Fuel Cells Design, Operations and Applications

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Abstract

Fuel cells convert the chemical energy of in fuel mainly hydrogen efficiently to electricity without combustion. The process has significantly low emissions with water as the main product of the reaction compared to conventional equipment/techniques that are associate with greenhouse gas emissions. The three main parts of a fuel cell assemble are the anode, cathode, and electrolyte. A catalyst oxidizes fuel with ions travelling via the electrolyte. At the cathode ions are reunited with the electrons. It is the electrons produced at the cathode that generate electrons which make the electrical circuit. Fuel cells development partially focuses on optimization of catalytic the layer 0f the catalytic electrodes, and by reducing metal without appreciable loss of the fuel cell performance. For fuel cells, power supply is uninterrupted during fuel supply and the oxidant, unlike a battery which relies on stored energy and is affected by amount of reagent available. The theoretical efficiency fuel cells is about 90% while in thermal engines the efficiency is about 40% for optimum conditions. However, practical fuel cell efficiency is usually less than 60%. which is still significantly greater than efficiency of combustion engines. The fuel cells operate with continuous replenishment of the fuel, and the oxidant at active electrode area and with no need for recharging. The elements of a fuel cell are the electrode, an oxidant or an air electrode, and an electrolyte. Common fuel cells used are hydrogen, oxygen (H_2, O_2), hydrazine (N_2H_4, O_2), carbon/coal (C, O_2) methane (CH_4, O_2). Hydrogen-powered fuel cells emit only water with virtually no pollutant emissions. On the other hand, fuel cells powered by hydrocarbon-based fuels have the potential to Employing hydrocarbon-based fuel inevitably leads to CO_2 emission. Since fuel cells are not subject to the limitations of the Carnot cycle efficiency, fuel cells attain higher efficiency that can be more than twice the efficiency of internal combustion engines. The transport sector operates with fuel cells having efficiency of up to 65%, compared to 25% for internal combustion engines. Application of heat produced by in fuel cells reaction for in combined heat and power (CHP) systems, increases overall efficiency to over 85%. Although fuel cells have significantly higher conversion efficiency compared to the internal combustion engines or and gas turbines across their output power range making them ideal for a variety of applications ranging from mobile phones to large-scale power generation, their largescale adoption is limited by high cost and lower reliability. The key to sustainability of fuel cells revolves around the production of hydrogen, the efficiency and capacity factor of fuel cells relative to other renewable sources of energy as well as the size of the installation
Key works: hydrogen fuel; fuel cell technology; sustainable energy; sustainable energy; renewable energy; electrolisers.

Introduction

Fuel cells are electrochemical devices used for the continuous conversion part of the free energy change in a chemical reaction to electrical energy. The fuel cells operate with continuous replenishment of the fuel, and the oxidant at active electrode area and with no need for recharging. The elements of a fuel cell are the electrode, an oxidant or an air electrode, and an electrolyte. Common fuel cells used are hydrogen, oxygen (H_2, O_2), hydrazine (N_2H_4, O_2), carbon/coal (C, O_2) methane (CH_4, O_2). A fuel cell is a device akin a battery that continuously recharges as it generates electric power using low-temperature electrochemical reaction oxygen and hydrogen. Unlike storage batteries whose main objective is to store energy, fuel cell fuel cells continuously generate as long as there is continuous supply of fuel and oxygen. Fuel cells employ an external or internal fuel-reforming process using any hydrogen-rich fuel can in different types of fuel cells. Hydrogen-powered fuel cells emit only water with virtually no pollutant emissions. On the other hand, fuel cells powered by hydrocarbon-based fuels have the potential to Employing hydrocarbon-based fuel inevitably leads to CO_2 emission. Since fuel cells are not subject to the limitations of the Carnot cycle efficiency, fuel cells attain higher efficiency that can be more than twice the efficiency of internal combustion engines. The transport sector operates with fuel cells having efficiency of up to 65%, compared to 25% for internal combustion engines. Application of heat produced by in fuel cells reaction for in combined heat and power (CHP) systems, increases overall efficiency to over 85% (Dutton 2002).(Edwards et al. 2008).

In a typical hydrogen–oxygen cell or hydrox cell. of two porous or permeable electrodes made up of either carbon or nickel are immersed in an electrolyte of KOH solution. The electrochemical reaction takes place at the porous electrode where the gas, electrolyte and electrode are in contact is slow, hence the use of a finely divided platinum or platinum material is embedded in the electrodes. The concentration of potassium hydroxide (KOH) solution is kept between 30–40 per cent. It has a higher thermal conductivity and less corrosive compared to acids, making it popular.

Fuel cell technology is a clean, flexible and already demonstrated that they can effectively be used in applications like space vehicles, portable devices and vehicle. Hydrogen can be sustainably produced from renewable sources with null amount of carbon dioxide. The power system using hydrogen from renewable resources and fuel cell operates like a closed system with no net loss to the environments since water consumed is converted to gases while the gases are converted back to water. Power produced is transferred to chemical energy in the gaseous state and the gases are converted back to electricity(Karishma Maheshwari et al. 2018).

The main objective of this study is to introduce fuel cells as a renewable source of energy for future sustainable energy needs as the global electricity demand continues to grow and the world races against time to cut down emissions from the energy sector and limit global climate change. There is need to a wide variety of technologies for power generation and thermal applications which is the key driver in fuel cell research.

Hydrogen in Fuel Cell Systems

Energy is a key component in all industrial applications and with sustainability concerns, hydrogen has emerged as one of the most abundant energy carriers in the world. Additionally, hydrogen fuel is fully environmental friendly since its combustion is emission free(Hüseyin Turan et al., 2020). Hydrogen energy is in line with zero-emission policy towards which makes it fundamentally attractive for transport and power generation. In addition to this, hydrogen is truly sustainable energy resource because of the zero-climate change effect, and it is a highly efficient, reliable, and noiseless source of power(Chakraborty et al. 2022; Hüseyin Turan et al. 2020)

Hydrogen can solve the pollution problems in power generation by producing emission free energy from renewable energy sources. A sustainability assessment of hydrogen fuel based on the various dimensions i.e. technical performance, environmental, renewability, social acceptability and possible applications in the energy transition has identified hydrogen as one of the best ever technical concept compared with other ongoing energy producing systems(Kabeyi, 2012, 2022; Kabeyi & Oludolapo, 2020d). Keeping in mind the current environmental conditions, the fuel cell technology is one of the most reliable future energy solutions. The fuel cell is simple in nature and works basic fundamentals of electrochemical reactions which converts chemical energy from fuel into electricity with byproducts being water and water vapors. Electricity production is done from simple reactions of hydrogen and oxygen. Hydrogen based fuel cells are truly found to be the viable option for the energy market with full potential to upgrade ongoing technologies(Karishma Maheshwari et al. 2018).
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Hydrogen is attractive because of ability to be produced from both renewable and non-renewable sources of energy i.e. hydro, wind, solar, biomass, geothermal and non-renewable sources like coal, natural gas, nuclear for application in high-efficiency power generation systems, like fuel cells, in vehicular transportation and distributed electricity generation. Fuel cells operate by converting the hydrogen gas or hydrogen in a hydrogen-rich fuel like biomethane and an oxidant usually pure oxygen or oxygen from air directly into electricity in an electrochemical process.(Edwards et al. 2008).

Unlike coal, gas or oil, hydrogen is not a primary energy source, instead its role closely mirrors that of electricity as an ‘energy carrier’, produced using energy from other sources and transported for future use, where the chemical energy stored can be used in transportation and distributed heat and power generation in fuel cells, internal combustion engines or turbines, with cleaner emissions mainly as water and no CO_2 at point of use (Edwards et al. 2008).

Hydrogen can be used as a storage medium for power produced from intermittent, renewable resources including solar, wind, wave and tidal power, thus offering a solution to one of the challenges of sustainable energy, i.e. intermittency and variability of renewable sources. Local production of hydrogen can introduce f renewable energy to the transport sector, and provide large economic and energy security and benefits of an infrastructure based on distributed energy generation. Hydrogen energy storage capacity provides a the potent link between sustainable energy technologies and a sustainable energy economy, within a hydrogen economy'(Edwards et al. 2008).

