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Alkaline Fuel Cell Technology: A Brief Review and Market Size Forecasting

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Abstract: With the advent of anionic exchange membrane fuel cells, the world of alkaline-based fuel cells has taken a giant step toward supplanting traditional liquid electrolyte alkaline fuel cells (AFCs). This work aims to introduce and discuss the alkaline fuel cell technology, in addition to discussing all types of fuel cells and the principle of work of each type, and comparing all types. By the end of this work, the global market and forecasting of the alkaline fuel cell was presented, as the growth of this technology is growing globally, which indicates that there will be a clear demand for this the alkaline fuel cell.

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1- Introduction

It is undeniable that enhanced alternative energy technologies are required in research and other applications. Fuel cells are one of the existing technologies, promising to be the best of the battery, with high energy density, low volume, and low maintenance costs. This has aided in the growth of demand in recent years [1, 2].

Fuel cells are one of the most environmentally friendly and efficient methods of generating electricity. Due to the absence of combustion, there are no pollutants produced by boilers and furnaces. The only goods produced by systems designed to use hydrogen directly are power, water, and heat. Fuel cells are a critical technology for a wide variety of potential applications, including on-site electric power generation for households and commercial buildings; supplemental or auxiliary power generation to support automobile, truck, and aircraft systems; power generation for personal, mass, and commercial transportation; and the modular addition of new power generation by utilities to meet growth in power consumption. These applications will span a broad range of sectors globally [3].

We can say that Fuel cells can provide heat and electricity for buildings and electrical power for vehicles and electronic devices.

2- Mechanism of a fuel cell

A fuel cell is made up of an electrolyte sandwiched between two electrodes and a conducting wire connecting them. Hydrogen injected into a single electrode (fuel electrode) splits into hydrogen ions and electrons. The electrolyte conducts hydrogen ions to the other electrode, which receives air (air electrode). Through the conducting wire that connects the two electrodes, electrons move from the fuel electrode to the air electrode. At this point, the electrical current reverses direction. Hydrogen ions combine with oxygen and electrons at the air electrode to form water and heat.

The Expanded View of a Basic Fuel Cell Unit in a Fuel Cell Stack is shown in Figure 2. A fuel cell, like a flat dry-cell battery, is composed of a cathode (air electrode) and an anode (fuel electrode), as well as a thin plastic sheet (electrolyte) sandwiched between the two electrodes. The air and fuel electrodes contain numerous fine grooves, and a chemical reaction occurs when oxygen (i.e., air; oxygen makes up approximately 20% of the volume of air) and hydrogen (which is obtained through the decomposition of natural gas, a material for city gas) supplied from an external source pass through these grooves. Hydrogen is injected into the anode side of the fuel cell, where the catalyst causes the hydrogen atoms to release electrons and form hydrogen ions; the electrons then flow in the form of an electric current. Hydrogen ions pass through the electrolyte to the cathode, where they combine with oxygen and the electrons returning via the external circuit to form water. A fuel cell works on the principle of hydrogen being dissolved into electrons and hydrogen ions. The movement of electrons across the external circuit's wire results in the generation of an electric current; in other words, electricity is generated.

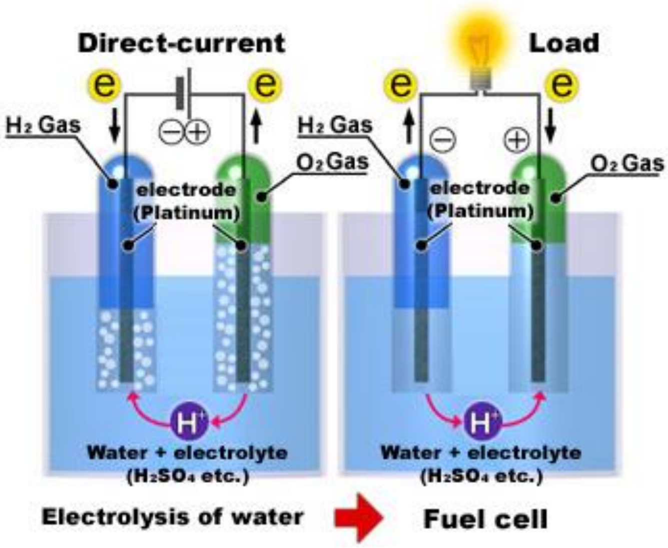

Figure 1 Fuel cell structure.

