**An Overview of Fuel Cell Technology: Fundamental and Applications.**

**Abstract**

Fuel cell technology has emerged as a promising alternative energy source due to its high efficiency, low emissions, and potential for diverse applications. This review paper explores the latest developments in fuel cell technology, categorizing various types based on electrolyte, operating temperature, and electrical efficiency. It discusses fuel cell setups, competing technologies, and ongoing research efforts. Additionally, the paper outlines fuel cell applications in stationary, portable, and transport sectors, highlighting their potential to revolutionize clean energy solutions.

**Keywords**

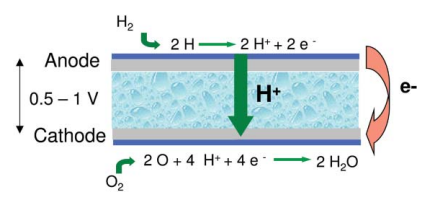
Fuel cell, AFC (Alkaline fuel cell), PEMFC (Proton exchange membrane fuel cell), DMFC (Direct methanol fuel cell), PAFC (Phosphoric acid fuel cell), MCFC (Molten carbonate fuel cell), SOFC (Solid oxide fuel cell), Anode, Cathode, Electrolyte, Stationary, Portable.

**1. Introduction**

One of the most difficult issues that must be forcefully addressed in the present is the dependency on fossil fuels. This is due to the fact that using them is not environmentally friendly and causes severe problems including air pollution and global warming. Development and economic security are impacted by this issue. It is very likely that there will be a fossil fuel substitute that is also more efficient, sustainable, and environmentally benign. One of the most promising technological developments to address the issue among all the various renewable energy-related technologies is fuel cell technology. Fuel cells are generally considered as a clean, efficient, and silent technology that can produce electricity and heat from fossil fuels, biofuels as well as hydrogen produced from renewable energy sources such as wind energy and solar energy. The main hurdles preventing commercial introduction still are too high cost, lack of durability, too high system complexity and a lack of fuel infrastructure. Use of renewable energy is already growing. Of the 300 GW of new electricity generation capacity built globally between 2008 and 2009, about 140 GW was the capacity generated from renewable sources. In 2005, renewables produced 16.5% of world primary energy. According to the special report on renewable energy sources and climate change mitigation [1,2], renewable energy could account for almost 80% of the world's energy supply within four decades. Fuel cells technology is one of the most promising technologies that can be developed in relation with the increasing renewable energy supply. Fuel cell according to [3,4] is gradually becoming a practical technology option that competes with conventional internal combustion engine generators and batteries.

**2. Fuel cell and its principle**

An electrolyte and two electrodes make up the basic components of each fuel cell. At the negative anode, a fuel such as hydrogen is being oxidized, while at the positive cathode, oxygen is reduced. From one side to the other, ions are moved via the electrolyte. The operating temperature range depends on the type of electrolyte. The catalyst that may be utilized and the fuel's purity are both determined by this window of operation. A hydrogen-oxygen fuel cell's voltage in open circuit is 1.23 V at 298 K. The cell voltage varies between 0.5 and 1 V when under load.



**Fig. 1** Basic principle of a fuel cell

**3. Different types of fuel cell**

Six types of fuel cells have evolved in the past decades. They are-

**3.1 Alkaline fuel cell, AFC**

The AFC uses liquid potassium hydroxide as its electrolyte. The temperature is typically around 80 °C, although it can reach 200 °C. The AFC is now employed by spacecraft to generate electricity. Because basically only pure hydrogen can be utilised as fuel, the use of AFCs is constrained. The AFC has a power density of about 0.1 and 0.3 W cm-2. In the kW range, alkaline fuel cells are very accessible [8].

**3.2 Proton exchange membrane fuel cell, PEMFC**

The PEMFC uses a cation-exchange membrane as its electrolyte. About 80 °C is the working temperature. Cold starts are feasible below 0 °C. The PEMFC is the preferred fuel cell for use in transportation applications. Additionally, PEM fuel cells are being developed for stationary applications. The PEMFC is sensitive to fuel contaminants. The PEMFC has a power density that falls between 0.35 to 0.7 W cm-2. PEM fuel cells in the 1 W to 250 kW range are currently being developed [8].