There are three major technological challenges that must be overcome for a transition from a carbon-based (fossil fuel) energy system to a hydrogen-based economy. They are

i.) The cost of efficient and sustainable hydrogen production and delivery should be reduced.
ii.) The new generations of hydrogen storage systems for vehicular and stationary applications should be developed
iii.) The cost of the fuel cell and other hydrogen-based systems should reduce(Edwards et al., 2008).

An integrated hydrogen energy system of the future should combine small and large fuel cells for industrial and domestic decentralised heat and electricity power generation with extended hydrogen supply networks that can also fuel conventional internal combustion or fuel cell vehicles(Edwards et al. 2008).

Design and Operation of Fuel cells

The fuel cell works like batteries except that it does not run down or need recharging, hence they generate electricity and heat continuously as long as there is supply of fuel. The device consists of two electrodes i.e. a negative electrode (or anode) and a positive electrode (or cathode) that are sandwiched around an electrolyte. Fuel cells require oxygen but the main fuel is hydrogen whose action produces electricity with water as the main product. The first fuel cell was designed in 1842 by W.R. Grove who named it as a gaseous voltaic battery (Cleveland and Morris, 2014). The term "fuel cell" was then coined in 1889, by the chemists L. Mond and C. Langer. The actual breakthrough in fuel cell development was a result of the introduction of a sulphonated polystyrene (SP) ion-exchange membrane for use as an electrolyte by W. T. Grubb in 1955, and by platinum deposition onto the membrane by L. Niedrach in 1958. The sulphonated polystyrene (SP) was replaced in 1966 by Nafion ionomer which is still in use today.(Sauermoser et al. 2020).

A membrane is sandwiched between two flow field plates in a single cell or between two bipolar plates in a PEMFC stack. A flow field plate (FFP) in a fuel cell is used to supply i.e. hydrogen, and oxidant (air, O_2) then, removes water, and collects generated electrons. Roles of the FFP also include separation of gases between the half cells and neighboring cells in a stack; act as an electronic conducting medium between the cathode and anode; facilitate even distribution of reaction gases since it possesses a specific flow field design with channels; provides reinforcement , and enable water and heat management and control.(Sauermoser et al. 2020)

Construction of Fuel Cells

Many types of fuel cells have emerged that are suitable for different energy applications at varying scales, the different fuel cells share the basic design of two electrodes (anode and cathode) that are separated by a solid or liquid electrolyte or a membrane. The fuel, usually hydrogen or hydrogen-rich fuel and air are supplied to the anode and cathode of the fuel cell, where electrochemical reactions occur often in presence of a catalysts. The ions created are transported between the electrodes using the electrolyte with excess electrons flowing via an external circuit to supply electricity (Edwards et al., 2008). Figure 1 shows the main elements of a fuel cell.

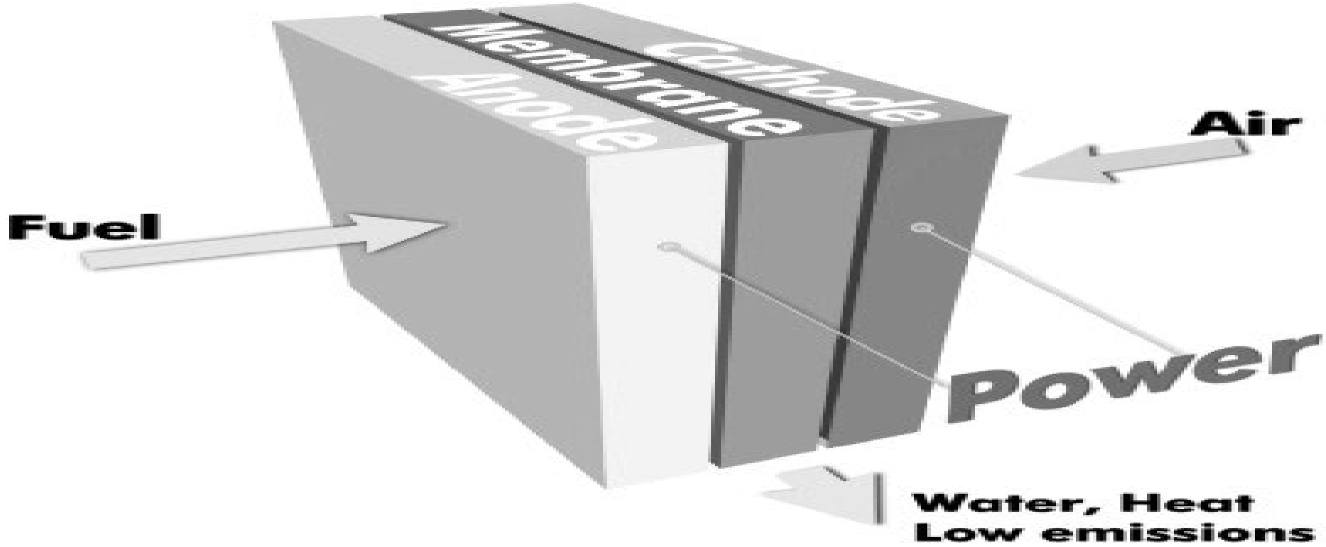

Figure 1. Schematic representation of a fuel cell

Figure 1 presents the general construction of fuel cells which consists of fuel supply, the anode, cathode, air or oxygen supply and the membrane Water and heat are the main products of fuel cell reactions.

Working Principle:

Hydrogen gas is converted into hydrogen ions releasing free electrons at the negative electrode,

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

Under the influence of the catalyst in the electrode, the hydrogen ions react with the hydroxyl ions in the electrolyte to form water:

$2H^+ + OH^- \rightarrow 2\,H_2O$ (2)

During operation, the free electrons from negative electrode flow through the external load towards the positive electrode. Negatively charged hydroxyl ions are formed when the electrons interact with oxygen and water in the electrolyte in a process shown below;

$O_2 + H_2O + 2e– \rightarrow 2OH–$ (3)

The hydrogen and hydroxyl ions formed then combine to form water as shown below:

$H^+ + OH^- \rightarrow H_2O$ (4)

A single hydrogen–oxygen cell generates electromagnetic force (emf) of about 1.23 V at atmospheric temperature of 298 K and pressure of 1 bar. Combining the cells in series, generates power ranging from few kilo-watts (kW) to mega-watts. (MW).

Fuel Cell Concepts

Fuel cells convert chemical energy of in fuel efficiently to electricity without combustion, with low emissions compared to conventional equipment/techniques. It is therefore a fuel cell defined as an electrical chemical device that directly convert chemical energy to electricity. The three main parts of a fuel cell assemble are the anode, cathode, and electrolyte. A catalyst oxidizes fuel with ions travelling via the electrolyte. At the cathode ions are reunited with the electrons. It is the electrons produced at the cathode that generate electrons which make the electrical circuit(Rowshanzadeh, 2020). Fuel cells development partially focuses on optimization of catalytic the layer 0f the catalytic electrodes, and by reducing metal without appreciable loss of the fuel cell performance (Alves et al., 2013). For fuel cells, power supply is uninterrupted during fuel supply and the oxidant, unlike a battery which relies on stored energy and is affected by amount of reagent available. The theoretical thermodynamic efficiency fuel cells is about 90% while in thermal engines the efficiency is about 40% for optimum conditions. However, practical fuel cell efficiency is usually less than 60% (Alves et al. 2013).

Types of Fuel Cells

A fuel cell is said to be an electrochemical device used to convert the chemical energy in hydrogen or other fuel directly to electricity. Six common fuel cells are Polymer Electrolyte Membrane (PEM), Alkaline (AFC), Phosphoric Acid (PAFC), Solid Oxide (SOFC) and Molten Carbonate (MCFC)(EG&G Technical Services, 2004; Smithsonian Institution, 2014).