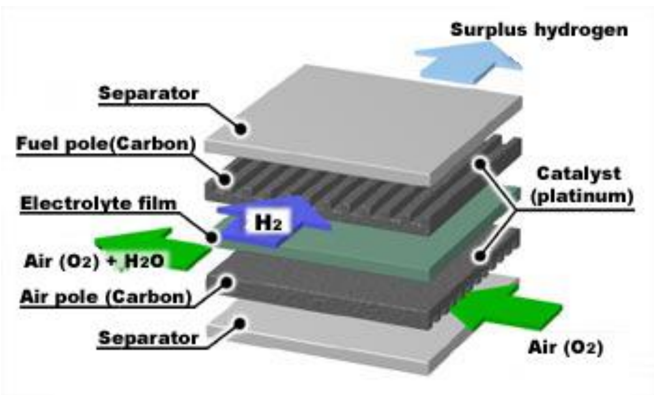

Figure 2 Expanded View of a Basic Fuel Cell Unit in a Fuel Cell Stack

3- Fuel cells classification and engineering

Although the basic operations of all fuel cells are the same, special varieties have been developed to take advantage of different electrolytes and serve different application needs. The fuel and the charged species migrating through the electrolyte may be different, but the principle is the same. An oxidation occurs at the anode, while a reduction occurs at the cathode. The two reactions are connected by a charged species that migrates through the electrolyte and electrons that flow through the external circuit.

3.1- Polymer Electrolyte Membrane Fuel Cells (PEM)

PEM fuel cells, also known as proton exchange membrane fuel cells, employ a proton-conducting polymer membrane as the electrolyte. Typically, hydrogen is used as the fuel. These cells operate at relatively low temperatures and are capable of rapidly varying their output in response to changing power requirements. PEM fuel cells are the most promising choices for automotive propulsion. They can also be utilized to generate electricity on a stationary basis. They cannot, however, directly use hydrocarbon fuels such as natural gas, liquefied natural gas, or ethanol because to their low working temperature. To be used in a PEM fuel cell, these fuels must be transformed to hydrogen in a fuel reformer. A cross-sectional view of a polymer electrolyte membrane fuel cell is shown in Figure 3 [4].

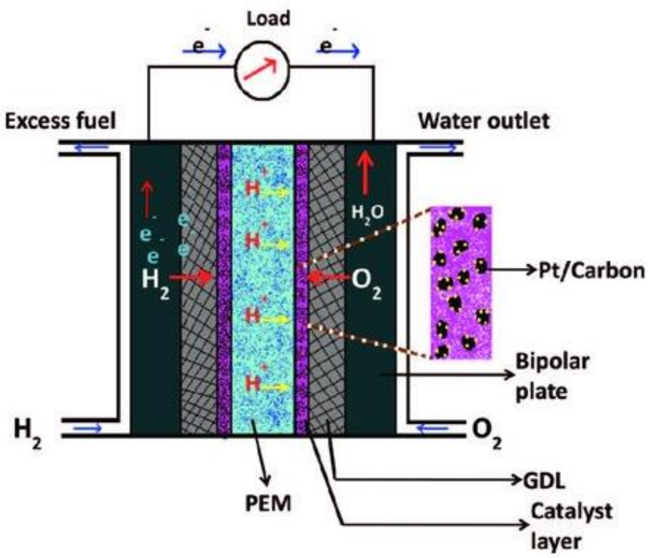

Figure 3 Cross-sectional view of Polymer Electrolyte Membrane fuel cell.

3.2- Direct-Methanol Fuel Cells (DMFC)

The direct-methanol fuel cell (DMFC) is similar to the proton conducting polymer membrane (PEM) cell in that it utilizes a proton conducting polymer membrane as the electrolyte. DMFCs, on the other hand, use methanol directly on the anode, obviating the requirement for a fuel reformer. DMFCs are of interest because they have the potential to power portable electronic equipment such as laptop computers and battery chargers. Methanol has a greater energy density than hydrogen, making it a desirable fuel for portable electronics. The accompanying illustration is a schematic representation of a Direct Methanol Fuel Cell (DMFC), a type of fuel cell that runs on methanol [5].

