



Advances in salt-based fuel cells technologies: A review

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Abstract

Fuel cell (FC) is an advanced energy production technology that converts the chemical energy into electrical energy through a series of redox reactions. They ensure the production of electrical energy with minimum emissions of toxic exhaust gases unlike all other conventional energy technologies. The most significant feature of FCs is their ability of direct conversion of chemical energy of fuel into electrical energy with the efficiencies much higher than the conventional gas and coal-thermal-power-plants. FCs ensure the minimum emissions of toxic pollutants and produce less noise as compared to all other energy technologies. FCs are cost-efficient devices as their spare parts are easily available and require low maintenance cost. Depending upon the operating temperatures, these devices are divided into various categories. Therefore, the present review is designed to study the different types of FCs such as high, medium and low temperature and type of electrolyte used like PEM (Polymer electrolyte membrane), AFC (Alkaline fuel cell), PAFC (Phosphoric acid fuel cell), MCFC (Molten carbonate fuel cell) and SOFC (Solid oxide fuel cell). Furthermore, some important components and working mechanisms of these FCs are also discussed in detail. In order to move towards a sustainable existence in our critically energy dependent society, there is a continuing need to adopt environmentally sustainable methods for energy production, storage and conversion. Therefore, this review stresses and recommends the use of FCs in both stationary and mobile power applications as it offers significant advantages for the sustainable conversion of energy over all other energy producing technologies.

Key words: FCs, PEM, AFC, PAFC, MCFC, SOFC, sustainable energy

Full length article *Corresponding Author, e-mail: farwa668@gmail.com

1. Introduction

In view of the current rate of energy consumption, production of energy using different materials and chemical substances is the major target of the global world these days. The world is now trying to find the highly efficient and highly environment friendly energy technologies to ensure the cleaner surroundings. The final destination and major goal of current global scientific researches is to move towards sustainable developments [1]. In this regard, FCs offer the most promising results for the direct conversion of chemical energy into electrical energy with minimum emissions of toxic pollutants [2].

Now-a-days, the world is trying to find out the number of alternative methods for the generation of energy and conversion of different materials into electrical energy. Efficient energy production to fulfill local energy demands is the key factor for economic sustainability and national prosperity. It plays a very important role in increasing the interactions between nature and society [3-5]. The non-renewable energy resources such as fossil fuels are known to cause a number of environmental problems including several

pollutants, toxic exhausts and greenhouse gases like carbon monoxide, carbon dioxide and methane [6]. Environmental degradation and number of health hazards are caused by the air pollutants and non-treatable viruses at local and global level [7]. Increasing energy demands are also increasing the environmental concerns due to the excessive use of coal and natural gas as a basic raw material [8].

Some conventional energy technologies such as natural gas, coal and crude oil based thermal power plants are the major sources of land sliding, flooding, stratospheric ozone depletion, global climate change and acid rain [9]. All these technologies are causing environmental problems in all the developed industrial countries of the world by the increase in concentration of carbon dioxide in air [10]. Therefore, development of energy efficient technologies and environment friendly approaches is a dire need of the hour. The emissions of carbon dioxide and carbon monoxide significantly reduce the thermodynamic efficiencies of the energy conversion systems [10-12].

Following steps are required to be adopted for the improvement of environment and to ensure the sustainable

future (i) strict environmental legislations (ii) intensification of fossil fuels prices (iii) development of energy efficient systems (iv) low emissions of carbon based compounds (v) cost-efficient methodologies and (vi) reduction in emissions of greenhouse gases [13]. Gradually increasing prices of fossil fuels, global warming, depletion of natural energy resources are some of the adverse effects of conventional energy technologies that are now spurring the exploration of new and efficient resources for the conversion of fuel based chemical energy into heat and electrical energy for thermal management of electronics and automotive [14].

Among all the previously used technologies, use of FCs is the most advanced and promising technique for production of electrical energy by avoiding the greenhouse emissions. It directly converts the fuel energy into electrical energy through number of electrochemical reactions resulting in the higher efficiencies and cleaner operations [15]. In addition, use of FCs are more efficient and cleaner alternative energy technologies due to (i) ease of operation (ii) easy installations (iii) capability of global and local scale production (iv) higher production rate and (v) versatile fuel range [16]. FC is an electrochemical device that is taking considerable attention in industrial sector by replacing all the conventional fossil fuel technologies [17].

These devices are much more efficient and cleaner in conversion of chemical energy into electrical energy by using fuels such as hydrocarbons, ethanol, methanol, natural gas and hydrogen. The efficiencies of these devices are higher than conventional combustion-engine-technologies and emit almost negligible greenhouse emissions [18]. Thus, FCs are regarded as the most promising energy conversion technologies ensuring the cleaner surroundings [19].

For the first time, FCs were invented by Sir William Robert Grove in 1839 and he is known as "father of fuel cells" [20]. He was a professor at London Institute when he first time used the "zinc platinum batteries" for the production of light to conduct his lectures. In FCs, energy of fuel is directly converted into "direct current" through an electrochemical reaction without undergoing any burning or heating process [21]. It drives the electrical energy directly from electrochemical reaction of hydrogen using mixture of air and oxygen. Hydrogen is an ideal fuel for production and storage of energy. On industrial scale, hydrogen is produced by "steam reformation" of methanol, methane and naphtha. For the low temperature FCs like alkaline-electrolyte-fuel-cells and polymer-electrolyte-fuel-cells, very high quality hydrogen gas is used [22].