PEM fuel cell (PEMFC)

The Proton Exchange Membrane fuel cells are equipped with a polymer electrolyte. And have efficiency range of 40-50%, The operate at a temperature of about 80°C. and therefore can be referred to as low temperature cells. Because of there are ideal for use in homes and vehicles. The fuel for proton exchange fuel cells need to be purified while the catalyst used normally platinum increase cost. The PEM cells can generate sufficient power to supply commercial and residential customers at varying temperatures. The PEM fuel cell generator with Na metal and water chemical reaction can produce hydrogen with low emissions and noise. For applications in medium and high duty vehicular use.

Advantages of PEM are low operating temperature, use of solid electrolyte, high power density, durability and reliability proton exchange. The operating parameters of PEM fuel cells depend on operating conditions, with accurate estimation of performance efficient mathematical modelling. When used as source of mechanical power the PEM fuel cell is subjected to dynamic loading. The response voltage becomes lower than the steady-state conditions with voltage gradually increasing which leads to deterioration .PEM fuel cell operations (Chakraborty et al. 2022). The proton exchange membrane fuel cell (PEMFC) is demonstrated in figure 2 below

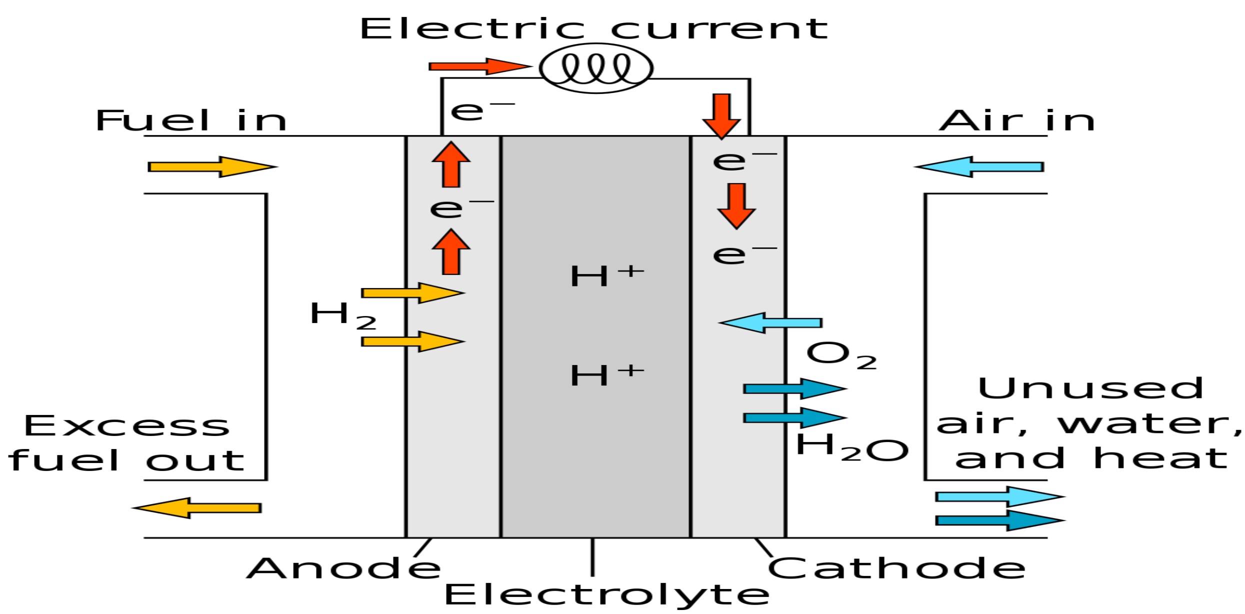

Figure 2. PEM fuel cell (PEMFC)(Sauermoser et al. 2020)

From figure 2, it is noted that hydrogen in the fuel cell is ionized to hydrogen ions which move through the electrolyte to the cathode where water is formed and discharged. Oxygen or air is supplied to the fuel cell through the cathode side. While fuel is supplied at the anode. Electrons flow externally from the anode as electric current through load. In the proton exchange membrane fuel cell (PEMFC) the chemical energy in fuel is converted into electrical energy and water in a fuel cell where the heart is the Membrane Electrode Assembly (MEA) composed of a proton conducting polymeric membrane (PEM) which is sandwiched between the anode and cathode catalyst layers (CL) and gas diffusion layers (GDL)(Sauermoser et al. 2020)

The applications of Proton Exchange fuel cells include power generation, transport and power for digital devices. They have a short life span caused by degradation awhile reusability of fuel cells limits its applications in the commercial sector. (Chakraborty et al. 2022). As a result of global concerns over greenhouse gases in the transport sector, many aviation companies are working on electrification of transport and use of fuel cells. It is at this point that the, PEM fuel cells seem to be the most suitable option based on its operating parameters. (Hüseyin Turan et al., 2020).

Molten oxide fuel cell (MOFC)

The molten oxide fuel cell (MOFC) is based on the oxygen-ion-conducting solid/molten oxide electrolyte also called liquid-channel-grain-boundary-structure (LGBS,) material that consists of TeO_2 solid grains and chemically compatible TeO_2+$Te_4Bi_2O_{11}$ liquid electrolyte located at the grain boundaries. The existing intergranular liquid channels facilitate the LGBS mechanical plasticity or ductility, that enable it to shape and alleviate problems caused by thermal incompatibility with electrodes (CTE), and high ionic conductivity. In the Molten oxide fuel cell (MOFC) the volume fraction of liquid varies between 0.15 and 0.17 at temperature range of 600–640 °C. Oxygen is supplied by air at the cathode. A single cell has power capacity 11.5 mW cm^{-2} at the current density of 90 mA cm^{-2}, at electrolyte thickness 2.5 mm, and temperature 640 °C(Belousov & Fedorov 2016).

The electrolyte in these fuel cells use salt components same as sodium or magnesium, and carbonates. Their efficiency varies between 60-80% and have a working temperature of about 600-700°C. So far molten oxide fuel cells with capacity of up to 2 (MW) have been developed. The main challenge is that the increase in temperature is limited as it leads to carbon monoxide (CO)poisoning which halts its operations(Belousov, 2017).

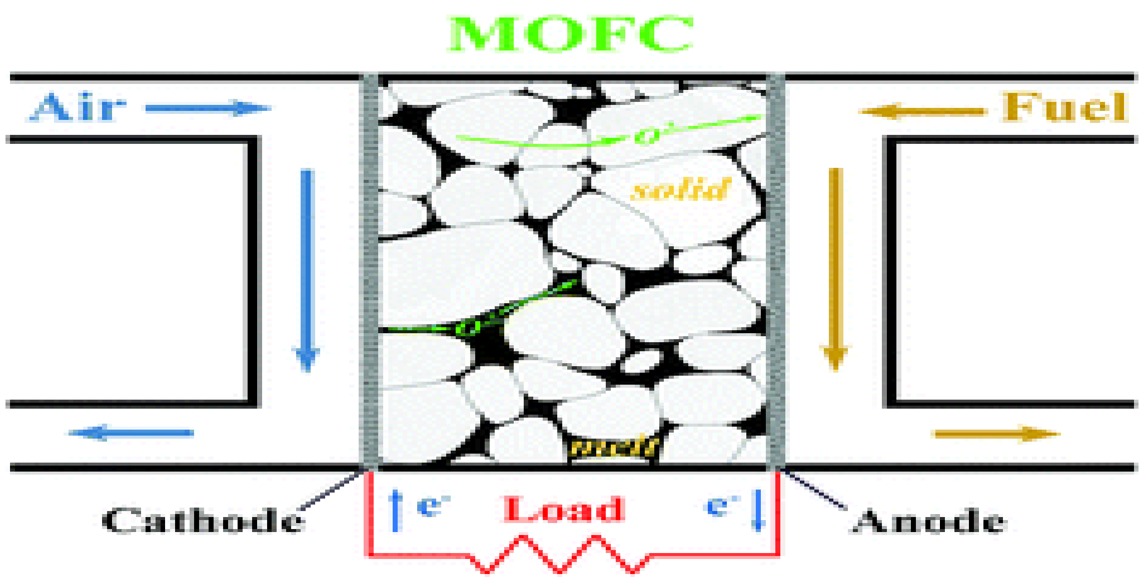

Figure 3. Molten oxide fuel cell (MOFC)(Belousov & Fedorov 2016)

Figure 3 shows a molten oxide fuel cell (MOFC) fuel cell with air flow at the cathode and fuel at the anode and solid oxide electrolyte at the centre.