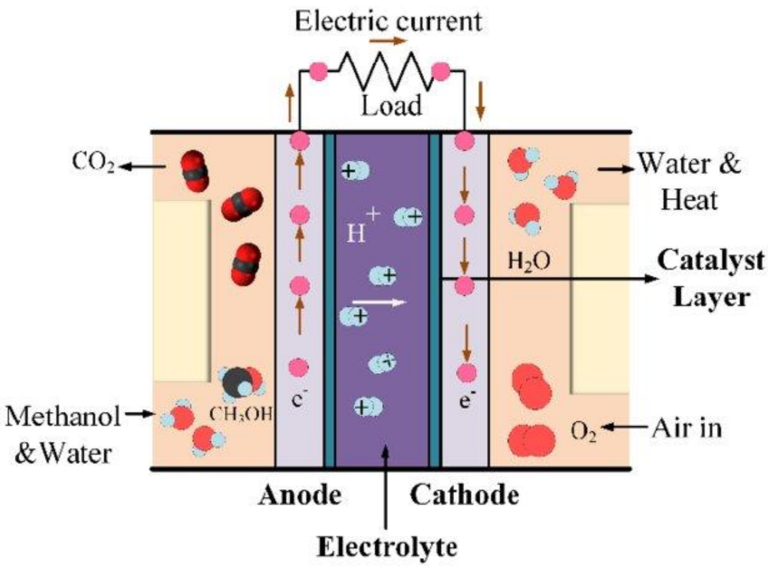

Figure 4 Schematic representation of Direct Methanol Fuel Cell (DMFC).

3.3- Phosphoric Acid Fuel Cells

Phosphoric acid fuel cells work at approximately 200°C and employ a phosphoric acid electrolyte that conducts protons contained inside a porous matrix. They are often installed in 400 kW or higher modules and are utilized for stationary power generation in hotels, hospitals, grocery shops, and office buildings, where waste heat can also be employed. Phosphoric acid can also be immobilized in polymer membranes, and these membrane-based fuel cells are being investigated for a range of stationary power applications. The image below depicts a phosphoric acid fuel cell (PAFC) schematically [6].

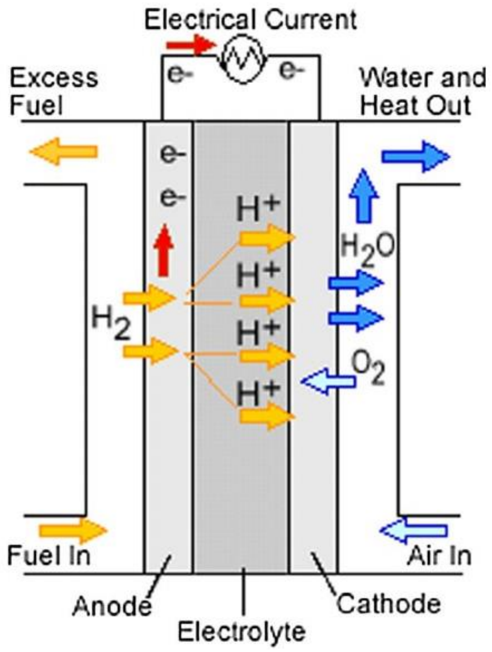

Figure 5 Schematic representation of a phosphoric acid fuel cell.

3.4- Molten Carbonate Fuel Cells

A schematic depiction of a molten carbonate fuel cell (MCFC) is shown in Figure 6 [2]. As their electrolyte, they use a molten carbonate salt trapped in a porous matrix that transmits carbonate ions. They are already being employed in a range of stationary medium- to large-scale applications, where their great efficiency results in net energy savings. Their operation at a high temperature (about 600°C) enables them to reform fuels such as natural gas and biogas internally.

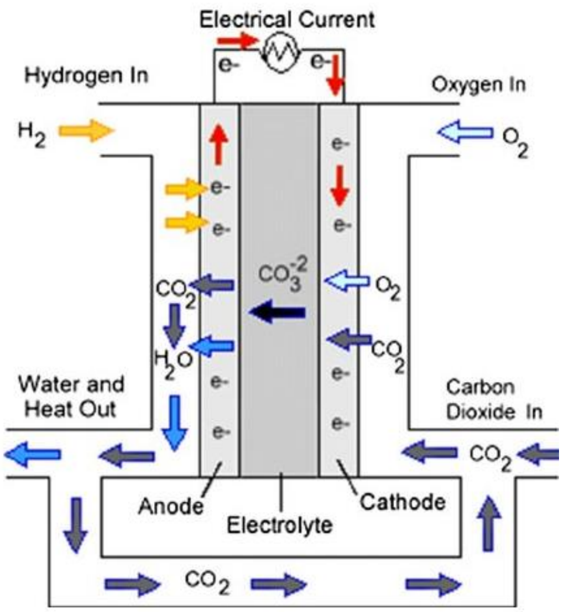

Figure 6 Schematic representation of a molten carbonate fuel cell (MCFC).