The system of FCs comprise of (i) an electrolyte solution and (ii) porous electrodes like cathode and anode [23]. In the typical setup, hydrogen gas is used as a fuel and continuously supplied to the negatively charged electrode (anode) and atmospheric oxygen is continuously fed to positively charged electrode (cathode) to complete electrochemical reaction for the production of heat and water [24].

The most significant feature of FCs is the direct production of chemical energy into electrical energy with efficiencies much greater than the coal and gas based electrical power generators [25]. If the heat produced by FCs is utilized by the same system, the efficiencies greater than ninety percent can be achieved. These efficiencies can further be enhanced by coupling the "low temperature systems" with "high temperature systems". The heat produced by this system is used by many other industries for number of processes [26].

2. Classification of fuel cell technology

There are three classifications of FCs depending upon the temperature (i) high temperature FCs (ii) medium temperature FCs and (iii) low temperature FCs. The second classification is based on the type of electrolyte used in this reaction media. There are following basic types of FCs (i) SOFC (ii) MCFC (iii) PAFC (iv) AFC (v) PEMFC [27]. The system of classification of FCs actually determine the (i) nature of fuel used (ii) operating temperature of FCs (iii) type of catalyst and (iv) the nature of chemical reaction. These conditions determine the application of FCs in several fields [28]. Table 1 gives the comparison of different FCs (based on electrolyte type) in terms of their operating temperature, power, efficiency and applications.

2.1. Proton exchange membrane system

In case of "proton-exchange-membrane-fuel-cell" (PEMFC), fluorinated sulfonic acid membrane is used to exchange the protons between electrolyte solution and polymeric membrane. Most significant problem of PEMFC is production of huge amount of wastewater as membranes are highly dependent on moisture contents. For the proper functioning of FCs, polymeric membranes must be fully hydrated. The hydration of these polymeric membranes depend on (i) steam humidification of reactant (ii) flow of gas-diffusion-layer and (iii) wetting property of polymeric membrane and gas-diffusion-layer [6-29-31]. It is shown in Figure 1.

2.1.1. Working of fuel cells

FCs consists of (a) anode (b) cathode (c) electrolyte solution and (d) fuel gas. Hydrogen is bubbled at anode that splits the electrons and protons from the layer of catalyst. These splitted protons are allowed to pass by electrolyte to reach towards the cathode. The electrons are not allowed to freely flow and to pass through electrolyte solution. Thus, these electrons follow an external circuit leading to the production of electrical energy. When the protons and electrons are allowed to flow from cathode to anode, oxygen gas is immediately pumped at cathode to undergo reaction. The oxygen, electrons and protons react at the cathode by using its surface as a catalyst for the production of heat, water and all other by-products. The continuous supply of fuel is ensured for the proper functioning of FCs [32].

2.1.2. Components of polymer electrolyte membrane fuel cells (PEMFCs)

Some major functions of the PEMFC are (i) ion exchange membrane (ii) solid electrolyte (iii) electrical conductor (iv) highly porous gas diffusion membrane (v) electro catalyst also known as "electrode". The interface also contains the (a) major membrane and (b) backing membrane [33]. The flow plates (designed to deliver the oxidant and fuel at the site of reaction) are responsible for electrically connecting the cell. In the beginning, first three components are joined to form "membrane-electrode-assembly" (MEA) that is considered to be the heart of PEMFC [34]. Materials and manufacturing processes for PEMFC stacks is shown in the Table 2 [35].

2.1.2.1. Proton conducting membranes

One of the major components of MEA is "proton-conducting-membrane" (PCM) which is responsible for the conduction of protons only and it acts as a barrier between electrons and reactants resulting in formation of PEMFC. By using these types of cells, very high power densities can be achieved [36]. Some major properties essentially required for the establishment of membrane in FCs are (a) low cost and highly durable membrane (b) minimum entry of reactant molecules to maximize the efficiency of entire process (c) compatible bonding requirements in between electrodes and membrane (d) hydrolytic and thermal stability (e) very high conductance of proton to support the currents with minimum possible losses and zero electronic conductivity and (f) good chemical, electrochemical and mechanical strength during operations of FCs [37].

2.1.2.2. Electro catalysts for PEMFC

The platinum is supposed to be the best catalyst for cathode and anode during regular FCs reactions despite the major difference in between "hydrogen oxidation reaction" (HOR) and "oxygen reduction reaction" (ORR). The reaction of ORR is quite sluggish at cathode and further complicates the two and four electron reactions [38]. In case of pure platinum, sometimes ORR undergo over potential almost greater than three hundred millivolts. Many research studies have attempted to develop the most appropriate catalyst for ORR. The use of platinum based catalysts is the major cause of carbon monoxide poisoning at anode [37].

2.1.2.3. Anode catalyst

For the hydrogen oxidation reaction, platinum is apparently the most appropriate catalyst having high current density. The only associated problem is poisoning of carbon monoxide. For number of practical industrial applications, trace impurities of carbon monoxide in hydrogen rich areas of FCs is inevitable [39]. Almost 10 ppm concentration of carbon monoxide can be absorbed by the platinum catalyst,

blocking the active site of catalyst, and decreasing efficiency of catalyst. This process is commonly known as "carbon monoxide poisoning". This study has been one of the most pronounced developments of PEMFC system [40].

2.1.2.4. Carbon monoxide tolerant catalyst

The two major challenges of PEMFC system are (i) catalyst development for anode with low concentration of carbon monoxide either in the presence of high contents of carbon monoxide or under steady state operations and (ii) low temperature PEMFC systems [41]. The results of large number of scientific studies have concluded that platinum-ruthenium catalysts are the best known catalysts that can bear the maximum concentration of carbon monoxide as compared to the all other simple platinum catalysts. High temperature also reduce the chances of catalytic poisoning [42]. The attachment of secondary metals with platinum is the basic element that determines the extent of catalytic poisoning of electrodes. It tends to reduce the bond strength of platinum and carbon monoxide and aid in the oxidation of carbon monoxide [43].