Molten Carbonate Fuel Cell

The molten carbonate fuel cells (MCFC) make use of high-temperature compounds of salt e.g. sodium or magnesium carbonates as the electrolyte. They operate with efficiency ranges of 60 to 80% and operating temperature of 650 ºC to 700 ºC . The output capacity is between 2 MW have to 100 MW. The advantage of the high temperature is that it limits the damage from carbon monoxide "poisoning" of the cell. Additionally, the waste heat can be applying to generate extra power in Rankine cycle plants or applied in thermal like process heating. The MCFC fuel cells use nickel electrode-catalysts which are cheaper than platinum electrodes used in other types of fuel cells. The challenge with high temperatures is that they limit materials used and applications off the MCFCs like homes –they would probably be too hot for home use. Also, carbonate ions from the electrolyte are used up in the reactions. This Often requires the injection of carbon dioxide to compensate which adds costs.(EG&G Technical Services, 2004; Smithsonian Institution, 2014)

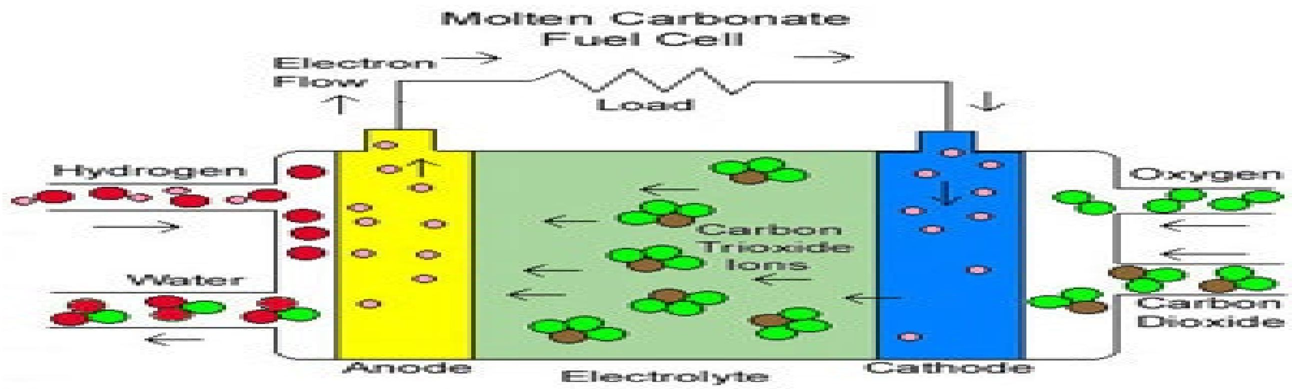

Figure 4. Molten carbonate fuel cell

Figure 4 shows the carbon trioxide fuel cell with carbon trioxide ions moving from the cathode to the anode and electrons flowing from the anode to the load as electric current. Hydrogen fuel is supplied to the anode side where water is also extracted from the fuel cell.

Solid oxide fuel cell (SOFC)

The solid Oxide fuel cells use ceramic compound of metal like calcium or oxides as the cell electrolyte. They operate with efficiency of about 60 percent, and operating temperatures of 1000°C(Moses Kabeyi & Oludolapo Olanrewaju, 2022). Fuel cells are the cleanest energy conversion systems but are limited by high investment costs compared to other energy conversion systems like gas turbines and internal combustion engines. They also operate at high operating temperatures which further limit their applications especially in automotive and domestic applications except for the proton exchange membrane fuel cells. The fuel cells also have high conversion efficiencies compared to conventional thermal conversion systems making them more competitive and attractive for long term investments. The fuel cells have wide range of applications and markets. With main limitations being size or weight and temperature for domestic and automotive use(Alves et al. 2013; Smithsonian Institution 2014).

The solid oxide cells need a high operating temperature operating environment and are commonly used in large, stationary power plants. High operating temperatures for the solid oxide batteries create opportunities cogeneration applications including space heating, industrial thermal and power applications, or use of a steam turbine in Rankine cycles for more power generation. Solid oxide fuel cells, need inverters to change the direct current to alternating current, and can be availed in relatively small, modular units. The solid oxide fuel cells are particularly attractive for urban application due to their compact size and cleanliness e.g. in Tokyo, there is are25 kw units in operation (Smithsonian Institution 2014).

Alkali Fuel cell

The Alkali fuel cells use compressed hydrogen and oxygen as a fuel and oxidant while the electrolyte generally used is the solution of potassium hydroxide (chemically, KOH) in water. The alkali fuel cell operates at an efficiency of about 70 %, and temperature of operations is between 150and 200 ^{0}C, (about 300 to 400 degrees F). The generation output is between 300 watts (W) to 5 kilowatts (kW). A typical application of the alkali fuel cells is in Apollo spacecraft to supply both drinking water and electricity. The main limitation is that alkali fuel cells use pure hydrogen fuel, and a platinum electrode catalyst which are expensive are expensive(EG&G Technical Services, 2004; Smithsonian Institution, 2014).. The alkali fuel cell is demonstrated in figure 4.

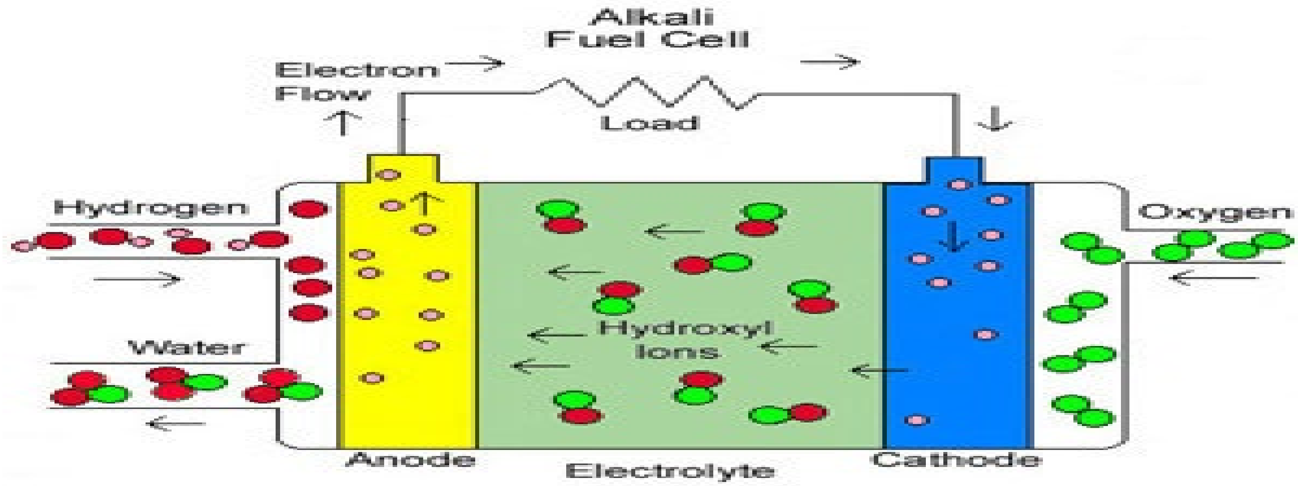

Figure 5. The alkali fuel cell

Figure 5 shows that that in the alkali cell, oxygen I supplied through the cathode while hydroxyl ions migrate from the cathode to the anode where electrons flow as current to the external load. Hydrogen fuel is supplied to the anode where water which is the by-product of the process is extracted.