3.5- Solid Oxide Fuel Cells (SOFC)

A thin coating of ceramic acts as a solid electrolyte that conducts oxide ions in solid oxide fuel cells. They are being developed for a variety of stationary power applications, as well as for heavy-duty truck auxiliary power devices. These fuel cells, which operate between 700°C and 1,000°C with zirconia-based electrolytes and as low as 500°C with ceria-based electrolytes, may internally reform natural gas and biogas and can be paired with a gas turbine to achieve up to 75% electrical efficiency. The operating principle, SOFC components, and associated half-cell processes using hydrogen as fuel are depicted in Figure 7.

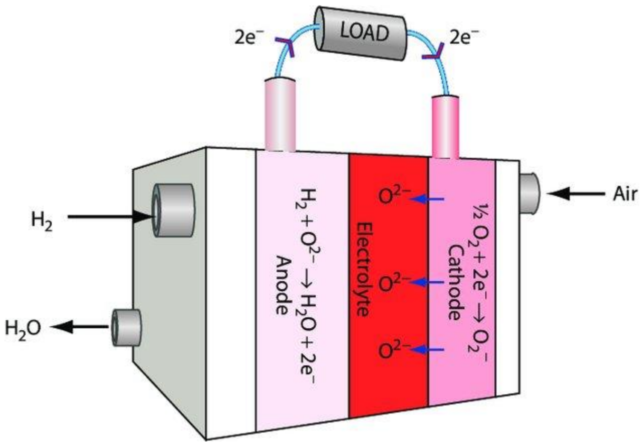

Figure 7 Solid oxide fuel cell (SOFC)

3.6- Combined Heat and Power Fuel Cells

Along with electricity, fuel cells generate heat. This heat can be used to meet a variety of heating requirements, such as hot water and space heating. Combined heat and power fuel cells are attractive for powering homes and buildings, as they can achieve a total efficiency of up to 90%. This highly efficient operation saves money, energy, and contributes to the reduction of greenhouse gas emissions. The gas distribution network seen in Figure 8 is used to transport natural gas. On the other hand, the fuel cell creates heat for the space, as well as water heating and power for lighting and other equipment [7].

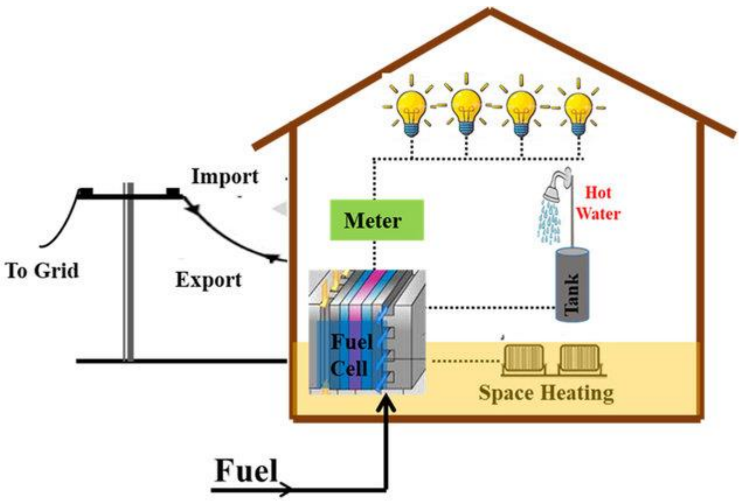

Figure 8 Fuel cell micro combined heat and power (CHP) for importing and exporting electricity.

3.7- Regenerative or Reversible Fuel Cells

The regenerative fuel cell systems consist of two different stacks (one fuel cell and one Electrolyzer) connected to three storage tanks (for hydrogen, oxygen and water) that operate in a closed loop [8]. This kind of systems can be used as auxiliary power supply for spacecraft's (satellites, rovers, etc.).