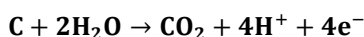
2.1.2.5. Cathode catalyst

Limitations of ORR catalyst is mainly responsible for the 1/3rd loss of performance in PEMFC [44]. The major challenge for the catalytic reaction of ORR is as follows: (i) stable cathode in highly corrosive environment (ii) chemical reactivity capable of activating the oxygen contents and (iii) capacity to liberate the oxygen from the surface as water. The activation of oxygen involves the oxygen adsorption on active site of catalyst through transference of electrons and protons for the formation of OOH before the breakage of dioxygen bonds. Therefore, the catalyst should be able to moderately stabilize the OOH. After the bond dissociation, absorbed hydroxal radical and oxygen radical is absorbed on the surface of catalyst and it must not bind these species strong enough for the easy desorption of water [45].

Both types of electrodes, based on noble metals and non-noble metals have been the topic of number of scientific studies since past few decades. These setups are mostly designed for the reduction of oxygen. Till now, platinum seems to be the best catalysts in this regard [46]. The catalytic activity of noble metals is comparable with the catalytic activity of palladium-based-materials. In addition, for non-noble-metals, pyrolyzed macrocyclic compounds, transition metal chalcogenides and other electro catalysts have been widely used [47].

2.1.2.6. Catalyst support

Carbon is the most important support material for the catalysts of FCs because of (i) highly porous structure (ii) high electrical conductivity and (iii) large surface area. The only problem is corrosion of carbon at cathode in the presence of water molecules as shown in following equation



When the poisoning of carbon-monoxide becomes more severe, platinum catalyst starts to agglomerate on the surface of carbon. This process degrades the performance of catalyst and reduces the lifecycle of PEMFC making it inappropriate for the number of applications [48]. Therefore, highly stable supports of catalysts are required to increase the lifecycle of catalyst. Some other studies are in agreement of exploration of some other supports including conducting polymers and metal oxides [38-49]. The most studied and best used support material for catalyst is "Vulcan" for FCs. Several other materials have also been investigated to be used as a catalytic support for PEMFCs. Carbon nanotubes are known to improve the durability of catalyst whereas combination of platinum and carbon nanotubes show the higher ORR activity, low electrochemical surface area loss and better corrosion resistance in comparison with platinum and carbon based catalysts and supports [50].

2.1.2.7. Gas diffusion layer

The gas-diffusion-layer consists of two basic layers (i) micro-porous layer and (ii) micro-porous substrate layer. In the PEM FCs, these porous gas-diffusion-layers ensure the effective diffusion of catalyst and minimum transfer of mass. These gas-diffusion-layers are mostly formed by the carbon cloth or porous carbon paper having the approximate thickness ranging from 100 μm to 300 μm . These layers are permeable and help in the distribution of gases over the entire layer of catalyst to conduct the electric current and to provide the network for liquid water to move from MEA towards the flow channel. The gas-diffusion-layers also help in the management of water by allowing the appropriate amount of water to reach and held at the surface of membrane for hydration. These gas-diffusion-layers are coated with Teflon to ensure that the pores of gas-diffusion-layers do not congested with liquid water [51].

2.1.2.8. Membrane electrode assembly (MEA)

Combined assembly of membranes and electrodes is known as "membrane-electrode-assembly" (MEA). All the electrochemical reactions of FCs take place at MEA and thus known as "heart of the FCs". These MEA consist of (i) gas-diffusion-layers (ii) catalysts layer (iii) proton exchange membrane. All these components are separately fabricated followed by the pressing at high temperature and high pressure. Therefore, designing and fabrication of MEA is a very crucial process directly affecting the performance of PEMFC. The assembly of MEA consists of two basic modes (i) the common mode is application of catalyst layer to gas-diffusion-layer also termed as "catalyst-coated-substrate" and (ii) the second mode is direct application of catalyst layer to catalyst-coated-membrane followed by the addition of gas-diffusion-layers [52].

2.1.2.9. High temperature-PEMFC

Globally, there has been an increasing interest on PEMFCs operating at the temperatures greater than 120°C and are termed as "high-temperature-PEMFCs". These new devices has large number of advantages over conventional PEMFCs such as (i) high tolerance to carbon monoxide (ii) improved reaction kinetics because of increasing operating temperature (iii) minimum water use and water management issues (iv) emitted heat is used by co-generation applications (v) small cooling units are required due to high temperature difference in between atmosphere and stacks (vi) minimized plant balance requirements.

The overall performance of PEMFC can be increased by increasing the temperature upto 120°C through improved reaction kinetics of anode and cathode reactions. The increased operating temperatures will also enhance the tolerance of FCs towards number of poisoning species like carbon-monoxide. However, considerable efforts are being made to develop the "liquefied-fueled PEMFC" for the large number of advanced transportation equipments. Majority of the practitioners believed that hydrogen storage will be an essential part of future transportation on practical basis. In ideal working conditions, these types of FCs will minimize the complexity of system when combined with modern cooling systems with reduced balance of plant components.

Based on the existing literature, following types of high temperature catalyst systems should be developed (i) durable catalyst supports capable of surviving under high temperature (ii) improved interactions in between catalyst and support for enhanced catalytic activity (iii) development of durable non-noble catalysts for long term sustenance and profitable commercialization in low cost (iv) optimization of catalysts and catalytic layers by improving the composition and basic structure by innovative ideas and fundamental understanding (v) improved gas-diffusion-layers and its materials for proper functioning in non-humid conditions and high temperature environment (vi) membrane having better stability and high conductivity and (vii) better and efficient distribution of phosphoric acid inside the electrode and membrane for improved performance.

