ E = -\Delta G \tag{14}$$

When ΔG, n, and F are all known, the theoretical potential of the fuel cell to LHV and HHV for hydrogen/oxygen can be given as:

$$E = \frac{-\Delta G}{n\ F} = \frac{237340\ \text{J/mole}}{2 * 96485\ \text{A}\cdot\text{s/mole}} = 1.23\ Volt\ \ for\ LHV \tag{15}$$

$$E = \frac{-\Delta G}{n\ F} = \frac{286000\ \text{J/mole}}{2 * 96485\ \text{A}\cdot\text{s/mole}} = 1.48\ Volt\ \ for\ HHV \tag{16}$$

Equation 14 shows that the theoretical potential of the H_2/O_2 fuel cell at 25 °C is 1.23 Volts.

2.3. Theoretical Efficiency of Fuel Cell

The ratio between electrical power output and fuel input is defined as the efficiency of a fuel cell. Assuming that all Gibb's free energy can be converted into useful electrical work, the maximum theoretical efficiency of a fuel cell possible using hydrogen high heating value (HHV) at 25 °C can be given as:

$$\eta = 100\frac{\Delta G}{\Delta F} = 100\frac{237340\ \text{J/mole}}{286020\ J/\text{mole}} = 83\%\ \ for\ HHV \tag{17}$$

Where η is the efficıency

Theoretical efficiency is sometimes known as thermodynamic efficiency or maximum efficiency limit. The cell theoretical efficiency is 1.23V and the potential corresponding to the high heating value (HHV) of hydrogen combustion, in other words, the thermal neutral efficiency, is 1.48V. If divided by both ΔG and ΔH (n F), fuel cell efficiency can be expressed as the ratio of the two potentials.

$$\eta = 100\frac{\Delta G/nF}{\Delta F/nf} = 100\frac{1.23\ \text{Volt}}{1.48\ \text{Volt}} = 83\%\ \ for\ HHV \tag{18}$$

The comparison of the efficiency of the fuel cell process and the Carnot process for heat engines at the lower temperature of 130 °C is shown in Figure 3.

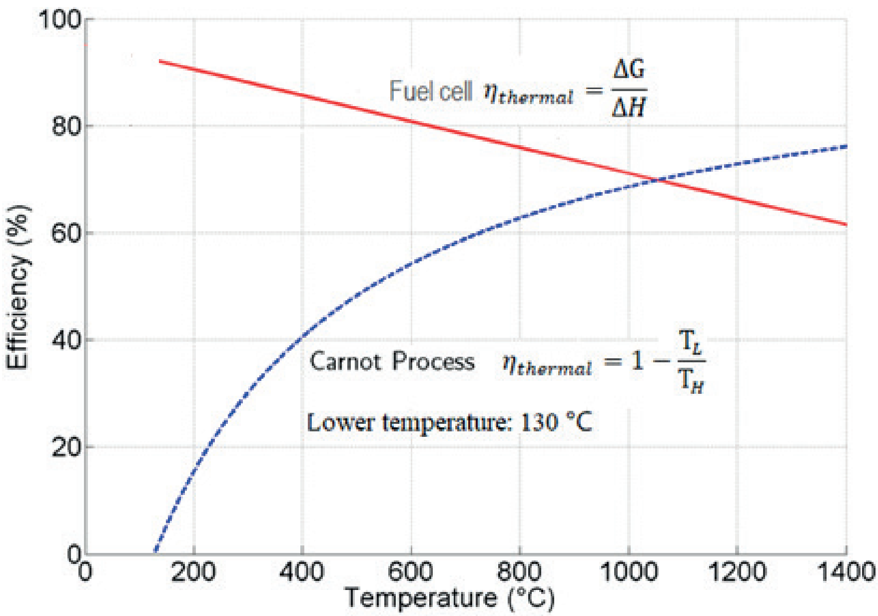

Figure 3. The comparison of the efficiency of the Carnot process and the fuel cell process for heat engines.

3. Fuel Cells Types

There are many types of fuel cells. The operating principles all work in the same general way. In principle, it consists of three adjacent parts: anode, electrolyte, and cathode. Two chemical reactions occur at the interfaces connecting three different parts of fuel cells. The result of these two reactions is the consumption of fuel, the formation of water or carbon dioxide, and the generation of an electric current. Many fuel cell designs are still being investigated for commercial application or have been partially deployed but are not widely used. Some of them are protonic ceramic, redox, microbial, direct-ethanol, and biofuel fuel cells. Table 3 shows the important fuel cell types available for use in commercial applications [7-10].

Table 3. Comparison of major fuel cell types used commercially.