Phosphoric fuel cells

The Phosphoric Acid fuel cells (PAFC) use phosphoric acid as the electrolyte and have efficiency range of 50 to 80 percent, operating at a temperature range of 150 to 200 ºC (about 300 to 400 degrees F). Operating phosphoric acid fuel cells have capacity range of 200 kW, and 11 MW. The advantage of PAFCs is that they can tolerate a carbon monoxide concentration 1.5%, making it possible to use a wide range of fuels. They use platinum electrode-catalysts and internal parts should withstand the corrosive acid(EG&G Technical Services, 2004; Smithsonian Institution, 2014)

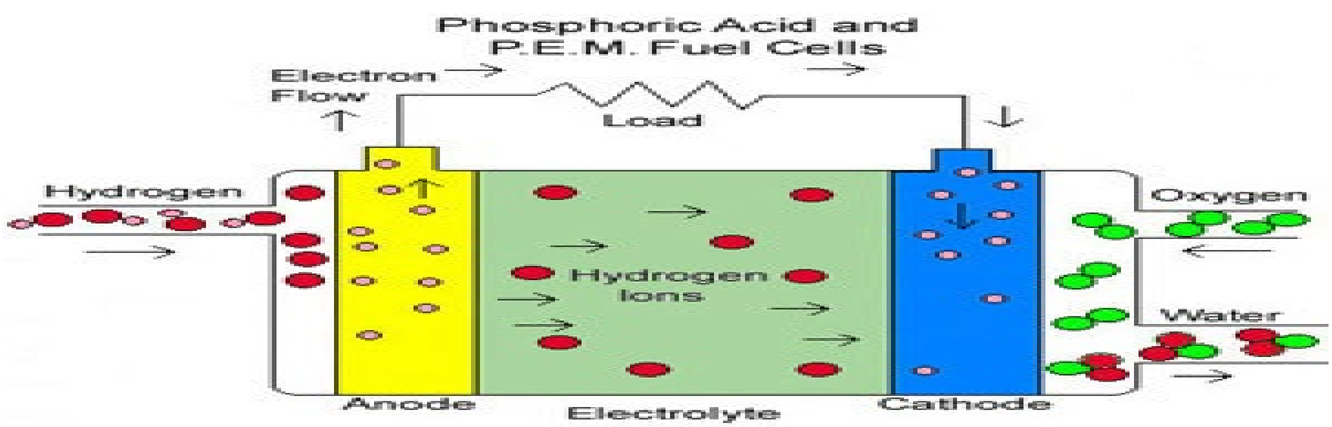

Figure 6. M Phosphoric acid fuel cells

Figure 6. demonstrates the construction and operation of the phosphoric acid fuel cell which is also similar to the PEM fuel cell. In this fuel cell, hydrogen fuel is supplied to the cell through the node side. The hydrogen ions flow internally in electrolyte to the cathode where water is discharged from and oxygen is fed to the cell.

Internal Reforming of Biogas in Fuel Cells

The technology to convert hydrogen to electrical energy is developed and close to commercialization, but parallel attempts for the direct use of biogas in fuel cells by internal reforming is also promising. This is feasible in high-temperature fuel cells like Solid oxide fuel cell (SOFC) and Molten oxide fuel cell (MOFC) because they have higher capacity to thermally integrate internal reforming and higher tolerance against contaminants while maintaining electrical efficiency close to 50% which is attractive (Alves et al., 2013). The main limitation of internal reforming process for biogas is generation of carbon monoxide (CO)poison which poisons the fuel cell for concentrations of 50 ppm and higher. Other challenges of biogas reforming are variability of biogas quality and the poisoning of fuel cell catalysts by carbon deposition (coke) by CO disproportionation as well as the presence of sulphur traces (Alves et al., 2013). Coke formation inhibits catalyst activity, blocks the pores leading to structural destruction destroy their structure. This carbon deposition can be reduced by addition of promoters like Sn, Li, Ru, Mo, Ca, Mg Sr, Ru, Ce, Rh, Pt and Pd at the anode (Alves et al. 2013; Moses Kabeyi & Oludolapo Olanrewaju, 2022). Sulphur causes a substantial decrease in the process of conversion to hydrogen because of strong sulphur chemisorption on the surface and within particles of the electrodic catalyst hence removal of sulphur is important. Poisoning is partially reversible but it limits conversion due to a slow desorption process(Alves et al. 2013). Additionally, temperature gradients from endothermic reforming reactions causes destruction of the electrolyte an effect that can be reduced by addition of air to the biogas which prevents coke formation, and also removes the high temperature gradient due to exothermic reactions of methane(Alves et al. 2013; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; Kabeyi & Oludolapo, 2020a, 2020b, 2020c).

Fuel cells using biogas offer a pathway to renewable and low carbon grid electricity generation(Remick, 2009). Biogas can directly be converted electricity using fuel cells. The main challenge with biogas fuel cells is that they need a very clean gas and the system quite expensive. And is currently still at research and development stage (Energypedia, 2016). Through steam reforming of biogas, "green" hydrogen can be produced which hydrogen with oxygen from air to produce electricity water vapor and heat. Fuel cells have wide application in cogeneration systems for use in hospitals, learning institution, and remote telecommunication stations as a reliable source of energy. Other applications are transport and as emergency electricity supply systems(Tagne et al. 2021).

In fuel cell generation, biogas is used to produce direct current electricity through electrochemical process. Fuel cells using biogas are cleaner than combustion as it produces as it produces less or no emissions at all (Remick, 2009). Typical stationary biogas fuel cells are the high-temperature internal reforming systems like solid oxide fuel cells and molten carbonate fuel cells(Rivera, 2021). High internal temperatures in the fuel cells, reforms methane with steam to produce hydrogen which is used to generate electricity by reacting with oxygen. The state of California alone in the USA has more than 400 stationary fuel cells of which more than 11 are biogas fuel all producing about 180 MWe(United States Environment Protection Agency, 2016). In a typical biogas fuel cell, synthesized biogas with about 65% methane + 35% carbon dioxide is reformed over a rhodium catalyst supported on a porous alumina-foam support. Reforming methods used include steam reforming and catalytic partial oxidation which use oxygen in air or pure oxygen for oxidation(Murphy et al. 2019).

Sustainability of Fuel Cells

Sustainability is an important analysis for energy systems as well as manufactured systems. Sustainability consists of three basic dimensions; the Environmental, Economic and Social dimensions. Sustainability analysis for hydrogen as a fuel in fuel cells gives positive results in all three dimensions (Hüseyin Turan et al. 2020; M. J. B. Kabeyi & O. Olanrewaju 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju 2022). Benefits of fuel cell system and hydrogen can be defined using the thermodynamic principles especially the insights revealed by means of the exergy analysis. Development of hydrogen and fuel cell technology is an opportunity to sustainable development. The production and use of hydrogen production in fuel cells as a renewable energy provides an important solution environmental challenge (Kabeyi 2012; Love et al. 2022; Karishma Maheshwari et al. 2018)

Emissions associated with fuel cell

Biogas fuel cells generate extremely low atmospheric emissions with the only notable emissions being a result of oxidation or combustion of anode off-gas consisting of free hydrogen that has not reacted with oxygen(O_2), carbon monoxide (CO), and volatile organic compounds. The anode gas is usually processed by means of surface or catalytic burners which oxidize components and in the process little low nitrogen oxide emissions are emitted(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; Rivera 2021).

Conventional fuels for vehicular applications produce pollutants that have adverse environmental effects. which has generated interest in s environment-friendly vehicles for the present mobility sector. Hydrogen fuel-based vehicular technologies have gained significance as a result of the zero-emission policy targeting sustainable solutions. Compared to electric vehicles with a 200-mile range, fuel cell cars will be cheaper in the future. However, there is need to promote use of hydrogen as a passenger automobile fuel, by reducing the cost of fuel cell vehicle (FCV) to the level of an electric vehicle. Studies show that fuel cell vehicles, consume about 43% less energy than gasoline cars and produce 40% less CO making them more efficient and more environmentally friendly (Chakraborty et al. 2022).