In the stacks of PEMFC, large numbers of material and manufacturing improvements are foreseen in future. Some of the improvements include (i) reduced catalyst load (ii) improved deposition techniques (iii) development of nano-structured catalytic supports (iv) use of carbon based composite materials (v) stamped metal sheets for low plates and (vi) reduction of the thickness of MEA [53].

2.2. Alkaline fuel cell (AFC)

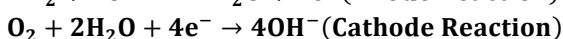
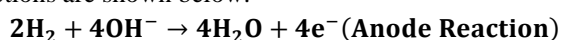
The first FCs technology applied for the practical implementation of power generators is "alkaline-fuel-cells" (AFC). These were introduced during Apollo missions in 1960s [54]. These systems are still working as a major

source of power supply for space shuttles. Huge amount of carbon dioxide is released by these systems therefore AFCs are still not considered suitable for the regular transportation and the concentration of carbon dioxide exceeds the regular acceptable level. In the year 1990, large number of scientific researches and developmental works were reduced and eventually terminated [55]. With the passage of time, the PEMFC emerged as a potential technology for large number of applications in transportation sector and gained increasing attention. Numerous methods have been developed to resolve the problems of AFCs. In past few years, poisoning problem of AFCs by carbon dioxide was possibly reduced to increase its applicability for the large number of terrestrial applications. According to some estimates, the kinetics of oxygen reduction reaction is more pronounced in alkaline environment as compared to the acidic environment. Therefore, cheaper metals like silver and nickel are more preferred instead of platinum to be used as a catalyst in AFCs [56].

In FC technology, much progress had been made but still people are not aware of these advanced versions due to the less commercial scale applications. In past few decades, AFCs received the renewed attention because of their high efficiency and low cost on commercial scale [57]. First FC technology was AFC that gained much importance due to its practical implementations and huge electricity production from hydrogen based fuels. In space devices and space equipments, these AFCs provided highly efficient and most reliable energy conversion without moving any part. In the late 1950s, first AFC experiment was conducted by using farm tractor to test its vehicular efficiency [58]. After this experiment, another famous scientist Karl Kordesch operated the Austin A40 in the late 1970s [59] and such types of devices are still being commercialized by the ZEVCO company [60]. It is shown in Figure 2.

2.2.1. Working principle of alkaline fuel cell

In such types of systems, electrolyte is flowed in between anodes. In addition to the conduction of electric current and ion transfer, the circulation of electrolyte leads to the excessive heat production. This heat is circulated within the system and out-side the system before reentering the cell and heat exchanger system. The continuous flow of electrolyte require an efficient pumping system to keep the fluid circulating [61]. In AFCs, aqueous solution of KOH is used as electrolyte having the approximate concentration of 30%. The entire chemical reaction and two half-cell reactions are shown below:



As a result of this electrochemical reaction, heat and water is produced that need to be removed gradually. This is done by

the circulation of electrolyte and coolant liquid whereas water is removed through evaporation [62].

2.2.2. Stack materials for alkaline fuel cells

The advanced materials used in the different types of AFCs are listed in the Table 3 and detailed processes are discussed in literature. With the advancements in the use of materials of AFCs, three major developments have been made such as (a) reduced catalyst loading (b) development of cobalt oxide catalyst and (c) the replacement of expensive nickle with cheaper metal mesh-current-collectors [53]. The use of liquefied fuels in FCs has always been a preferred option for the end users due to some logistic advantages over gaseous fuels. However, in case of AFCs, KOH is used as electrolyte and its chemical reactions make this approach impossible. Therefore, proper fuel processing is the ultimate requirement prior to the utilization in FCs.

Methanol is the most common example of such types of liquid fuels. After methanol, hydrazine is another liquid fuel that appears to be the most compatible liquid to be used as alkaline electrolyte. Hydrazine is known to be a major liquid source of "hydrogen" and "nitrogen" as it can readily be decomposed in basic components at anode. In the early 1950s and late 1960s, the experimental setups have been working on the use of hydrazine as electrolyte in FCs. Depending upon the nature of working projects, hydrogen peroxide, pure oxygen and air can be used as an oxidant. Some major disadvantages of this technology are (a) high cost (b) poisonous nature of hydrazine (c) difficulties during the process made this concept quite inappropriate. Thus, use of hydrazine based FCs came to an end till the beginning of 1970s. Till date, it does not seem to be reemerged in near future. Due to this reasons, the scientists are now looking for the direct use of hydrogen as a fuel [63].

2.2.3. Manufacturing techniques and materials

2.2.3.1. Electrode and catalyst

Up till now, extensive research and developments have been made in the field of FCs. Even by limiting the discussions to AFCs, only the development of catalyst and electrode could compile a book leaving the impression about the amount of work done on the FCs in past few decades. The basic focus of this review is to shortly compile the major breakthroughs in this field. Unlike PAFCs, AFCs also encourages the use of non-precious metals to make the entire process cost-effective. The most common anodic metals are based on Raney nickel catalysts and cathodic metals are silver based catalysts. Similarly, the use of pure platinum metal or platinum alloy is more common in the development of metallic electrodes and to act as a support material of carbon.