**3.3 Direct methanol fuel cell, DMFC**

A version of the PEMFC that makes use of the same electrolyte is the direct methanol fuel cell. Methanol in water is directly oxidized to CO2 as a fuel. The DMFC's power density is significantly lower than the PEMFC's. At cell voltages as low as 0.2-0.3 V, maximum power densities of 0.25 W cm-2 are achieved [5] [6]. High noble metal loadings, at least 1.2 mg cm-2, are used in comparison to the PEMFC. The DMFC is being developed primarily for 1-100 W portable applications. Micro fuel cell technologies could potentially replace batteries due to the high energy density of methanol [8].

**3.4 Phosphoric acid fuel cell, PAFC**

The PAFC uses liquid phosphoric acid as its electrolyte. The temperature is about 200 °C when it is working. Reformate with CO concentrations of up to 1-2% can be used in the PAFC. In 2003, 245 of the 200 kW systems for the fuel cell with the greatest commercial success to date were already in place. The PAFC has a power density of around 0.14 W cm-2 [7].

**3.5 Molten carbonate fuel cell, MCFC**

The electrolyte in the MCFC is a molten mixture of lithium, sodium, and potassium carbonate. In operation, the temperature ranges from 600 to 700 °C. The possibility of internal reformation of hydrocarbon fuels is made possible by the high working temperature. The MCFC has a power density in the region of 0.1-0.12 W cm-2. MCFC systems have a power range of 50 kW to 5 MW [8].

**3.6 Solid oxide fuel cell, SOFC**

In the SOFC, yttrium stabilised zirconia is typically utilised as the solid electrolyte. The SOFC can run between 600 °C and 1000 °C depending on the electrolyte and the material composition of the electrodes. Fuels ranging from hydrogen to higher hydrocarbons and natural gas can be employed. The SOFC is primarily being developed for stationary power production systems with capacities between 1 kW and 5 MW. However, it is also regarded as a significant choice for 5-kW or less auxiliary power units installed inside of automobiles. The SOFC's power density ranges from 0.15 to 0.7 W cm-2 [8].

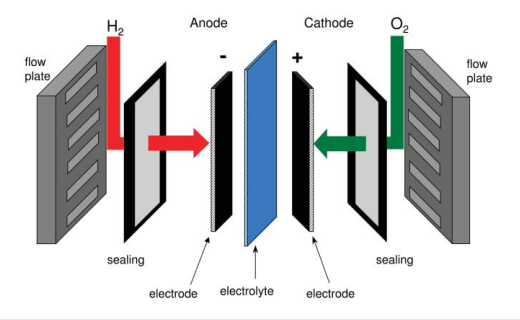
But now there are many types of fuel cell available in the market today. Fuel cell conventionally categorized according to their electrolyte material. They differ in their operating temperatures, electrical efficiencies, and typical applications. Table 1 describes the main differences between the most common fuel cell types available in the market.