Fuel cell type	Electrolyte	Electrolyte	Working temperature (°C)	Electric Efficiency
By electrolyte	Alkaline (AFC)	Aqueous alkaline solution	40-200	40-60%
	Molten carbonate (MCFC)	Molten alkaline carbonate	600–650	45-60%
	Phosphoric acid (PAFC)	Molten phosphoric acid	150–200	40%, [a]90%
	Proton-exchange membrane (PEMFC)	Polymer membrane (ionomer)	50–100 (Nafion) 120–200 (PBI)	30-55%
	Solid oxide (SOFC)	Oxide ion conducting yttria-stabilized zirconia	700–1100	55-60%
By fuel	Direct methanol (DMFC)	Polymer membrane (ionomer)	90–120	20-40%
	Reformed methanol (RMFC)	Polymer membrane (ionomer)	250–300	25-40%
	Direct carbon (DCFC)	Several different	700–850	70%
	Metal hydride (MHFC)	Aqueous alkaline solution	> −20	
	Direct borohydride (DBFC)	Aqueous alkaline solution	70	
	Direct formic acid_ (DFAFC)	Polymer membrane (ionomer)	< 40	

[a] cogeneration

4. Fuel Cells Applications

Fuel cells commonly used in commercial applications are divided according to electrolyte types, as shown in Table 3. Different electrolytes act at various temperatures. The alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEMFC), and phosphoric acid fuel cell (PAFC) are examples of low-temperature fuel cells. All of these fuel cells run on hydrogen. The method of reformation can extract hydrogen from natural gas, biogas, methanol, or propane. Hydrogen can also be produced via electrolysis of water. Molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) are examples of high-temperature fuel cells. These fuel cells have the advantage of being able to use either natural gas or untreated coal gas as a fuel without the necessity of a reformer, a process known as “Direct Internal Reforming.”

Application examples of fuel cells used in power stations, distributed energy production, mobile applications, industrial, residential and vehicle applications. Developmental work and significant increases in power density indicate that the commercial use of fuel cells will increase significantly throughout the 21st century. Emissions in the transportation sector are divided into two types: local pollutants (carbon monoxide and nitrogen oxides, etc.) and greenhouse gases (carbon dioxide). For fuel cell cars, the values in both categories are quite low. Figure 4 shows the total emissions in vehicles [11].

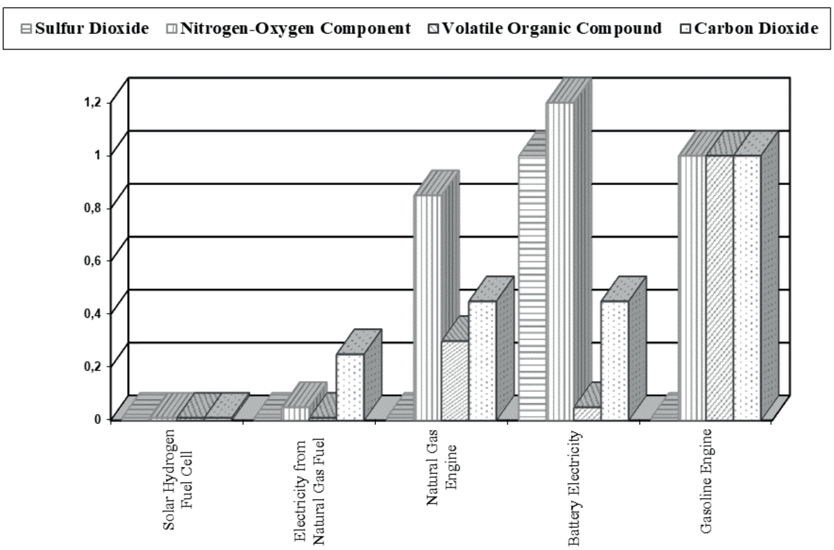

Figure 4. The total emissions in vehicles

4.1. Alkaline Fuel Cell (AFC)

Alkaline fuel cell (AFC), also known as Bacon fuel cell, is one of the most advanced fuel cell technologies. Alkaline fuel cells use potassium hydroxide (KOH) as the electrolyte and operate at 160°F. Alkaline fuel cells can achieve power-generating efficiencies of up to 60 percent (up to %85 combined heat and power). The fuel cell produces power through a redox reaction between hydrogen and oxygen.

Reactions

At Anode: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ (19)

At Cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ (20)

Overall reaction: $O_2 + 2H_2 \rightarrow 2H_2O$ (21)

Schematic representation of the general operation of an alkaline fuel cell using liquid or polymer electrolyte as shown in Figure 5.