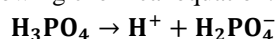
For all types of electrodes, there are some general requirements such as (i) excellent electronic conductance to avoid the ohmic losses (ii) suitable porosity and adequate

mechanical strength (iii) high chemical stabilization even in alkaline electrolytes and (iv) electrochemical stability with the passage of time. It indicates that the stability of catalyst and methods of incorporation of electrodes, both are very important. In addition, hydrophilic and hydrophobic nature of metallic electrodes of FCs is another most important characteristic feature. Hydrophobic metallic electrodes are only partially wetted due to the presence of poly-tetra-fluoro-ethylene (PTFE) in the carbon based electrodes.

This phenomenon is of extreme importance for the long life of electrodes as the hydrophobic nature of these electrodes can adequately be preserved by using appropriate structure of poly-tetra-fluoro-ethylene containing catalytic layers. In usual cases, different types of electrodes contain different layers with variable porosities. These catalytic layers are arranged within the electrodes to maintain the flow of gaseous fuel (including hydrogen and oxygen/air as oxidant) and liquid electrolyte. Large numbers of advanced techniques have been used for the manufacturing of several electrodes and their layers. For these types of setups, the powdered catalysts are mixed and calendared into several layers. Sedimentation and spraying can also be used in case of high temperature sintering processes that are known to have excellent mechanical strength [64].

2.3. Phosphoric acid fuel cell (PAFC)

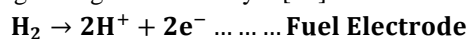
The special type of FCs that uses the solution of phosphoric acid as a basic electrolyte is called "phosphoric-acid-fuel-cell" (PAFCs). In aqueous solution, the phosphoric acid dissociates into basic components (i) positively charged hydrogen ions and (ii) negatively charged phosphate ions as shown in the following chemical equation:



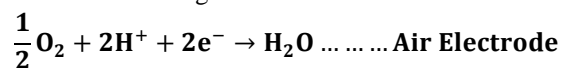
Phosphoric acid is very easy to handle as it is chemically a stable acid of nature. The most significant advantage of the use of phosphoric acid is its low vapor pressure at even high operating temperatures of 200°C. It means that phosphoric acid cannot be easily discharged from FCs along with the release of exhaust gases. These minute discharges result in the degradation of cell performances. PAFC is shown in the Figure 3.

2.3.1. Working principle of fuel cell

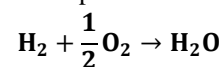
In these types of FCs, pure hydrogen gas is used as a principle component of entire cell. At the one electrode, hydrogen gas is supplied and air is pumped in, from second electrode as oxidant resulting in electrochemical reactions to produce electrical energy. At the surface of electrode, supplied hydrogen split into hydrogen ion and electrons. These hydrogen ions migrate towards the second electrode by passing through the electrolyte [65].



The migrated hydrogen ions, produced electrons by electric circuit and supplied oxygen combines to form the oxygen as shown in the following chemical reaction:



Hence the net FC reaction produces water as follows:



2.3.2. Cell structure

The setup of PAFC consists of (a) combination of porous electrodes having air electrode and fuel electrode formed by the carbonaceous material (b) layer of electrolyte constituting integrated matrix impregnated with highly concentrated solution of phosphoric acid. Catalytic layers of electrodes are formed by the combination of carbon, metal catalyst and water repellent materials. Catalytic layers provide the site for chemical reactions to take place. During the construction, these layers are arranged in such a way to provide the complete cyclic reactions for the production of electrical energy. From these electrochemical cells, voltage of about 0.6 to 0.8 can be obtained. Therefore, for the large scale utilization of these FCs, hundreds of cells are stacked and connected in a series resulting in the formation of "cell stack". Huge amount of energy is produced by the electro-chemical reaction of oxygen (oxidant) and hydrogen (fuel). Therefore, cooling plates are arranged at regular intervals in between FCs to ensure the flow of coolant and to maintain the operating temperature of about 200°C [66].

2.3.3. Features of phosphoric acid fuel cells

Unlike the AFCs, PAFCs do not face degeneration of electrolytes caused by the induction of carbon dioxide. Therefore, these types of FCs can also use the reformed gases emitted from fossil fuels by using platinum metal as a catalyst in order to promote the electrode reactions. These types of FCs can use the infrastructure quite similar to the natural gas and coal. However, the presence of appreciable concentrations of carbon monoxide leads to the poisoning of catalysts resulting in the inappropriate performances. Thus these types of FCs are practically non-effective to be used without eliminating the carbon monoxide poisoning. This gives an additional constraint in terms of cost.

The operating temperature in these types of FCs is almost equal to 200°C or 473K. If the cell is designed in such a way that it does not come in direct contact with iron, copper and phosphoric acid then various other types of metals can also be used. In order to make sure the use of electrode catalyst layer having "water repellent properties", the PTFE or various other heat resistant organic layers can also be used. There is a complete setup for "water coolers" in these types of FCs for the removal of heat produced by the electrodes [67].

Waste heat is known to have the temperature range of 200°C and it can be used for number of heating purposes

in space and water. Sometimes, extracted heat is converted into steam to be used for heating the refrigeration systems. According to an estimate, the efficiency of electrical power generation in PAFCs is forty percent and this value is quite competitive with existing gas engines and gas turbines. The ability of low noise production and minimum emissions of toxic oxides of nitrogen; make this technology suitable for cogeneration systems in urban areas. Unlike all the high temperature FCs systems such as the SOFCs and MCFCs, a combined cycle system coupled with steam turbine or gas turbine generators is most appropriate for maximization of system's efficiency. However, the amount of heat liberated by PAFCs is inadequate to achieve this purpose. In case of pressurized PAFC systems, exhaust gases are passed by the expander at elevated temperature and extreme pressure to drive the air compressors and electric power generators for the production of electrical energy. By using these types of systems, almost forty four to forty six percent efficiencies can be achieved [68].