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| **Table 1-** Fuel cell types according to electrolyte [9] |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Fuel cell type | Typical electrolyte | Typical anode and cathode catalyst | Operation temperature (°C) | Electrical efficiency (%) |
| Low-temperature proton exchange membrane | Solid Nafion | Anode: Platinum supported on carbon.  Cathode: Platinum supported on carbon. | 60-80 | 40-60 |
| High-temperature proton exchange membrane | Solid composite Nafion, Polybenzimidaz-ole doped in phosphoric acid | Anode: Platinum-Ruthenium supported on carbon  Cathode: Platinum-Ruthenium supported on carbon | 110-180 | 50-60 |
| Solid oxide | Solid yttria-stabilized zirconia (YSZ) | Anode: Nickel-YSZ composite  Cathode: Strontium-doped lanthanum magnetite (LSM) | 800-1000 | 55-65 |
| Molten Carbonate | Liquid alkali carbonate (LiCO3, Na2CO3, K2CO3) in Lithium aluminate (LiAlO2) | Anode: Nickel Chromium (NiCr)  Cathode: Lithiated Nickel oxide (NiO) | 600-700 | 55-65 |
| Phosphoric acid | Concentrated liquid phosphoric acid (H3PO4) in Silicon carbide (SiC) | Anode: Platinum supported on carbon  Cathode: Platinum supported on carbon | 160-200 | 36-45 |
| Alkaline | Potassium hydroxide (KOH) water solution,  Anion exchange membrane | Anode: Nickel  Cathode: Silver supported on carbon | 80-200 | 60-70 |
| Direct methanol | Solid Nafion | Anode: Platinum-Ruthenium supported on carbon  Cathode: Platinum supported on carbon | Ambient-110 | 36-60 |
| Direct ethanol | Solid Nafion, Alkaline media, Alkaline-acid media | Anode: Platinum-Ruthenium supported on carbon  Cathode: Platinum supported on carbon | Ambient-120 | 20-40 |
| Direct ethyele glycol | Solid Nafion,  Anion exchange membrane (AEM) | Anode: Platinum supported on carbon  Cathode: Platinum supported on carbon | Ambient-130 | 20-40 |
| Microbial | Ion exchange membrane | Anode: Biocatalyst supported on carbon  Cathode: Platinum supported on carbon | 20-60 | 15-65 |
| Enzymatic | Membrane-less, Ion exchange membrane | Anode: Biocatalyst supported on carbon  Cathode: Biocatalyst supported on carbon | 20-40 | 30 |
| Direct carbon | Solid yttria-stabilized zirconia (YSZ), Molten carbonate,Molten hydroxide | Anode: Graphite or carbon-based material  Cathode: Strontium-doped lanthanum magnetite (LSM) | 600-1000 | 70-90 |
| Direct Borohydride | Solid Nafion,  Anion exchange membrane (AEM) | Anode: Gold, silver, nickel or platinum supported on carbon  Cathode: Platinum supported on carbon | 20-85 | 40-50 |
| Direct formic acid | Solid Nafion | Anode: Palladium or platinum supported on carbon  Cathode: Platinum supported on carbon | 30-60 | 30-50 |

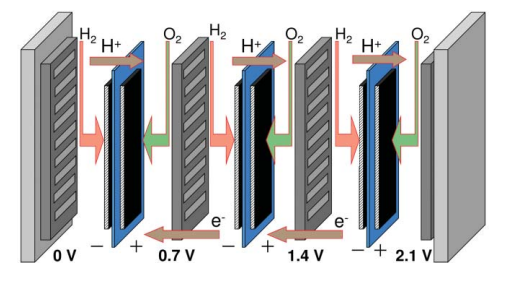
**4. Fuel cell setup: from single cell to systems**

**Single cell.** The electrolyte performs dual roles as an electrical insulator and gas separator in addition to transmitting ions from one electrode to the next. The locations of the electrochemical reactions are the electrodes. Along with having the appropriate catalysts, the electrode architecture should be such that the reactants and products are transported to and from the catalyst-electrolyte interface as quickly as feasible.A single fuel cell, as displayed in Fig. 2, produces the power, which results from the area × the current density of the cell × the cell voltage. The typical cell voltage under load conditions amounts to 0.7 V, which is too low for practical applications [8].



**Fig. 2** Fuel cell components of a single cell

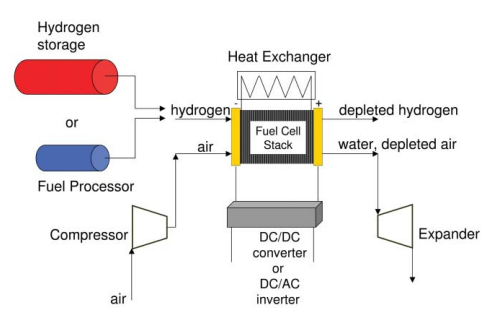
**Stacks.** As a result, connecting several cells in series to create a fuel cell stack is a popular practice. Two adjacent cells are connected by flow plates. These flow plates should have a high electronic conductance and function as a gas separator between the two neighboring cells. They are also known as separator plates or bipolar plates when a single plate is utilized for the anode side of one cell and the cathode side of the other cell. On the cell side of the flow plates are flow patterns that produce an even distribution of reactants throughout the cell area. On the underside, heat is transferred to a system heat exchanger by cooling liquid flow patterns. The stack power and voltage are obtained by the number of cells × the individual cell power and voltage. A three-cell stack is schematically drawn in Fig. 3. [8]



**Fig. 3** Schematic, simplified overview of a fuel cell stack.

**Systems.**  Although the fuel cell is the core of any fuel cell system, it does require a number of other parts in order for it to function and complete its task in the application. A typical fuel cell setup is shown schematically and simply in Fig. 4. The components other than the fuel cell stack and the fuel processor are often called balance of plant components. These balance of plant components play a significant role in terms of system cost, system efficiency, and system durability.