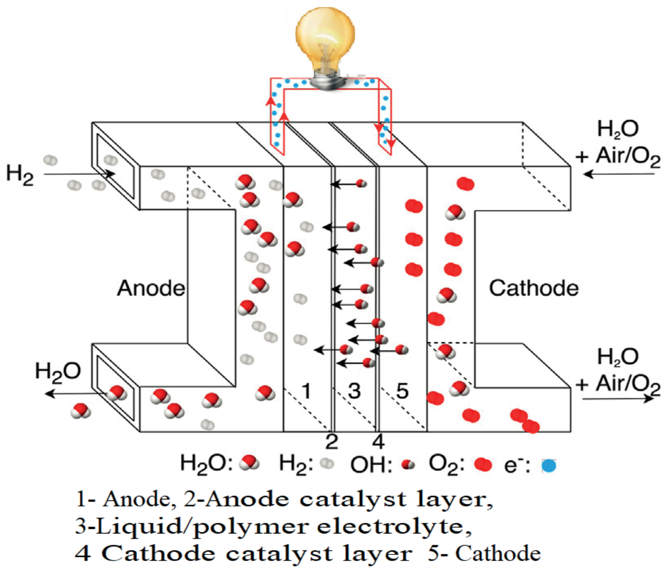

***Figure 5.** Schematic representation of the general operation of an alkaline fuel cell using liquid or polymer electrolyte [12].*

As shown in equation 19 above, after the Gas diffusion layer penetrates and reaches the catalyst layer, humidified hydrogen gas is supplied to the anode, which reacts with hydroxide ions in the electrolyte to produce water and electrons. As shown in equation 20 above, a humidified oxygen source, typically purified air/oxygen, is fed to the cathode along with water. Oxygen gas dissolved in water is reduced to the cathode layer to form hydroxide ions, which diffuse throughout the electrolyte to participate in the hydrogen oxidation reaction occurring at the anode. The ideal oxygen reduction reaction also called the direct 4-electron pathway, occurs. The red-ox reactions in equations 19 and 20 are combined to form the overall mechanism given in equation 21. Characteristics of the traditional alkaline fuel cell are shown in Table 4.

Table 4. Characteristics of traditional alkaline fuel cell [12].

Electrolyte	30–40 wt% KOH
Anode catalysts	Pt, Pd, Raney Ni
Cathode catalysts	Pt, Pd, Ag, MnO_2
Current collector materials	Stainless steel, steel varieties
Pressure (bar)	1–3
Peak power density (mW/cm^2)	50–300
Current density(mA/cm^2)	100–300
Lifetime (h)	>5000

4.1.1 Alkaline Fuel Cell Applications

- Primarily military and space programs to provide electricity have used the alkaline fuel cell and drinking water onboard Apollo Spacecraft by NASA, where water and electricity were supplied from an alkaline fuel that delivered 1.5 kW and weighed 113 kg.
- The recently developed bi-polar plate variant of this technology holds the most commercial promise for AFCs.
- The UK company Zetek modified a London taxi to be powered by an AFC in 1999 (100 km range), in addition to the first AFC-powered boat in 2000 [13].
- Existing companies providing AFC solutions, UK-based AFC Energy and GenCell Energy, produced an alkaline fuel cell generator project that uses potassium hydrochloride (KOH) electrolyte to produce 4 kW AFC, employing cracked ammonia (99.5%) as a hydrogen source (Project Alkammonia) as a stationary off-grid power supply of power, from hydrogen fuel [14].

4.2. Molten Carbonate Fuel Cell (MCFC)

Molten carbonate fuel cells use lithium potassium carbonate salt as an electrolyte, composed of a molten carbonate salt mixture suspended in a porous, chemically inert matrix, and operate at high temperatures of approximately 600 °C and above. Molten carbonate fuel cells can reach efficiencies approaching 60 %. Molten carbonate fuel cells (MCFCs) have been developed for natural gas, biogas, and coal-fired power plants, as well as for electrical utility, industrial, and military uses. Molten carbonate fuel cell disadvantages include slow start-up times because of their high operating temperature; this makes the molten carbonate fuel cell systems not suitable for mobile applications. The electrolytes in the molten carbonate fuel cells are heated to 600°C, at which point the salts melt and conduct carbonate ions (CO_3^{2-}) from the cathode to the anode.