The emission factor for biogas fuel cells emissions is 0.09 kg CH4/MWh while the for carbon dioxide produced, the average GHG emission factor is 658.3 kg CO_2/MWh, and the while for N_2O (nitrous oxide), the emission factor is 0.001kg N_20/MWh(Rivera, 2021). Based on these emission factors, the global warming potential over 100 years' time scale (GWP100) of the greenhouse gases i.e., the output-based greenhouse gas emissions in terms of CO_2 of methane for biogas fuel cells about 0.3 kg CO_2eq/MWh. The biogenic GHG of carbon dioxide is about 658.3 kg CO_2eq/MWh(Rivera 2021). For nitrous oxide, the greenhouse gas emissions is about 0.26 kg CO2eq/MWh (United States Environment Protection Agency 2016)

Cost of Fuel Cells

The installation costs for biogas fuel cells range over $8,000/kW for a fuel cell with a 250-300 kW capacity to about $3,800/kW for a 6,140-kW fuel cell. This cost includes the cost of gas cleaning equipment, engineering, permits, and other direct costs(United States Environment Protection Agency, 2016). The estimated Levelized cost estimated Levelized cost of biogas fuel cells energy is $0.164 per kwh for a 200-kW fuel cell to $0.079 per kwh for a 6,000-kW fuel cell.

High installation costs require state backed incentives to encourage the development of fuel cells. With 30% of the project or $3,500/kW incentives, a payback period of less than five years can be realized. Through tri-generation of electricity, heat, and hydrogen from fuel cells, a feasible route to solving the hydrogen infrastructure problem facing fuel cell vehicle deployment. Can be achieved. (Remick 2009).

The most practical system of biogas to electricity conversion is the use electric an electric generator set driven by a mechanical prime mover like an engine or gas turbine. Biogas is superior to natural gas as a fuel because its combustion is characterized by a high knock resistance and hence can accommodate higher compression ratios leading to more output and higher power density when used in internal combustion engines (Energypedia 2016). In some applications biogas is used as fuel for combustion engines, which convert it to mechanical energy that rotates a generator to produce electricity. Theoretically, biogas can be used in all types of combustion engines, engines like gas turbines, diesel engines, and Stirling engines and others etc. (Energypedia 2016, 2018; Mary et al. 2007).

Hydrogen Safety

Hydrogen safety also critical, encompassing technological, scientific, psychological and societal issues. Hydrogen has an extraordinary safety record during many the many years of use. However, it is different other fuels due to its ability to migrate through tiny channels, while combustion properties are different from carbon-based fuels. This calls for diverse safety measures for those who interact directly with hydrogen and fuel cell technologies(Edwards et al., 2008). The main safety challenge with hydrogen fuel is that it can leak easily and ignite at relatively low temperature. Safe handling of hydrogen fuel just like other fuels depends on particular physical, chemical, and thermal properties and consideration of safe ways to accommodate those properties. If handled carefully, hydrogen is a safe fuel, even safer than conventional fuel currently in use. Unlike conventional fuels which produce hot ash, hydrogen combustion does not produce hot ash, Hydrogen in its pure form, burns with no hot ash and very little radiant heat. (Love et al. 2022; Karishma Maheshwari et al. 2018).

Sustainability measures for Fuel Cells

The key to increased or enhanced sustainability of fuel cells revolves around the production of hydrogen, the efficiency and capacity factor of fuel cells relative to other renewable sources of energy as well as the size of the installation. It is necessary to improve these factors for fuel cells to be competitive energy sources(Karishma Maheshwari et al. 2018). A fuel cell is an energy conversion devise or system that generates electricity from the chemical reaction producing water as the main byproduct, rendering the process very clean and renewable. The fuel cell economy and supply chain is strongly related to the country's economic aspect, like local and infrastructure costs, which makes it more relevant for implementation in developed countries(Baharuddin et al. 2021). Sustainability in fuel cells can be increased by;

i.) The energy source pathway should be clean with low/no long-term carbon emissions., technology be applied to cut down emissions e.g. where carbon capture and sequestration (CCUS) is applied, the efficiency should exceed 90%

ii.) Maximum efficiency of conversion from primary energy source to end use as electricity at point of use

iii.) There has to be interdependence of fuel cell technology, energy use and primary energy source for sustainable outcomes and

iv.) The materials used in construction and infrastructure assets should be sustainably sourced, and should have low energy demand, environmental impact and have established recycling pathways.

Results and Discussions

Fuel cells are electrochemical devices that produce electricity from chemical energy through a chemical process between oxidizing and reducing agents. Fuel cell have emerged as top alternatives energy source for automotive and industrial applications. The, solid oxide fuel cell has shown the most potential device for high efficiency power generation above 100 KW as a result of pollution free reforming process (Hüseyin Turan et al. 2020).

A sustainable fuel cell and hydrogen energy industry will depend on cost reduction in hydrogen production methods, development of a large network of Hydrogen Refuelling Stations and further increase in fuel cell efficiency to lower cost of energy conversion. (Hüseyin Turan et al., 2020). The main materials for improvement in fuel cell technology are the membranes, plates and electrolytes whose performance and costs and recyclability should be improved through research and development for cost competitiveness. Sustainability aspects of fuel cell technology should likewise address the efficiency of conversion, affordability, legal and policy framework, environmental impacts and social impacts and acceptance. (Hüseyin Turan et al. 2020).

Fuel cell s mainly use hhydrogen as a fuel for the electrochemical process which combines oxygen and hydrogen to directly produce electricity and water. Green hydrogen can be obtained by the reverse process of electrolysis, which oxygen and hydrogen using a renewable energy source like wind, wave, and solar energy. Clean hydrogen power is a uniquely clean energy source for heat and power generation since water is the only by-products. Therefore, use of fuel cells operating with hydrogen-rich or pure hydrogen fuel is a major factor in catalysing the transition to a future sustainable energy system.(Edwards et al. 2008).

There is a global debates on hydrogen fuel cells and their advantages and disadvantages, which indicate that hydrogen is an environmentally-friendly alternative fuel to fossil fuels and can be applied in flexible and high-density power and propulsion in a wide range of industrial plant and transportation applications based on the hydrogen fuel cell technology(Edwards et al. 2008)

Operating Temperatures

The main difference between the different fuel is the operating temperatures and type of electrodes used (Hüseyin Turan et al. 2020). Figurer 1 shows the operating temperature range for common fuel cells

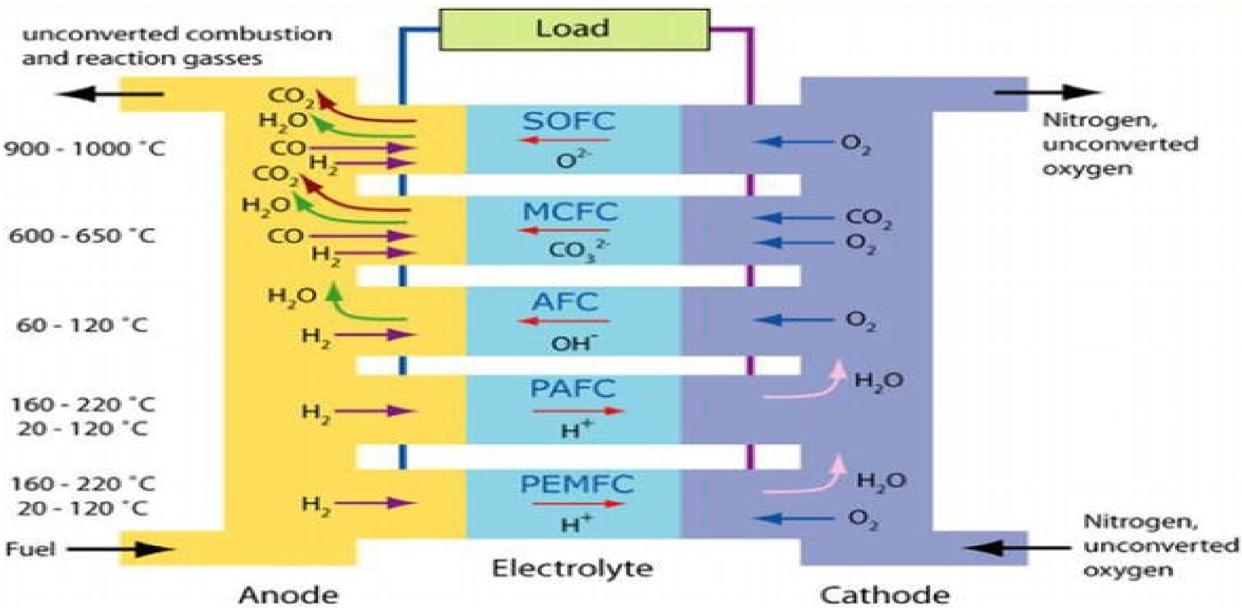

Figure 7. Fuel cells structures and operation temperatures(Hüseyin Turan et al. 2020)

From figure 7, it is noted that the Solid Oxide (SOFC) has the highest operating temperature of 900 to 1000°C followed by the Molten Carbonate (MCFC) which operates between 600 and 650°C. Phosphoric Acid (PAFC) and Polymer Electrolyte Membrane (PEM) have lowest operating temperature of 20 to 220°C.