In low temperature fuel cells, except the DMFC, hydrogen is oxidized at the anode to protons. The hydrogen can either be fed from a hydrogen storage container, or produced from another fuel in a so-called fuel processor. Generally, hydrocarbons or alcohols are used as fuels to feed fuel processors. The complexity of the fuel processing depends strongly on the fuel cell type and the primary fuel. In high temperature fuel cells, such as the MCFC and SOFC, fuel processing can be done in the fuel cell itself. This process is referred to as internal reforming.



**Fig. 4** A simplified overview of a fuel cell system.

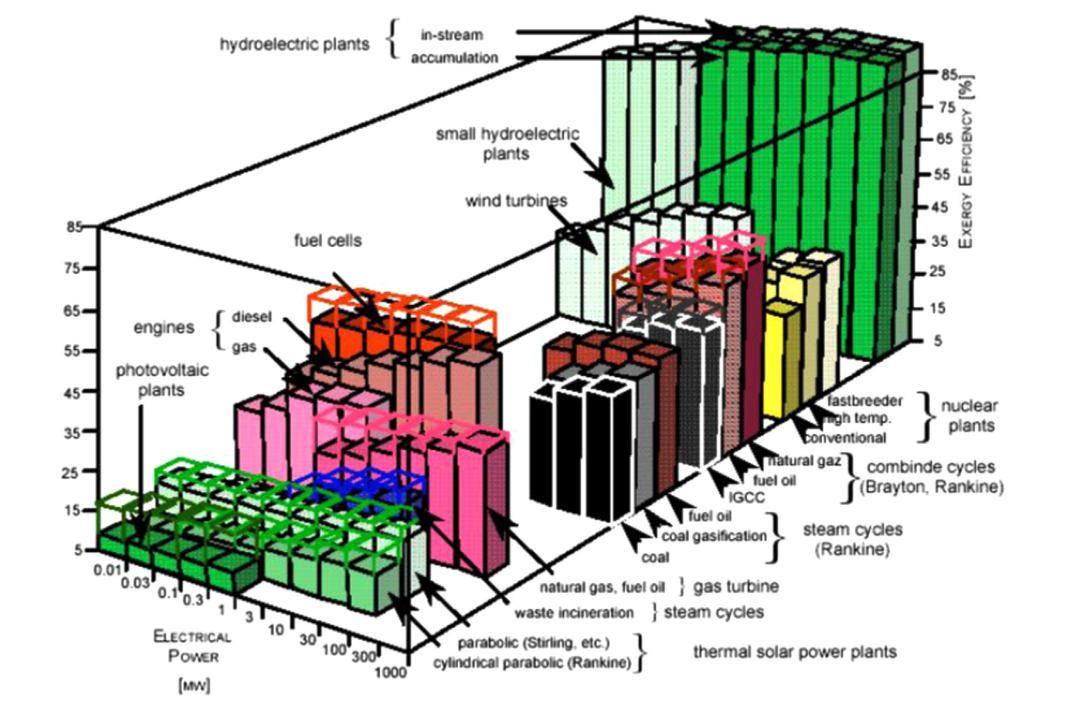
The air pressure needs to be raised from ambient pressure up to a level, which depends on the operation pressure and the pressure drop in the complete system. This can range from a gauge pressure of 100 mbar to several bars. The power of the fuel cell stack generally increases with increasing pressure.

The voltage of the fuel cell stack is the product of the number of cells × the individual cell voltage, which is typically 0.6–0.7 V DC. For stationary applications, generally AC voltage is needed, which requires a DC/AC inverter [8].

**5. Competing technologies**

Fig. 5 presents a comparison of energy conversion devices, including photovoltaic panels, thermal solar power plants, waste incineration, gas turbines, diesel engines, gas engines, Rankin cycles, combined Rankin–Brayton cycles, nuclear power plants, wind turbines, and hydroelectric plants [8]. Fuel cells have one of the highest energy efficiencies among these technologies. Fuel cells have advantages in the portable sector, high efficiencies and capacity factors in the stationary sector, and high efficiencies and fuel flexibilities in the transportation sector.