The hydrogen oxidation reaction mixes with carbonate ions at the anode, creating water and carbon dioxide and releasing electrons to the external circuit [15]. Because oxygen is reduced to carbonate ions at the cathode by mixing with carbon dioxide and electrons from the external circuit. The electrochemical reactions occurring in the molten carbonate fuel cell are:

At the anode: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ (22)

At the cathode: $½O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$ (23)

The overall cell reaction: $H_2 + ½O_2 + CO_2 \rightarrow H_2O + CO_2$ (24)

Schematic representation of the general operation of a molten carbonate fuel cell as shown in Figure 6.

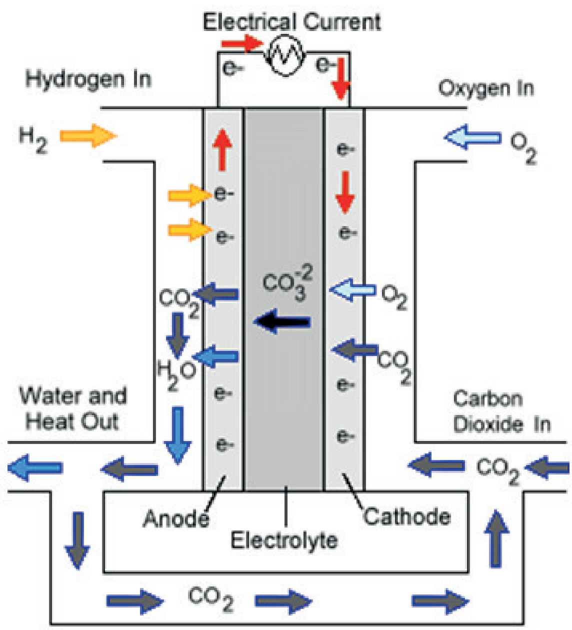

Figure 6. Schematic representation of the general operation of a molten carbonate fuel cell [16].

4.2.1. Molten Carbonate Fuel Cell Applications

- Mainly used for stationary power generation. Molten carbonate fuel cells have a power output of 10 kW to 3 MW that achieves 47% electrical efficiency and can utilize combined heat and power (CHP) technology to obtain higher overall efficiencies [17].
- Consumer electronics
- Light traction vehicle
- Commercial and industrial distributed power generation
- Emergency backup power supply

4.3. Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid fuel cells operate between 170°C to 210°C and use liquid phosphoric acid as the electrolyte. Phosphoric acid fuel cells produce electricity at a rate of more than 40% efficiency, and nearly 85% of the steam produced by this fuel cell is used for cogeneration. Aside from the nearly 85% cogeneration efficiency, one of the main advantages of this type of fuel cell is that it can use impure hydrogen as fuel. The electrolyte, primarily composed of phosphoric acid, is a proton conductor, thus the protons migrate from the anode to the cathode, while the electrons migrate through an external circuit. At the cathode side, air is provided, where oxygen reacts with the protons and the electrons, coming from the electrolyte and the external load [15]. The overall reactions for the phosphoric acid fuel cells are given below:

At the anode: $H_2 \rightarrow 2H^+ + 2e^-$ (25)

At the cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (26)

The overall cell reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (27)

Schematic representation of the general operation of a phosphoric acid fuel cell as shown in Figure 7.

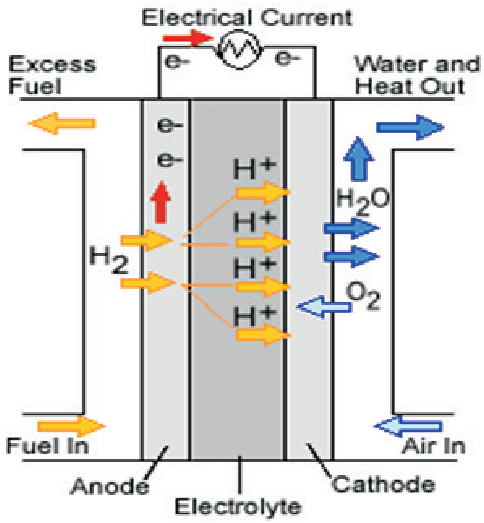

Figure 7. Schematic representation of the general operation of a phosphoric acid fuel cell [16].

4.3.1. Phosphoric Acid Fuel Cell Applications

- Residential and commercial distributed generation and light traction vehicle
- Commercial and industrial distributed power generation
- Emergency backup power supply

4.4. Proton-Exchange Membrane Fuel Cell (PEMFC)

Proton-exchange membrane fuel cells operated at low temperatures of 50 to 100 °C. Efficiencies of PEMs are in the range of 40–60% and 85% cogeneration. Important criteria in the design of proton-exchange membrane fuel cells; the membrane must have high proton conductivity and low water permeability, it works best when the electrodes are made from noble metal catalysts. For optimum channel geometry for the cathode side of the bipolar coating, it is important to minimize the width between the channels, reduce the channel cross-section, and increase the channel depth [18].