2.4. Molten carbonate fuel cell (MCFC)

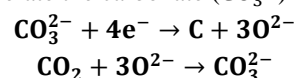
The MCFC is the simplest devices having high performance matrix-free-biomass even without recirculation of carbon dioxide. According to an estimate, almost eighty seven percent of all energy sources, is supplied by the fossil fuels all across the globe [69]. However, it is the major source of atmospheric carbon dioxide. Therefore, it is the dire need of the hour to integrate the renewable energy resources having negligible emissions of carbon contents. Biomass energy derived from forestry products, agricultural wastes and crop residues are the most important renewable energy resources. The estimated global biomass potential is about two hundred exa-joules accounting for 1/3rd of total world's energy consumptions [70]. Heat energy is produced by the combustion of biomass for the generation of electrical energy aided by steam. Instruments similar to fossil fuels can be used for this purpose. Pyrolysis is used for the production of charcoal by using biomass and charcoal is an ideal fuel for DCFCs [71]. Schematic diagram of MCFC is shown in Figure 4.

2.4.1. Carbon dioxide conversion into useful products

The "carbon capture and storage" (CCS) is the most pronounced method known to compromise the advantages and disadvantages of fossil fuels. In CCS, the first step is capturing of carbon dioxide followed by the compression and storage quite away from the atmosphere for a specified period of time in geological formations. In spite of storage only, capture and conversion of carbon dioxide into useful final products is more desirable to get the hydrocarbons, alcohols and many other chemical compounds [72]. Another proven method is "electrochemical reduction of carbon dioxide" in aqueous media that requires the use of catalyst, electrode material, electrolyte and highly specified operating

conditions [73]. After this, another important method of conversion of carbon dioxide into useful final products is reduction of atmospheric carbon into solid carbon through electrolysis in molten-alkali-metal-carbonates. In the late 1960s, researchers and scientists studied that carbon could easily be electro-deposited from the molten salts containing carbonate ions and lithium ions (CO_3^{2-} and Li^+) [74].

In some recent scientific researches, the researchers suggested that this process can be used for direct conversion of atmospheric carbon dioxide into various other carbon based compounds [75] by using the electro-reduction of carbonate ions into solid carbon and solid oxide ions by using molten salts electrolyte. The oxide ions obtained from this reaction can easily react with atmospheric carbon dioxide to regenerate the carbonate (CO_3^{2-}) ions [76].



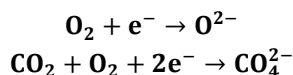
2.4.2. Fuel processing

There are two basic types of the fuel processing in MCFCs like (a) external-reforming-MCFCs and (b) internal-reforming-MCFCs. The external-reforming-MCFC produces significant amount of hydrogen ions outside the stacks of MCFC. In such types of setups, the stack temperature can only be controlled by the convection of heat transfer. Hence, external-reforming-MCFC adopts the pressurized system for the instant supply of cooling gas. The other type of system is internal-reforming-MCFC that directly generates hydrogen in MCFC stack. The temperature of stack is controlled by the removal of heat produced from endothermic reactions during the reforming operations. However, these MCFCs can operate under moderate conditions of temperature and pressure thus high flow rate is not required during internal reforming [77]. The processes of internal reforming can be further categorized into two groups: (a) direct-MCFC and (b) indirect-MCFC. In direct-MCFC, reforming operations takes place on anode and high thermal efficacy is achieved. On the other hand, reforming operations can also be made on the sides adjacent to anode. Sometimes, these two types can also be integrated in a two-step reforming of anode inlet flow [78].

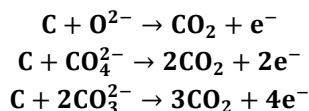
2.4.3. Working principle of FC

In the newly designed FCs, oxygen and air are not allowed to bubble in the molten carbonate electrolyte. The only possible direct chemical reaction in between oxygen and fuel is through dissolved molecular oxygen. According to some recent reports, at the approximate temperature of 600°C, the molecular oxygen, lithium carbonate, potassium carbonate, sodium carbonate, super-carbonates and per-carbonates are found in dissolved and ionized form at high temperature [79]. In the chemical reaction between anode and charged oxygen species, the loss of electrons should lead to the production of electrical energy. Under these sets

of conditions, dissolved oxygen is used as a basic charge carrier. The possible cathodic chemical reactions are:



The anions formed on the anodes will diffuse in the molten carbonate and react with solid fuel. In case if carbon is used as a fuel, the anodic reactions are as follows:



For the second and fourth step electrochemical reactions, the O^{2-} ions are the basic charge carriers. Therefore, utilization of carbon dioxide is not required ultimately. Theoretically, these MCFCs can work without the flow of carbon dioxide. In the high temperature FCs, fuel and steam are mixed to be directly fed at anode of FC stack. The reforming stage of the MCFCs can be integrated either in direct or indirect mode. In the indirect integrated reforming, reforming unit is placed inside the stack. It is responsible for the conversion of steam and natural gas into hydrogen rich gas before entering the anodic part of the FCs.

In case of direct integrated reforming, catalyst bed is found located inside the same anodic chamber thereby ensuring the proper steam management and better thermal efficiency. During the processing of these cells, sometimes it is assumed that hydrogen is the only element undergoing the electrochemical reactions. Few other major components are higher and lower hydrocarbons such as methane along with carbon monoxide; undergo the process of reforming and shift the direction of reaction. In case of indirect integrated reforming, fuel attains equilibrium in integrated reformer at specific temperature before transmitting to the anode. However, in case of direct integrated reforming, reforming temperature is almost the same as regular FC. Similarly, the conversion of methane is strongly affected by the mutual interactions of oxidation reactions and reforming processes on the anodic side [80].