Applications of Fuel Cells

Fuel cells are alternative technology internal combustion engines in as prime movers for vehicles and stationary applications like distributed power generation. It is also projected that future demand for portable power generation supplies will exceed the capability of current battery technology(Edwards et al., 2008). This provides further market opportunities for fuel cells.

The transport sector has emerged as a leading user of fuel cell technology generally using the PEM type fuel cell as a preferred choice mainly due to the operation temperature. Many automotive manufactures for fuel cell vehicle i.e. Toyota, Hyundai, Honda, and Mercedes tend to use PEM whose efficiency is generally between 45–60% es(Moses Kabeyi & Oludolapo Olanrewaju 2022; Moses J. B. Kabeyi & Oludolapo A. Olanrewaju, 2022). On the other hand, not only automotive sector but also all fields of transportation industry, given importance on fuel cells. Figure 1 below illustrates products in the transport sector which includes land, marine and air vehicles and the general capacity of fuel cells used ranging from bicycles as the simplest to aeroplanes (Hüseyin Turan et al. 2020).

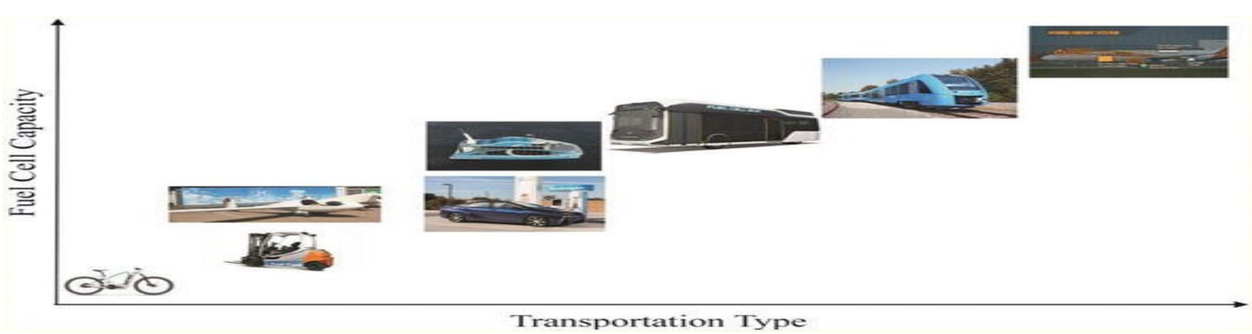

Figure 8. Fuel cells in transportation industry.

Fromfigure1, it is noted that fuel cells have potential use in all sectors of transport and vehicles ranging from bicycles, vehicles, buses and aircrafts.

Fuel cells are classified based on the nature of their electrolyte, which influences the operating temperature, fuel type and the range of applications. Electrolytes used can be classified acid, base, salt, solid ceramic or polymeric membrane and should have ability to conduct ions. Table 1 summarises the characteristics of various fuel cell types(Edwards et al., 2008). The various applications of fuel cells are summarised in table 2 below;

Table 1. Fuel cells and their applications(Smithsonian Institution, 2014)

	Type of fuel cells	Applications
1	PEM type fuel cell	Used in transport sector has emerged as a leading user of fuel cell technology generally using the
2	The high-temperature solid oxide fuel cells (SOFCs)	Can be used in distributed generation
3	molten carbonate fuel cells (MCFCs)	Can be used distributed generation, Large-scale power generation
5	Solid oxide	Medium- to large-scale power and CHP, vehicle auxiliary power units, off-grid power and micro-CHP. The solid oxide cells need a high operating temperature operating environment and are commonly used in large, stationary power plants
6	Phosphoric acid	Medium- to large-scale power and CHP
7	Proton exchange membrane	Mobile, portable, low power generation
8	Alkaline fuel cell	Mobile, portable, low power generation
9	Direct methanol	Portable, mobile

From table 1, it is noted that furl cells are mainly used in transport sector, decent raised generation of power and heat (CHP) and charging applications. Fuel cells in power generation can be used in off grid and off grid applications.

Summary of types of fuel cells and applications

The various fuel cells available have different characteristics, features and ideal applications. Fuel cell technologies have emerged as a good solution for clean anustainable power supply by meeting the energy demand in a positive manner. Fuel cells are used for stationary applications like power generation and CHP and mobile like transport applications, portable power among others (Garraín et al.,2021). The fuel cells and applications are summarised in table 2 below

Table 2. Types of fuel cell, features and applications
(EG&G Technical Services, 2004; Smithsonian Institution, 2014)

Type of electrolyte	Operating temperature (ºC)	Average (ºC)	Applications	Electricity capacity range (kW)	Average kW	Electrical efficiency (%)	Average Efficiency (%)
Proton exchange membrane or Polymer electrolyte membrane (PEM**)**	60–110	85	Mobile, portable, low power generation	0.01–250	125	40–55	43
Alkaline	150 –200	175	Space, military, mobile	0.1–50	25	60–70	65
Direct methanol	60–120	90	Portable, mobile	0.001–100	50		
Phosphoric acid	175–210	192.5	Medium- to large-scale power and CHP	50–1000	525	40–45	43

Molten carbonate	600 –650	625	Large-scale power generation	200–100,000	50.100	60–80	70
Molten oxide fuel cell (MOFC)	600-700°C	650	Stationary medium to large-scale CHP	2,000	1000	60-80	70
Solid oxide	500–1000	750	Medium- to large-scale power and CHP, vehicle auxiliary power units, off-grid power and micro-CHP	0.5–2000	1000	40–72	56
Global average		427			10, 365		58

From table 1, it is noted that the common types of fuel cells are the proton exchange membrane alkaline and direct methanol which have lowest temperatures of operation, phosphoric acid fuel cell, molten carbonate and solid oxide fuel cell which have higher operating temperature range. It is noted from table 1 that the average operating temperature for fuel cells across all types is about 325^{o}C, temperature, average capacity of 10.4 MW, and electrical efficiency of 51.4%

Fuel cells have significantly higher conversion efficiency compared to the internal combustion engines or and gas turbines across their output power range making fuel cells ideal for a variety of applications ranging from mobile phones to large-scale power generation. However, the main undoing for fuel cells in competing applications with thermal engines is their high cost and limited reliability(Edwards et al. 2008; Moses Kabeyi & Oludolapo Olanrewaju, 2022)..

The high-temperature solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) can be used in distributed generation that currently use natural gas, hence an opportunity to develop and use of this technology independently from the establishment of a hydrogen infrastructure which will provide a transition to the hydrogen economy, with significant efficiency gains the commercially available hydrocarbon fuels which can also effectively operate on renewable biofuels if they become cost-effective, and ultimately competitive with high efficiencies on hydrogen.(Edwards et al., 2008; Kabeyi, 2022). Fuels cells are also being developed as alternatives for auxiliary power units for vehicles and for off-grid power applications as replacement of small diesel generators. Fuel cells do not require an external reformer for conversion of a hydrogen-rich fuels like biomethane to hydrogen enabling them to work on a variety of fuels and eliminate cost incurred in external reforming. Therefore, fuel cells are particularly suitable for cogeneration applications because they produce high-grade waste heat alongside electricity. (Edwards et al. 2008).