Fuel cells produce fewer-to-zero pollutants and have higher theoretical and practical efficiencies. on the other hand, heat engines are limited by the Carnot efficiency between their low and high working temperatures and are responsible for a significant portion of the world's pollution. Fuel cell stacks are static devices with minimal noise or vibrations, while heat engines have many dynamic components that produce noise and vibrations, limiting their applications.



**Fig. 5** Energy efficiencies of main energy conversion devices. [10]

Both fuel cells and heat engines typically use a hydrogen-based fluid and atmospheric air as the fuel and oxidant, respectively. However, fuel cells combine the fuel and oxidant electrochemically, while heat engines combine the fuel and oxidant via combustion. Additionally, fuel cells produce electrical work directly from chemical energy. While in the case of heat engines, producing electricity is a multi-step process that involves combustion to produce thermal energy from the internal chemical energy of the fuel. Then this thermal energy is converted into mechanical energy, and finally this mechanical energy is converted into electrical energy through the use of a generator. Generally, as the number of energy conversion processes increases in a certain device, the overall system efficiency of the device decreases. Fuel cells and batteries are similar electrochemical cells that use internal oxidation-reduction reactions to convert the chemical energy content of a fuel to DC electricity. However, the composition and role of the electrodes differ significantly between the two energy devices. Batteries use chemical energy stored in their electrodes to fuel electrochemical reactions, while fuel cells use reactants supplied from a separate storage device.

Rechargeable batteries suffer from technical issues that limit their applications, such as power storage and retrieval potential, depth of charge, and number of charge/discharge cycles. In contrast, fuel cells do not suffer from leakage or corrosion of cell components when not in use, unlike batteries.

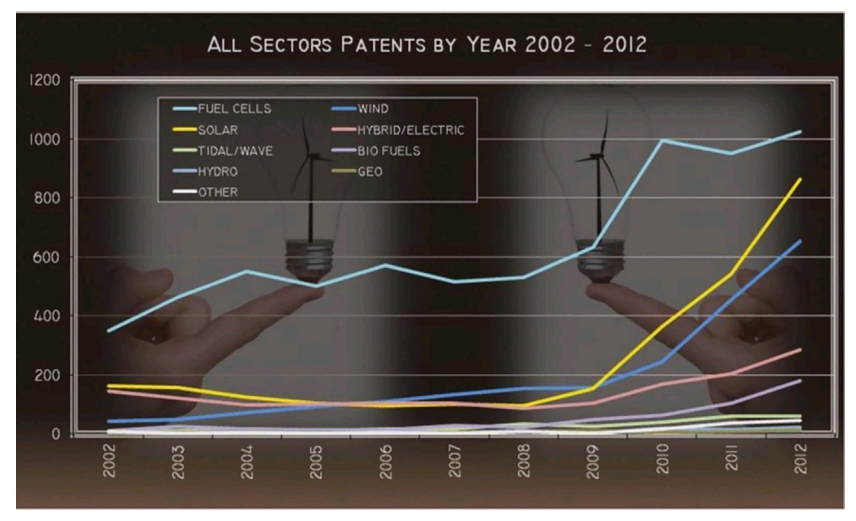
In summary, fuel cells, heat engines, and batteries are all electrochemical devices that have their advantages and disadvantages. Developing more efficient and cost-effective energy generation alternatives is crucial for achieving sustainable and sustainable energy solutions.

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| **Table 2**- Technoeconomic comparison between fuel cells and their competitors. [11] |

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| --- | --- | --- | --- |
| Technology | Efficiency (%) | Lifetime (Years) | Capital cost ($/kW) |
| **Phosphoric acid fuel cell** | 30-45 | 5-20 | 1500 |
| **MCFC/ gas turbine hybrid** | 55-65 | 5-20 | 1000 |
| **SOFC/ gas turbine hybrid** | 55-65 | 5-20 | 1000 |
| **Steam cycle (coal)** | 33-40 | >20 | 1300-2000 |
| **Gas turbine cycle (natural gas)** | 30-40 | >20 | 500-800 |
| **Microturbine** | 15-30 | 5-10 | 800-1500 |
| **Nuclear** | 32 | >20 | 1500-2500 |
| **Hydroelectric** | 65-90 | >40 | 1500-3500 |
| **Wind turbine** | 20-50 | 20 | 1000-3000 |
| **Geothermal** | 5-20 | >20 | 700-1500 |
| **Solar photovoltaic** | 10-15 | 15-25 | 2000-4000 |