Water management is important because drying causes decreased cell performance due to reduced conductivity, water saturation causes degradation of fuel cell materials and reduces mass transfer. The reason for using thermal management is that increasing the temperature is generally to evaporate water and increase mass transport. The use of waste heat from

PEMs is limited due to the small temperature difference. The operating cell temperature is a very important parameter because it has a great effect on both PEM fuel cell electric and thermal efficiencies: the electric power generated and the quality of the heat available for cogeneration depend on it. As the operating temperature increases, the ideal voltage of the fuel cell (reversible) decreases theoretically [19].

The majority of commercially available fuel cell membranes are based on perfluorosulfonic acid polymer membranes (e.g., Nafion, Flemion, and Acipex). Commercial PEMs have several advantages, including strong proton conductivities at low working temperatures, a wide range of relative humidity, and good physical and chemical stabilities [20]. However, various limitations limit perfluorosulfonic utilization, including its expensive cost, high methanol permeability, and incompatibility with other elements in the environment [21, 22].

The overall reactions for the proton-exchange membrane fuel cells are given below:

At the anode: $H_2 \rightarrow 2H^+ + 2e^-$ (28)

At the cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (29)

The overall cell reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (30)

Schematic representation of the general operation of a proton-exchange membrane fuel cell as shown in Figure 8.

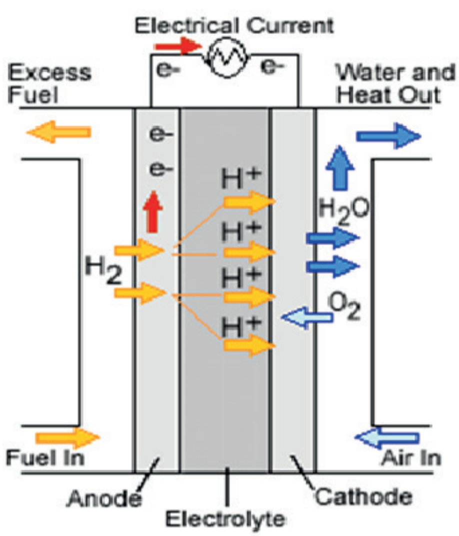

Figure 8. Schematic representation of the general operation of a proton-exchange membrane fuel cell [16].

4.4.1. Proton-Exchange Membrane Fuel Cell Applications

- Power output of 50-250 kW. Mainly used in mobile applications.
- Portable power such as cell phone batteries can be instantly recharged with plug-in fuel (Methanol).
- Transportation such as Electric automobiles can use fuel cells to generate electricity to drive the electric motors that drive the wheels.
- Backup power
- Small distributed generations

4.5. Solid Oxide Fuel Cell (SOFC)

Solid oxide fuel cells operate at temperatures very high temperatures between 500 and 1000 °C. The electrolyte in solid oxide fuel cells is often a hard ceramic metal compound such as calcium oxide or zirconium oxide. In solid oxide fuel cells, hydrogen and carbon monoxide can be employed as reactive fuel. Solid oxide fuel cells are ideally suited for large-scale stationary power generators that can power companies and cities. Solid oxide fuel cells are projected to convert fuel into electricity at a rate of 50-60%. Overall fuel consumption efficiency can be as high as 80-85% in applications designed to capture and utilize the system's waste heat (co-generation). At the cathode, oxygen is typically supplied by air. Oxygen ions travel through the crystal lattice at very high temperatures. Solid oxide fuel cells use a solid oxide electrolyte to conduct negative oxygen ions from the cathode to the anode [23].

The overall reactions for the solid oxide fuel cell fuel cells are given below:

Hydrogen is used as the fuel for the reactions	Carbon monoxide is used as the fuel	
At the anode: $\frac{1}{2}O_2 + 2e^- \rightarrow O$	$CO + O^{2-} \rightarrow CO_2 + 2e^-$	(31)
At the cathode: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O + 2e^-$	$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$	(32)
The overall cell reaction: $\frac{1}{2}O_2 + H_2 \rightarrow H_2O$	$CO + \frac{1}{2}O_2 \rightarrow CO_2$	(33)

Schematic representation of the general operation of a solid oxide fuel cell as shown in Figure 9.