Although the Low-temperature proton exchange membrane fuel cells (PEMFCs) and alkaline fuel cells (AFCs) have higher power density than any other fuel cell systems, they are limited by the requirement for expensive platinum catalyst and require very clean or very pure hydrogen. The PEMFCs and AFCs were developed in the 1950s and used in the NASA space programme. The proton exchange membrane fuel cells (PEMFCs) are favourites for mass-market applications in automotive and small-scale cogeneration applications, with ongoing global effort to develop commercial systems(Edwards et al. 2008).

The Phosphoric acid fuel cells (PAFCs) have the advantage of more tolerant to impurities in hydrogen than the proton exchange membrane fuel cells (PEMFCs) or AFCs. The PAFCs are preferably used for stationary power generation and commercial vehicles like city buses. The Phosphoric acid fuel cells (PAFCs) are available commercially but are relatively expensive thus limiting the market uptake. The direct methanol fuel cells (DMFCs) use methanol and can be used in applications mobile phones and laptop computers(Edwards et al. 2008).

Advantages of Fuel cells

Hydrogen based fuel cell technology presents several advantages over other power sources, which are summarised in table 3.

Table 3. Benefits /advantages of fuel cells (Hegde, 2015).

	Benefit	description
1	Renewable and Readily Available	Hydrogen is the most abundant and renewable element globally in the universe even though its extraction, mainly from water is a challenge.
2	Hydrogen is a Clean and Flexible resource to support Zero-Carbon Energy Strategies	Hydrogen fuel cells are clean with no adverse environmental impact during operation the products are simply heat and water unlike. Land requirements for hydrogen is significantly smaller than biofuels or hydropower.
3	More Powerful and Energy Efficient than Fossil Fuels	The fuel cells provide high-density source of energy at higher energy efficiency. Hydrogen fuel has the highest energy content by weight compared to other fuels. Hydrogen at High pressure as a gas and liquid hydrogen contains about three times the gravimetric energy density i.e. about 20MJ/kg of diesel and LNG and has a similar volumetric energy density to natural gas. These
4	Highly Efficient when Compared to Other Energy Sources	Hydrogen fuel cells are more efficient than many other renewable and non-renewable sources, including hence more output per of fuel input e.g. a conventional. combustion-based power plant has about 33-35% efficiency compared about 65% for hydrogen fuel cells while vehicles with hydrogen fuel cells use 40-60% of the fuel's energy and offer 50% reduction in fuel consumption.
5	Almost Zero Emissions	Hydrogen based fuel cells do not generate greenhouse gas emissions compared to for fossil fuel sources, making them a clean source of power for the global energy transition
6	They can be used to reduce Carbon Footprints	Fuel cell operating on hydrogen do not directly emit greenhouse gases which imply that the operation stage of fuel cells has no carbon footprint hence an ultimate choice in low carbon transformation of energy sector.
7	They can afford Fast Charging Times	The time taken to charge time for hydrogen fuel cell power units is as short and the time needed to refuel a conventional internal combustion engine (ICE) cars i.e. as flow as 5 minutes to charge and much faster charging the battery-powered electric vehicles which between 30 minutes and several hours to charge, which provides flexibility as conventional cars.
8	No Noise Pollution	Hydrogen fuel cells are noiseless devices compared to wind and thermal sources of power like internal combustion engines hence they are much quieter than many other power sources
9	No Visual Pollution	Wind, biofuel and some other low-carbon energy options can be an eyesore to users and the environment, but not for hydrogen fuel cells hence fuel cells have limited or no visual pollution issues
10	Rural and remote areas application	The availability of hydrogen through local generation and storage will gradually substitute diesel-based power and heating generation in remote and off grid areas. This will improve the lives of rural poor and offer pollution free energy options

11	Long Usage Times	The fuel cells offer greater efficiencies with regard to usage times with a hydrogen vehicle having the same range as fossil fuels of about 300 miles, which is superior to electric vehicles. The performance of hydrogen fuel cells is not significantly impacted by the environmental or outside temperature and doesn't diminish in cold weather compared to electric vehicles.
12	Versatility of Use	Fuel cells have potential applications in a wide range of stationary and mobile applications e.g. hydrogen powered vehicles, cogeneration, and domestic applications.
13	Democratisation of Power Supply	The hydrogen fuel cells have significant potential to reduce the consumption of fossil fuels, hence democratise energy and power supplies globally. Reduced use of fossil fuels will limit the avoid the problem of fossil fuel prices increase and stock reduction rate

From table 3, it is noted that there are various benefits of fuel cells, like the democratisation of power generation which is a shift from traditional source, long usage durations in transport application, high conversion efficiency and clean source of energy.

Disadvantages of fuel Cells

The production of green hydrogen by electrolysis is a high energy process while the use of renewable energy sources remains a costly option and accounts for a low of about 5% of total hydrogen production globally. A vast majority of global hydrogen production is derived from fossil fuel sources through methane reforming processes and this is expected to remain the most feasible option for many years as the capacity for more efficient and cost-effective electrolysers increases and reduce the production costs. This is a drawback to the fuel cell technology as a truly green energy option(Edwards et al., 2008). Other disadvantages of fuel cells are;

i.) It has high initial investment cost
ii.) It is associated with low voltage
iii.) Fuel cells have lower service life (Hegde, 2015)

Conclusions

Fuel cells convert chemical energy of in fuel efficiently to electricity without combustion, with low emissions compared to conventional equipment/techniques. It is therefore a fuel cell defined as an electrical chemical device that directly convert chemical energy to electricity. The three main parts of a fuel cell assemble are the anode, cathode, and electrolyte. A catalyst oxidizes fuel with ions travelling via the electrolyte. At the cathode ions are reunited with the electrons. It is the electrons produced at the cathode that generate electrons which make the electrical circuit. Fuel cells development partially focuses on optimization of catalytic the layer 0f the catalytic electrodes, and by reducing metal without appreciable loss of the fuel cell performance. For fuel cells, power supply is uninterrupted during fuel supply and the oxidant, unlike a battery which relies on stored energy and is affected by amount of reagent available. The theoretical thermodynamic efficiency fuel cells is about 90% while in thermal engines the efficiency is about 40% for optimum conditions. However, practical fuel cell efficiency is usually less than 60%. The fuel cells operate with continuous replenishment of the fuel, and the oxidant at active electrode area and with no need for recharging. The elements of a fuel cell are the electrode, an oxidant or an air electrode, and an electrolyte. Common fuel cells used are hydrogen, oxygen (H_2, O_2), hydrazine (N_2H_4, O_2), carbon/coal (C, O_2) methane (CH_4, O_2). Unlike storage batteries whose main objective is to store energy, fuel cell fuel cells continuously generate as long as there is continuous supply of fuel and oxygen. Fuel cells employ an external or internal fuel-reforming process using any hydrogen-rich fuel can in different types of fuel cells. Hydrogen-powered fuel cells emit only water with virtually no pollutant emissions. On the other hand, fuel cells powered by hydrocarbon-based fuels have the potential to Employing hydrocarbon-based fuel inevitably leads to CO_2 emission. Since fuel cells are not subject to the limitations of the Carnot cycle efficiency, fuel cells attain higher efficiency that can be more than twice the efficiency of internal combustion engines. The transport sector operates with fuel cells having efficiency of up to 65%, compared to 25% for internal combustion engines. Application of heat produced by in fuel cells reaction for in combined heat and power (CHP) systems, increases overall efficiency to over 85%

The major technological challenges that must be overcome for a transition from a carbon-based (fossil fuel) energy system to a hydrogen-based economy are cost of efficient and sustainable hydrogen production and delivery remain high and should be reduced, need to develop new generation of hydrogen systems for automotive applications e.g. refuelling stations across the transport networks and need to reduce the cost of hydrogen fuels and hydrogen-based systems. An integrated hydrogen energy system of the future should combine small and large fuel cells for industrial and domestic decentralised heat and electricity power generation with extended hydrogen supply networks that can also fuel conventional internal combustion or fuel cell vehicles

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