**6. Current and future research and development (R&D)**

**6.1 Current status:** The fuel cell industry has experienced significant milestones and accomplishments in the past decade. Between 2002 and 2012, the cost of customized fuel cells for electric vehicles decreased by 83%, from $275/kW to $47KW [12]. This reduction was primarily due to the decrease in platinum group metals (PGM) loading in PEM stacks, which has decreased by two orders of magnitude since the 1960s [13]. The fuel cell industry led in patents granted in various alternative energy sectors between 2002 and 2012, with 44% of these patents going to US developers, followed by 33% in Japan, 7% in Korea, and 6% in Germany [12]. General Motors, Honda, Toyota, Samsung, and UTC Power secured over 60% of these patents. The number of patents granted reflects the level of industrial research in renewable sectors.



**Fig. 5** Patents granted in the alternative energy sector between 2002 and 2012 [14]

**6.2 Future targets:** The fuel cell industry faces significant challenges in achieving widespread commercialization. Advancements in fuel cell technology are crucial for hydrogen production, storage, and delivery. Fundamental breakthroughs in material engineering, nanotechnology, transport phenomena, electrocatalysts, stack engineering, measurement technologies, molecular process simulation, auxiliary components development, and multi-phase science are needed to reduce costs and increase fuel cell durability. Understanding liquid water formulation and interactions can improve water balance and avoid flow misdistribution, enhancing fuel cell performance and efficiency [15]. Key limitations call for R&D focus from both industrial and academic communities include:

a) Developing electrolyte materials that maintain conductivity and stability over a wide range of temperature and humidity.

b) Minimizing or eliminating catalyst PGM loading.

c) Maximizing membrane and catalyst impurities tolerance.

d) Identifying membrane and catalyst stability with voltage and humidity cycling.

e) Developing air managements techniques with reduce noise and cost.

f) improving and simplifying fuel reformation methods.

g) Conducting cost analyses for niche markets along with updated status report.

**7. Application of fuel cell in the stationary, portable fields, and transportation.**

Applications for fuel cells were noted as having different characteristics, such as high-power reliability (telecommunication, high-tech manufacturing facilities, data processing, and call centers), emission minimization or elimination (urban areas, industrial facilities, airports, and vehicles), areas with limited access to the utility grid (portable applications, remote areas), and applications for biological waste gases management. However, this section reviews fixed and portable fuel cell applications [16].

**7.1 Fuel cell application in portable sector**

The portable power production market is driven by the increasing demand for quality, density, and time performance in power supply. Fuel cells offer energy density, durability, simple design, and low cost, making them suitable for portable applications. They are primarily used in outdoor personal uses, commercial applications, and emergency relief efforts. Fuel cells also help preserve the environment and reduce noise. The second market is consumer electronic devices, with fuel cells being potential candidates for portable personal electronics.

They can provide power for communication switching nodes, transmission towers, and reception systems. Portable battery chargers, miniature demonstration vehicles, and educational kits are also growing. The military market demands power systems for portable electronic equipment, with portable DMFCs and PEMFCs being popular due to their silent operation, high power, and low weight. But the problem with the large PEM fuel cell (>2kW) is that they need hydrogen fuel to operate, while hydrogen should be generated from existing logistic fuels [17, 18, 19].

2012 held great potential for portable fuel cells. It should be noted that compared to 2011, there was still a 174% rise in fuel cell shipments. Unit shipments in 2013 were almost 13,000 less than in 2012. However, the portable fuel cell market saw a significant increase in shipments from 2013 to 2014, with several manufacturers reporting annual sales in the 10,000-unit level.

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| **Table 3**- Power Demand for portable devices that may require fuel cell. [20] |

|  |  |
| --- | --- |
| Devices | Power required (W) |
| Cellular phone, Digital camera | 1 |
| Notebook personal computer | 20-30 |
| Flashlight and toys | 1-10 |
| PlayStation portable (PSP) | 2 |
| Robot | 10-15 |

**7.2 Fuel cell application in stationary sector**

Stationary fuel cells, including PEMFC, SOFCs, MCFCs, AFCs, and PAFCs, can be used in power plants for various applications [19]. Low-temperature fuel cells are faster during start-up, while high-temperature systems produce heat for other applications and operate directly on fuels [21]. They can serve as primary power sources, remote area power supplies, hybrid power systems, distributed power, or emergency backups. And we can divide the stationary sector into two parts. One is large stationary power plants (power output from 300 kW up to 20 MW), and the other is small-medium power plants (power output from a few watts up to 10 kW for small stationary power plants and from 10 kW up to 300 kW for medium stationary power plants).