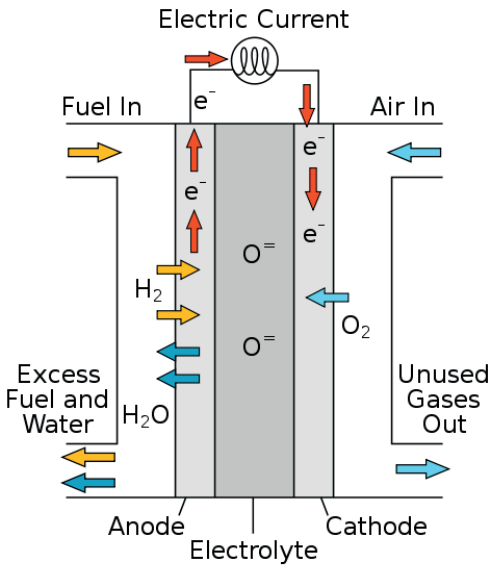

Figure 9. Schematic representation of the general operation of a solid oxide fuel cell [16].

4.5.1 Solid Oxide Fuel Cell Applications

- SOFCs are suitable for stationary applications as well as for auxiliary power units used in vehicles to power electronics [24]. Mainly used for industrial applications, may be used in automobiles as an auxiliary power unit. Power output of 100 kW
- Auxiliary power
- Large distributed generation
- Electric utility

5. Fuel Cell Applications – an Overview

While fuel cells efficiently convert chemical energy into electricity, some of the energy is produced in the form of heat due to inevitable losses. Fuel cell systems can therefore be used for combined heat and power production even on a small scale in individual buildings. Combined heat and energy production allow for more efficient use of heat than traditional methods of producing heat alone [25]. A comparison of fuel cell applications with advantages and disadvantages is shown in Table 5.

Table 5. A comparison of fuel cell applications.

Fuel cell type	Rated Power	Applications	Advantages	Disadvantages
PEMFC	1-250 KW	-Transportation -Backup power -Portable power	-Solid electrolyte reduces corrosion -Low temperature -Low pressure -Quick start-up -Compact and robust	-Requires expensive catalyst -High sensitivity to fuel impurities -Waste heat temperature not suitable for combined heat and power
AFC	10-100 KW	-Space -Military	-Cathode reaction is faster in alkaline electrolyte, leading to higher performance -High efficiency -Low weight and volume	-Expensive removal of CO_2 from fuel -Fuel must be pure hydrogen. -Short lifetime. -Water treatment complex
PAFC	50 KW- 1 MW	-Distributed generation	-Increased tolerance to impurities in hydrogen -High efficiency -Higher overall efficiency with combined heat and power	-Require expensive platinum catalyst -Low current and power -Large size/weight -Maximum tolerance of 2% CO
MCFC	1 KW- 1 MW	-Large distributed generation -Electric utility	-Suitable for combined heat and power -High efficiency -Fuel flexibility -Can use a variety of catalysts -High-speed reactions.	-High temperature enhances corrosion and breakdown of cell components -Slow start-up -High intolerance to sulphur
SOFC	1 KW-3 MW	-Large distributed generation -Auxiliary power -Electric utility	-Suitable for combined heat and power -Can use a variety of catalysts -Fuel flexibility -Variety of fuels -Chemical reactions are very fast	-Brittleness of ceramic electrolyte with thermal cycling -High temperature enhances corrosion and breakdown of cell components -Slow start-up

Fuel cells are used to generate primary and backup electricity in commercial, industrial, and residential settings. Stationary fuel cells, remote weather stations, spacecraft, huge parks, communications centers, research stations, and some military applications all employ fuel cells as a power source in remote regions such as rural areas. Currently, three sectors are receiving increased attention for fuel cell applications. Transportation (cars, buses, trucks, submarines, ships, spacecraft, and so on), stationary power (power for remote locations, backup power, stand-alone power plants for towns and cities, distributed generation for buildings, and co-generation), and portable power (cell phones, radios, and laptops, among other things) are examples of these uses [9, 26]. The fuel cell technology power application range is shown in Figure 10.

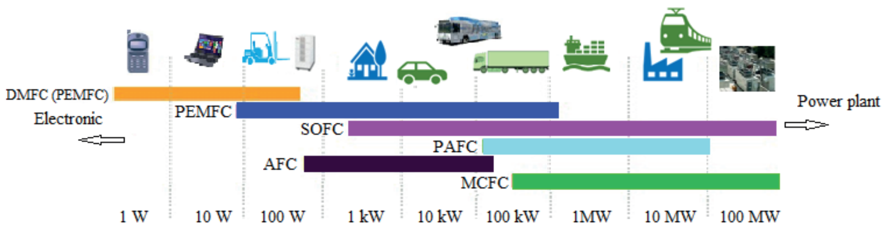

Figure 10. Fuel cell technology power application range.

Fuel cell applications are given below according to their usage areas.