2.5. Solid oxide fuel cell (SOFC)

The type of an electrochemical device that is used to generate the electrical energy directly from the oxidation of fuel is called "solid oxide fuel cell" (SOFC). It generates the electrical energy based on the chemical reaction of reactants [81]. SOFC is shown in Figure 5.

2.5.1. Working principle of solid oxide fuel cell

In case of SOFC, hydrogen gas is allowed to flow towards the direction of anode and the chemical reaction split the hydrogen atoms into electrons and protons. These produced electrons are allowed to flow in the external circuit and generate the electrical energy. Similarly, protons move towards the cathode by passing through electrolyte. Oxygen gas is allowed to flow at cathodic end in FCs. At cathode,

the chemical reaction takes place between incoming protons, oxygen, and electrons to form heat and water.

2.5.2. Components of solid oxide fuel cell

There are three major components of SOFCs such as (a) cathode (b) anode and (c) electrolyte.

2.5.2.1. Anode

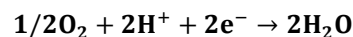
The anode is where electrochemical oxidation of the fuel gas occurs as shown in this reaction



The anode should have many qualifications and the most important ones are high electrical conductivity and high porosity.

2.5.2.2. Cathode

The cathode is where electrochemical reduction of oxygen occurs as shown in this reaction:



The cathode should have many qualifications such as high electronic and oxygen ion conductivity, chemical stability at different operating temperatures, enough porosity and chemical compatibility with the electrolyte.

2.5.2.3. Electrolyte

Electrolyte is the part of SOFC where chemical constituents are allowed to react and transport the ions in between the anode and cathode. The electrolytes used in SOFC have (i) low porosity (ii) high ionic conductivity and (iii) high oxygen conductivity. All these chemical reactions produce water, heat and electrical energy as shown by the following chemical equation:



The O^{2-} ions are passed through the electrolyte in more or less hydrated form. The collected anodic electrons are joined at the cathodic end, resulting in the formation of oxygen, hydrogen, electricity, heat and water vapors. This entire process is interpreted as "reverse reaction" of the electrolysis of water. Both the electrodes are separated from each other by using the solid electrolyte that allows the movement of ions from one part of the cell to the other under the effect of electric field [82].

2.5.3. Energy efficiency

The SOFCs are getting more attention in all FCs technologies mainly due to the number of advantages such as (i) low toxic exhausts and (ii) high energy efficiency. The efficiency of FCs is much higher than all the combustion based thermal power plants. The efficiency of FCs ranges from fifty to sixty percent and this can even be enhanced upto seventy percent by combining the "gas turbine hybrid systems" with "SOFCs" [83].

2.5.4. Solid oxide fuel cell designs

There are two basic types of the cell structure for SOFC batteries such as (i) planar batteries and (ii) tubular batteries. Each type of battery has different performance and tubular technology is simplest in design. The Figure 6 shows the potential performance of SOFC operating at about 1000°C. Planar design has better performance as compared to the tubular design. However, setup for planar technology is quite difficult and has large number of leakage problems due to the excessive expansions of materials at elevated temperature. The potential difference created by the power source is: "electrical pressure triggering the flow of electric current inside the electrical circuit". It represents the amount of work done per unit of charge when charged object moves in between two electrodes in electric field [84]. Performance of SOFC operating at 1000 °C is shown in Table 4.

2.5.4.1. Tubular design

All the important components of "tubular designs" are manufactured in form of hollow tube. The cells are built in form of layers all around the tubular cathode and air is allowed to flow through the inside of tubes. Fuel is allowed to flow through the exterior of tubing. Figure 6 explains all the essential components of tubular solid oxide FCs.

2.5.4.2. Planar design

The major components of these planar designs are generally manufactured in form of horizontal stacks having the fuel and air flowing through hollow canals fabricated in between positively and negatively charged electrodes [82]. Figure 7 explains the parts of FC. The comparison between planar and tubular solid oxide fuel cell is shown in Table 5. This table shows the comparison between some properties of Planar and Tubular SOFC.

3. Characteristics and applications of fuel cells

In order to survive in the energy dependent society, there is an increasing demand for the use of environmentally sustainable energy production, energy storage and energy conversion technologies. Therefore, use of FCs in mobile and stationary power applications, is gaining significant attention for ensuring the sustainable energy conversion technologies. There are number of advantages for the use of FCs such as (a) high efficiency and better reliability (b) cost-effective method (c) unique operating characteristics (d) high flexibility and (e) future developmental potentials. The sustainable energy requirements can easily be realized by integrating the applications of FCs with large number of renewable energy production processes. This technology is also very interesting for large number of applications such as (i) distributed power generators (ii) stationary power generators (iii) auxiliary power generators (iv) micro power generators and (v) portable power generators designed for

the automotive market and military projects. All these types of applications have extensive applicability on industrial scale all over the world [85].

3.1. PEMFC advantages and disadvantages

There are following advantages of PEMFC like (i) high power density in pressurized system (ii) high operative pressure in between the cathode and anode because of the mechanical properties of solid polymer electrolyte (iii) easy pressure handling during entire process and (iv) variety of cellular components and cell materials due to low operating temperature such as 80°C. The use of low cost carbon in the manufacturing of FCs contributes in the cost reduction of entire cell stack. On the other hand, there are also some disadvantages of PEMFCs like (a) catalysts of PEMFC are highly susceptible to the poisoning of carbon monoxide because of low operating temperature (b) the temperature of obtained waste material is much lower than other types of FCs thus cannot be used for heating and conversion of water into steam and (c) extensive water management system is of extreme importance to improve the performance of cell and to achieve the sufficient ionic conductivity.