**7.2.1 Large stationary power plants:** Fuel cells can aid in the transition from massively centralized to decentralized distributed energy production. Both on a household-by-household basis and on a basis of larger residential blocks, they can be utilized for domestic electric power or CHP distributed generation. Although they function at low temperatures of between 100 and 200 degrees Celsius, proton exchange membrane fuel cells (PEMFC) and phosphoric acid fuel cells (PAFC) are frequently employed for CHP applications. For bigger residential block-based CHP generation, high-temperature fuel cells are a better option. The architecture of fuel cell systems used for CHP generation could be either grid-independent or grid-assisted.

The first case is more complicated with higher cost, as the system will have to meet dynamic load fluctuations, but it is possible to solve the problem over sizing the fuel cell system and integrating it with battery-banks or ultracapacitors. Grid-assisted systems export electricity to the grid during low load demands and import electricity from the grid during peak load demands. [22]

**7.2.2 Medium and small stationary power plants:** Medium-small power plants (MSPs) are designed for supplying electric power and heat to various structures, including cottages, administrative buildings, and hospitals. These fuel cell-based power plants are ideal for electricity production, co-generation, and industrial and commercial applications. They offer premium quality power, independent power sources, and can operate for onsite or continuous power backup. PEMFCs and DMFCs are the dominant fuel cell types in the electro power system (EPS) market, which requires high reliability but not necessarily high operational lifetimes. The Japanese company Ebara “Ballard” developed a 1-kW power plant for combined heat and power production. The unit was designed to operate for 10 years, in accord with requirements set by the Japanese government. A similar unit is also designed for an operating time of 10 years was developed by the Japanese company “Fuji electric”. These units cost $12.000 to $16.000 [23].

Small power units are also important in remote-area power supply (RAPS) applications, where power may be needed in grid-isolated locations like islands, deserts, forests, and remote technical installations. A project in Australia involves using fuel cells in the Antarctic base on “Bechervaise” Island to produce hydrogen by electrolysis with wind energy and use in low-power fuel cell units producing electric power and heat. This project supported by a grant of $600000 from the Australian government [23].

The limited availability of fossil fuels is making renewable energy sources like wind and solar power promising alternatives due to their environmental impact. Energy storage mediums must be explored to ensure production can continue during unforeseen occurrences. Combining energy storage systems with renewable energy sources through an electrolyser is considered a sustainable process for producing and exploitation of renewable energies.

Standard fuel cell systems have been championed by several developed countries, including the USA, Canada, Japan, South Korea, and Europe. Companies like Fuel Cell Energy, “Accumentris”, “ClearEdge”, and “Bloom Energy” are known for producing stationary fuel cells. The progress of stationary applications has been fueled by government support and the rapid growth of installations of micro-e CHP units [24].

**7.3 Fuel cell application in transportation sector**

The transportation industry is a major contributor to clean energy technologies, as it contributes to 17% of global greenhouse gas emissions annually. To address this issue, the industry is investing in technologies that offer significant reductions in harmful emissions and better energy conversion efficiencies. Fuel cells, which offer near-zero emissions without compromising vehicle propulsion efficiency, have shown efficiencies that are almost twice those of conventional internal combustion engines. These fuel cells offer advantages such as static operation, fuel flexibility, modularity, and low maintenance requirements, making them an ideal future alternative for current combustion engines. Japan has announced a plan to deploy two million fuel cell electric vehicles (FCEVs) with 1,000 hydrogen refueling stations by 2025 [25, 26].

**8. Conclusion**

Fuel cell technology has the potential to revolutionize the way we produce and consume energy. With the ability to generate electricity through a chemical reaction between hydrogen and oxygen. Fuel cells offer a clean, efficient, and reliable alternative to traditional fossil fuel-based power generation. While there are still challenges to overcome, such as reducing costs and improving durability, fuel cell technology has already made significant strides in recent years. As the world continues to seek ways to reduce greenhouse gas emissions and combat climate change, fuel cell technology represents a promising pathway towards a more sustainable future.

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