- **Stationary applications**

Fuel cells have some fixed applications: Hospitals, shelters, centers for elderly care, hotels, offices schools, landfills and wastewater plants. Over 2,500 fuel cell systems have been built globally in hospitals, shelters, senior care centers, hotels, offices, and schools. The fuel cell system is frequently connected to the grid in these places to supply additional electrical power to the facility. Today, electrical energy production systems based on fuel cells reach an efficiency of up to 50% in the process. Because fuel cells are used at high temperatures in stationary applications, cogeneration can reduce energy consumption while increasing efficiency by up to 85%. Fuel cells are beginning to compete with batteries in the power ranges of 1 to 5 kW in telecommunications systems located in distant regions where the electrical grid is inaccessible [27]. Fuel Cells produce 95% less nitrogen oxide emissions than conventional coal-fired power plants. A typical capacity range of a home fuel cell is 1–3 kW of electricity and 4–8 kW of thermal energy [8].

- **Transport applications**

Most vehicle manufacturers have fuel cell vehicles and are continuing research, development or testing. Some fuel cell cars manufacturer are Mercedes-F-Cell, Daimler-Chrysler, Fiat-Panda, Ford- HySeries edge, GM-Provoq, Honda-FCX Clarity, Hyundai-I-Blue, ix35 FCEV, Morgan-LIFECar, Peugeot-H2Origin, Renault-Scenic FCV H2, Mitsubishi-SX4-FCV, and Toyota-FCHV-adv, Mirai. In recent years, many fuel cell buses have come into operation around the world. Some of fuel cell bus manufacturers are Volvo, Mercedes Benz-Citaro, Bavaria, Neoplan, Van Hol, Toyota, and UTC bus. UTC buses had driven more than 970,000 km by 2011. An international consortium has been developing since 2003 a locomotive of 109 metric tonnes with a 1.2 MW power plant based on eight modules of the same type of fuel cell PEM 150 kW [27]. The German Navy operates type 212 submarine with fuel cell propulsion. In 2018, the first fuel cell-powered trains, Alstom Coradia iLint multiple units, began service on the Buxtehude-Bremervörde-Bremerhaven-Cuxhaven route in Germany. In the United States, over 4,000 fuel cell forklifts were employed in material handling. A British manufacturer of hydrogen-powered fuel cells, Intelligent Energy (IE) in 2005.

- **Portable applications**

Portable fuel cell systems can generally be classified as those weighing less than 15 kg and providing power below 5 kW. Fuel cells can provide substantially longer battery life in mobile phones and computers. A Direct Methanol battery is typically used in these applications. Fuel cells can power telecommunications equipment, as proven by Motorola, Toshiba, Samsung, Panasonic, Sanyo, and Sony. Micro fuel cells can also be used in pagers, video rewriters, hearing aids, smoke detectors, security alarms, and inspection meters. Methanol is used to power fuel cells in these circumstances.

6. Conclusion

Interest in renewable and alternative energy sources is increasing due to global energy supply, global warming and environmental pollution problems. Nowadays, as a result of various regulations, the production and use of electric vehicles have begun to increase rapidly, while coal-fired thermal power plants continue to be closed. Fuel Cell production systems, especially those using hydrogen energy, are one of the most likely to be used among alternative energy sources in the 21st century due to their high efficiency and ability to accommodate a wide variety of different fuels. Once the problem of storing hydrogen, the main fuel of fuel cells is solved, the use of fuel cells will increase rapidly. As the use of renewable energy production systems becomes widespread, hydrogen production from this energy will increase and a significant market potential will arise with the rapid development of fuel cell production systems. In this section, the operating principles of the fuel cell and the types of fuel cells that have commercial applications are examined in detail. Theoretical efficiency calculations of the fuel cell have been made. When combined with the efficiency of battery and combined heat and power systems, it appears to be advantageous compared to today's energy production systems. It is necessary to foresee that the future will be the field of energy production with the advances in fuel cell technology, which is a clean and safe system. Fuel cell applications were examined and classified according to their usage areas.

References

[1] Kothari R., Buddhi D., Sawhney R.L., Comparison of environmental and economic aspects of various hydrogen production methods, Renew Sustain Energy Review, 12(2), 2008, 553–63.

[2] Mueller-Langer F., Tzimas E., Kaltschmitt M., Peteves S., Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium term. International Journal of Hydrogen Energy, 32(16), 2007,3797–810.

[3] O'Hayre R., Cha S.W., Colella W.G., Prinz FB. Fuel Cell Fundamentals. John Wiley & Sons Inc., Hoboken, NJ, USA, 2016.