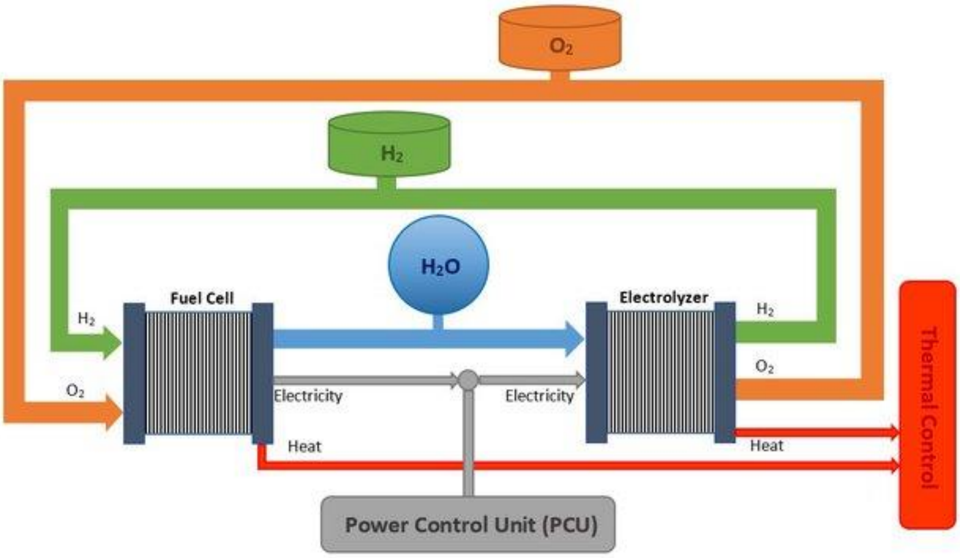

Figure 9 Regenerative fuel cell system schema.

3.8- Alkaline fuel cell (AFC)

Francis Thomas Bacon (1904-1992) of the United Kingdom began experimenting with alkali electrolytes in the late 1930s, eventually settling on potassium hydroxide (or KOH) rather than the acid electrolytes discovered by Grove. KOH exhibited comparable performance to acid electrolytes while being less corrosive to the electrodes. Bacon's cell, like Grove's, featured porous "gas-diffusion electrodes." Gas-diffusion electrodes increased the surface area of the electrode, the electrolyte, and the fuel where the reaction happens. Additionally, Bacon employed pressured air to prevent the electrolyte from "flooding" the electrodes' small pores. Bacon made sufficient progress with the alkali cell during the next two decades to provide large-scale demonstrations.

In this study, this type was well defined in terms of the basics of its work and its use. Alkaline fuel cells use an alkaline electrolyte such as potassium hydroxide or an alkaline membrane that conducts hydroxide ions rather than protons. Originally used by the National Aeronautics and Space Administration (NASA) on space missions, alkaline fuel cells are now finding new applications, such as in portable power.

The following figure shows the difference in all types of fuel cells in terms of production in megawatts, as it is very clear that the production of the alkaline fuel cell is superior to all other types.

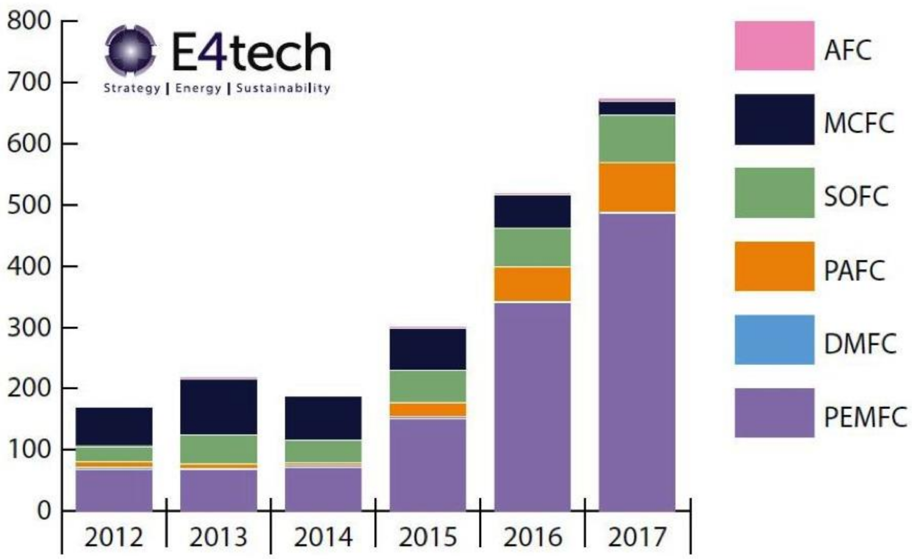

Figure 10 The energy production of the Fuel cells due to 2012-2017, Source: Fuel Cell Industry Review 2017

3.8.1- **Alkaline fuel cell working principle**

AFCs are the first and only cell type to have achieved successful routine applications, mostly in space exploration, such as the United States' space shuttle missions [6]. As shown in Figure 11, AFCs employ a liquid electrolyte solution of potassium hydroxide (KOH) due to its strong alkaline hydroxide conductivity [9]. AFCs generate electricity from hydrogen by facilitating the migration of the hydroxyl ion (OH) from potassium hydroxide from the cathode to the anode. Hydrogen gas combines with the OH ions at the anode to form water and liberate electrons [10, 11].

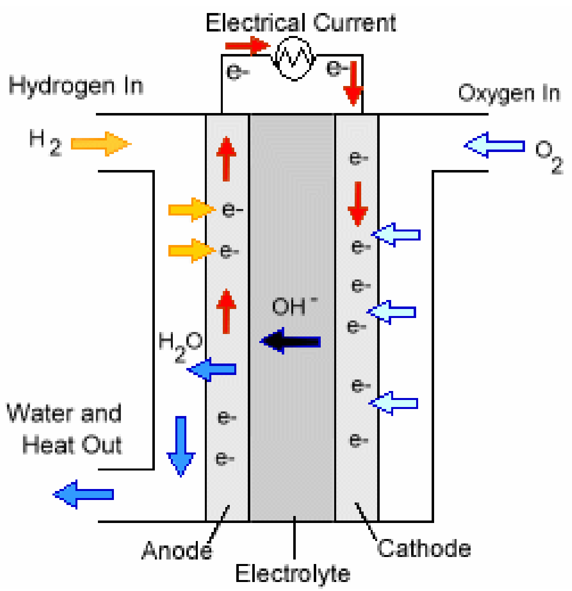

Figure 11 Schematic representation of an alkaline fuel cell.

3.8.2- Chemical Reactions

The operating temperature of alkaline fuel cells range between room temperature to approximately 250 ˚C and can achieve power-generating efficiencies of up to 70 percent. A diagram of the alkaline fuel cell is shown in Figure 12. The chemical reactions that occur in an AFC are as follows:

Anode: $2H2 + 4(OH)^{-} \rightarrow 4H2O + 4e^{-}$

Cathode: $O^{2} + 2H_2O + 4e^{-} \rightarrow 4(OH)^{-}$

Overall cell reaction: $2H_2 + O_2 \rightarrow 2H_2O$ +electrical energy + heat

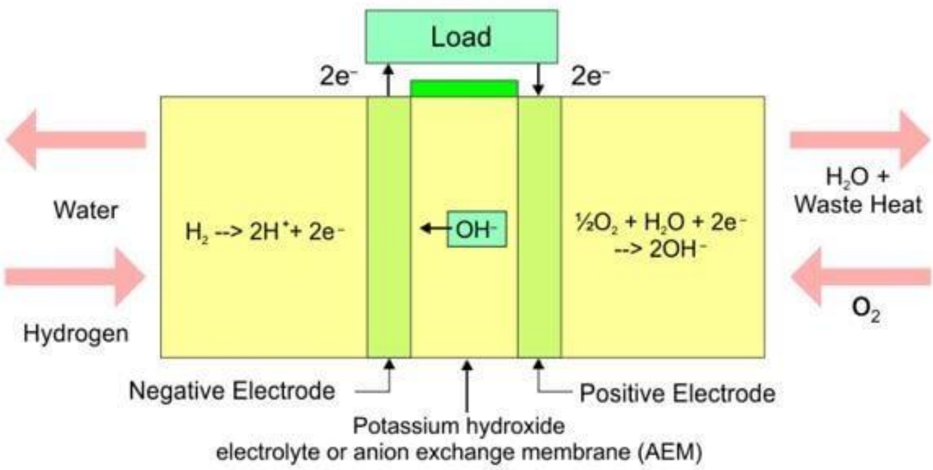

Figure 12 Chemical Reactions in an Alkaline Fuel Cell.