[4] Shin C., Nam HT., Lee S., Effect of hydrogen addition on flame stability and structure for low heating value coaxial nonpremixed flames, Combustion Science and Technology, 195:12, 2933-2951, 2023.

[5] Ahmed S., Krumpelt M.,, Hydrogen from hydrocarbon fuels for fuel cells, International Journal of Hydrogen Energy, 26:4, 291-301, 2001.

[6] Stolten D, Hydrogen and fuel cells: fundamentals, technologies and applications. John Wiley & Sons; 2010.

[7] Fan L., Tu Z., Chan S.H., Recent development of hydrogen and fuel cell technologies: A review, Energy Reports, 7, 8421-8446, 2021.

[8] Cigolotti V., Genovese M., Fragiacomo P., Comprehensive Review on Fuel Cell Technology for Stationary Applications as Sustainable and Efficient Poly-Generation Energy Systems, Energies, 14(16),4963, 2021.

[9] Raza R., Akram N., Javed M.S., Rafique A., Kaleemullah M., Ali A., Saleem M., Ahmed Riaz., Fuel cell technology for sustainable development in Pakistan – An over-view. Renewable and Sustainable Energy Reviews, 53. 450–461, 2015.

[10] Blum, L., Deja, R., Peters, R., Stolten, D., Comparison of efficiencies of low, mean and high temperature fuel cell systems\ International Journal of Hydrogen Energy, 36(17), 11056-11067, 2011.

[11] Özdemir E., Ermiş K., Using fuel cell in electric transportation systems, National Transportation Symposium, 541-548, İstanbul, 1996.

[12] Hamada A.T., Orhan M.F.,. Kannan A.M., Alkaline fuel cells: Status and prospects, Energy Reports, 9, 6396-6418, 2023.

[13] Ferriday T.B., Middleton P.H., Alkaline fuel cell technology - A review, International Journal of Hydrogen Energy, 46(35), 2021.

[14] GenCell production, assessed at 10/09/2023 available online at https://www.Gencellenergy .com/our-products/gencell-a5/

[15] Kılıçaslan A., Ermiş K., Investigation of fuel cell types, I. National Sakarya Alumni Group Science and Social Sciences Symposium, Sakarya, 57-66, 2019.

[16] Xianguo L., Principles of Fuel Cells, New York, Taylor and Francis group, 2006.

[17] Özdemir E., Ermiş K., Electrochemical fuel cell technology, Metal and Machinery, 76, 67-70 (1996).

[18] Aktaş A.B., Ermiş K., Mesta O.Ö., Exergy analysis of PEM fuel cell, I. National Sakarya Alumni Group Science and Social Sciences Symposium, Sakarya, 21-31, 2019.

19] Ermis K., Toklu E., Yegin M., Investigation of operating temperature effects on PEM fuel cell, Journal of Engineering Research and Applied Science, 9(2), 1538-1545, 2020.

[20] Ermiş K., Karacan U., Comparison of proton exchange membrane fuel cells and the current system used in buildings, I. National Sakarya Alumni Group Science and Social Sciences Symposium, Sakarya, 40-46, 2019.

[21] İsmail Ö., Ermiş K., Investigation of parallel, serpentine and non-directional flow channel designs in PEM fuel cells, I. National Sakarya Alumni Group Science and Social Sciences Symposium, Sakarya, 12-20, 2019.

[22] Çözül İ., Gündoğdu R., Ermiş K., Instant monitoring and control of power, temperature, relative humidity and speed of an electric vehicle powered by fuel cell, I. National Sakarya Alumni Group Science and Social Sciences Symposium, Sakarya, 67-76, 2019.

[23] Ermis K., Investigation on cobalt-free anodes and cathodes for solid oxide fuel cell, Journal of Engineering Research and Applied Science, 8(2), 1160-1167, 2019.

[24] Kılıçaslan, I., Ermiş K., Özdemir E., analysis and economic aspects of fuel cell power plant instead of Gökova Thermoelectric Power Plant in Turkey, Proc. of 1st Trabzon International Energy and Environment Symposium, Trabzon, 85-91, 1996.

[25] Ekmekçi, I. Ermiş K., The importance and application areas of fuel cells, 3e Electrotech, 105, 142-148, 2003.

[26] Ermiş K., Bacak S., Applications of fuel cell in domestic and commercial buildings, I. National Sakarya Alumni Group Science and Social Sciences Symposium, Sakarya, 32--39, 2019.

[27] Andujar J.M., Segura F., Fuel cells: History and updating. A walk along two centuries, Renewable and Sustainable Energy Reviews 13, 2309–2322, 2009.