3.8.3- Alkaline fuel cell advantages

Alkaline fuel cells provide several advantages over other types of fuel cells, which can be summarized as follows: operating temperature is low. Alkaline high-temperature fuel cells function between 100°C and 250°C. However, modern alkaline fuel cell designs work at temperatures ranging from 23 to 70 degrees Celsius. Additionally, increased reaction kinetics at the electrodes results in increased cell voltages. This great electrical efficiency enables the use of smaller amounts of a precious metal catalyst such as platinum [9].

3.8.4- Alkaline fuel cell market and forecasting

Alkaline fuel cells have existed for the longest period of any form of fuel cell. This form of fuel cell, developed in the 1930s by Francis Bacon, was used to power a number of the very first fuel cell automobiles (FCVs). Additionally, it was this type of fuel cell that resulted in the iconic "Houston, we have a problem" comment made by James Lovell, the Captain of Apollo 13.

The alkaline fuel cell (AFC) operates by utilizing an alkaline electrolyte such as potassium hydroxide (often in a solution of water). Alkaline fuel cell systems are classed as low-temperature fuel cells since they function at temperatures ranging from 60 to 90 degrees Celsius. Alkaline fuel cells accelerate the processes at the anode and cathode using a range of metals, with nickel being the most frequently employed catalyst.

Due to the rapidity with which chemical reactions occur within the cell, alkaline fuel cell systems often achieve efficiencies of between 45 and 60%. Alkaline fuel cells have a capacity of up to 20 kW and some newer types have been claimed to work at temperatures as low as 23-70oC.

The downside of alkaline fuel cells is that their strongly alkaline electrolytes absorb even trace amounts of CO2, gradually reducing the electrolyte's conductivity. (Several alkaline fuel cell manufacturers assert that this effect is reversible because the electrolyte may be changed.) Additionally, for successful functioning, it is necessary to purify the oxygen used in the cell, and both purifications can be quite costly when combined.

Also as the electrolyte, material is corrosive, and being in liquid form, it makes the sealing of the anode and cathode gases more problematic than when a solid electrolyte is used.

Though this type of fuel cell is well known and understood, it currently (up to 2007), in terms of numbers, makes up less than 5% of new units produced each year, shown in Figure 13.

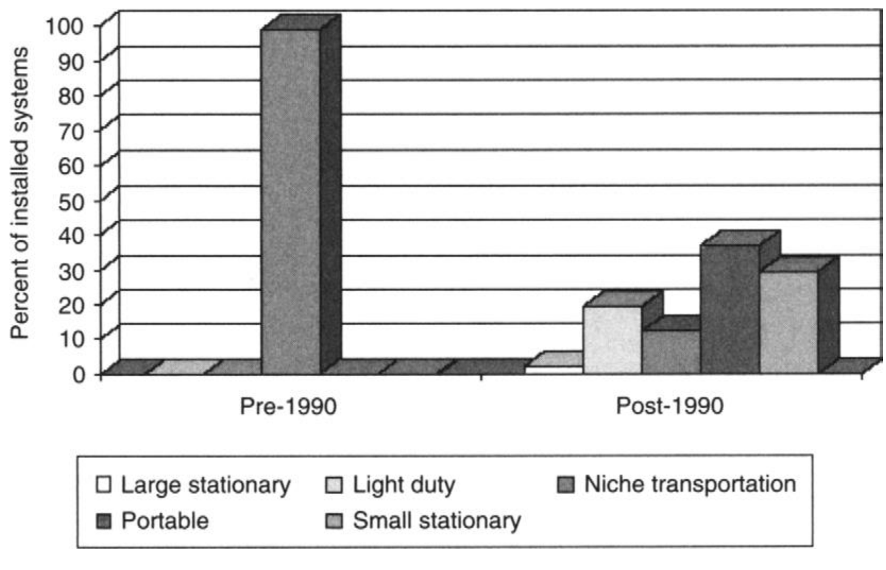

Figure 13 Historical alkaline fuel cell (AFC) market development, *Source:* Fuel Cell Today

The global fuel cell market is being aided by the growing stationary fuel cell shipments, which reached a volume of about 283 megawatts in 2020. The global demand for stationary fuel cell shipments is further expected to grow at a CAGR of 9% in the forecast period of 2022-2027.

Stationary fuel cells can be used for primary power, backup power, or combined heat and power (CHP). According to application, the stationary segment accounts for a sizable portion of the business. The growing demand for stationary fuel cells is due to their capacity to power everything from a laptop to a single family house or even larger loads (200 kW and higher), making them a versatile alternative for a variety of applications including retail, residential, and telecommunications. This has considerably aided the fuel cell industry's expansion. Meanwhile, the transportation market is predicted to expand significantly during the projection period, owing to growing acceptance of fuel cell-powered forklifts and favorable government efforts, particularly in developed nations.

Figure 14 shows the global Alkaline Fuel Cells market (Billion USD) between 2017-2026, while figure 15 denotes the global automotive fuel cell market: industry analysis (2020-2027). The expected to reach US$ 14.23 Bn by 2027, at a CAGR of 34.75% during the forecast period.

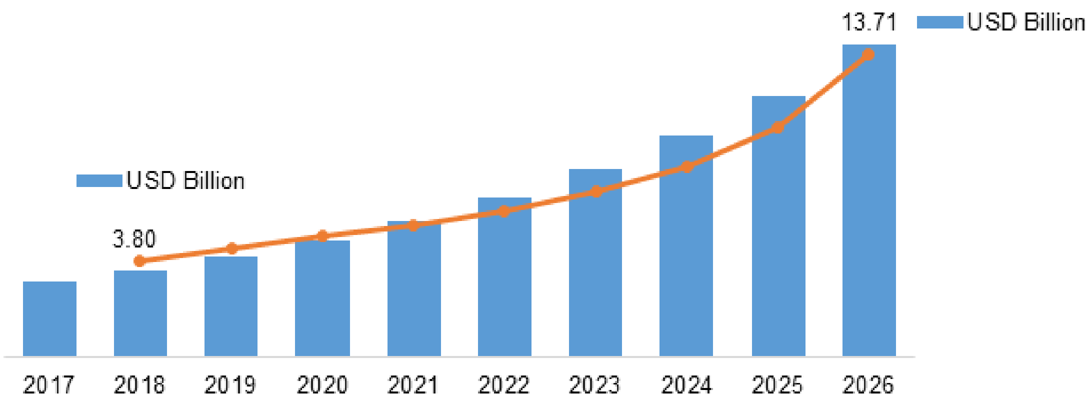

Figure 14 shows the global Alkaline Fuel Cells market (Billion USD) between 2017-2026.

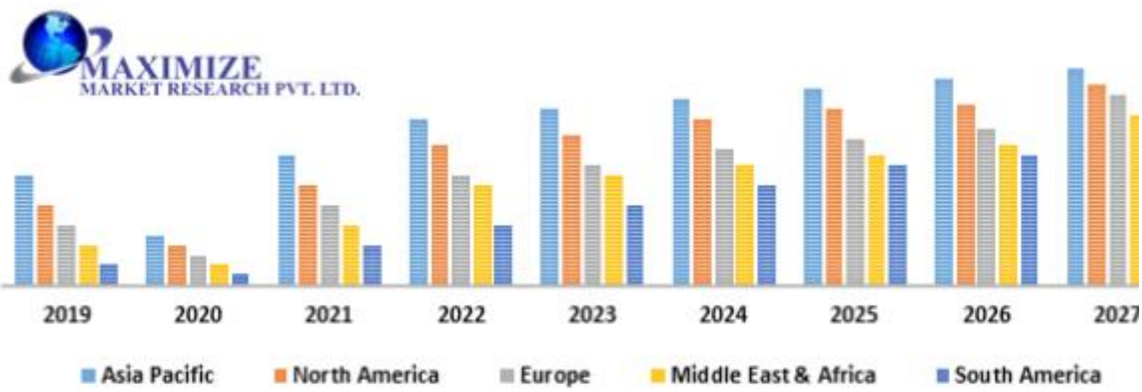

Figure 15 The global automotive fuel cell market: industry analysis (2020-2027).

Conclusion

Fuel cells are without a doubt one of the cleanest and most efficient methods of generating electricity. Because there is no combustion, there are no pollutants released in the same way that boilers and furnaces do. Through the published research and what was contained in this work, it was found that alkaline fuel cells offer some advantages over other fuel cells, one of these advantages can be summed up as low operating temperature. High-temperature, alkaline fuel cells operate at temperatures between 100°C-250°C, alkaline fuel cells produce potable water in addition to electricity, therefore, they have been a logical choice for spacecrafts and alkaline fuel cells can achieve power-generating efficiencies of up to 70 percent. This work has also shown that alkaline fuel cells are witnessing a clear growth in global markets in the previous years, and it is expected that this growth will continue in the coming years.

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