Depending upon these features and existing short comings, development of PEMFC are of great importance for the applications in portable power appliances and high tech electric vehicles. This energy technology is also very promising for number of residential cogeneration systems when coupled with small scale natural gas fuel processors [86]. PEMFCs are highly energy efficient devices due to their excellent mode of operations. They are capable of producing maximum electrical energy per unit of the fuel cells with negligible emissions of carbon dioxide. PEMFCs work at low operating temperatures and have quick startup mechanism unlike all other conventional methods [87].

3.2. PEMFC applications

The PEMFCs can generate the huge amount of energy starting from few volts to hundreds of kilovolts. Due to these reasons, these FCs are most commonly used for (i) domestic electric power generation (ii) to run the bicycles, scooters, utility vehicles, buses and automobiles (iii) military and aerospace equipments and (iv) shuttles and submarines. PEMFCs have also found the number of uses in distribution of electric power for homes, buildings, offices and other communities due to the modularity and excellent flexibility in regular power supply [88].

3.2.1. Applications for transportation and automotive sector

The transportation sector is very promising and highly competitive sector for PEMFCs because of two major reasons (i) fossil fuel reserves are going to be depleted in near future and (ii) PEMFCs ensure environment friendly motor vehicles in society for regular use. The development

of fuel cell vehicles requires the proper integration of entire fuel cell systems and electric storage devices having enough potential and cost competitiveness. The "fuel cell vehicles" equipped with "direct conversion fuel processors" possesses enough potential to compete with the "conventional internal combustion engine" in all aspects except high maintenance cost. Some major requirements to compete the global market trends and to fulfill the emerging energy demands are as follows: (a) short startup time (b) less weight and small size of PEMFCs and (c) longer operative life spans ranging from three thousand to five thousand hours [89].

3.2.2. Stationary applications for distributed power generation

The efficient distribution of generated electrical energy is another major aspect of PEMFCs that is getting more attention these days. Low toxic emissions, huge power generation, high electrical efficiency and high modularity are some of the major advantages of PEMFC stacks. As a result of these processes, loads of the entire power systems can be directly managed by specially designed power plants inside the homes and offices of residential sectors.

3.2.3. Applications for portable power systems

Portable "power generation systems" of PEMFC technology consists of two major types of applications [88] such as (a) power cells for the replacements of batteries having the power just below the one hundred watts and (b) portable generators with at least one kilowatt power based on the power cells. Some major factors that must be ultimately considered in these types of systems are (i) operative time of battery and (ii) weight and size of entire system. The power units having larger energy storage capacities and higher power densities are best suited for applications like remote meteorological systems, new power tools, communication devices, transmission systems and portable computers. This technology also has number of advantages like (a) speedy startup (b) simplicity of operations (c) low capital cost (d) low maintenance cost and (e) negligible toxic emissions.

3.3. AFC characteristics and applications

The AFCs are known to have number of benefits such as (a) simplest cell structure (b) fast startup (c) less expensive material (d) low capital cost (e) efficiencies upto sixty five percent (f) life cycle in between ten thousand to fifteen thousand hours and (g) higher compatibilities of used materials inside the AFCs. The AFCs are cheaper and more efficient than PEMFCs. Therefore, AFCs are less popular than PEMFCs. AFCs are also more vulnerable to catalytic poisoning due to the toxic emissions of carbon dioxide in electrolyte. However, in case of PEMFCs, very expensive cleaning and purification systems are required making it cost inefficient. Summarizing the entire discussions, it can be concluded that AFCs are still the major source of energy

production and has number of applications in submarines and various other static and mobile applications [90].

3.4. PAFC characteristics and applications

PAFCs are still the most reliable energy resources due to following characteristic features (a) the operating life cycle comprising of sixty five thousand hours (b) operating temperature ranging from 150°C to 220°C (c) the power generation efficiency ranging from forty percent to sixty percent when coupled with combined-heating-system (d) partially immune to the poisoning of carbon monoxide (e) potential to use hydrogen fuels without ensuring the high level of purity like reformed carbon fuels (f) capacity to use the hydrogen based fuels without ensuring the high level of purity and (g) reducing the capital cost of power generation. However, PAFCs are still not able to be considered as high-temperature-FCs as this technology is in between the high-temperature and low-temperature FCs. Thus, relatively low operating temperature is the major cause of its use in big stationary power generation systems [91].

3.5. MCFC characteristics and applications

MCFCs are the currently developing and recently adopted methodologies in various countries all over the world. This technology is more preferably used in Germany, Korea, Japan and the United States of America. The applications of this emerging technology range from 125 kilowatts to 1 megawatts in terms of power generation [92]. The major advantages of MCFCs are as follows: (a) it can attain the efficiency upto forty five percent (b) production of heat and generation of steam can even enhance its efficiency upto fifty to sixty percent (c) ease of formation of combined cycle systems (d) MCFCs can use the hydrogen rich fuels as a source of energy just like coal gasified gases and natural gas (e) in case if fuel reformation takes place inside the cell, construction of external reformer is not needed and it lower the cost of power generation (f) it can use low cost nickel based alloys and stainless steel materials as a catalysts that significantly reduces the cost of entire project.

However, there are also some disadvantages related to the chemistry of electrolyte and high temperature systems such as (a) low operative life cycle caused by corrosion due to the use of electrolyte (b) loss of electrolyte due to high operating temperature (c) slow starting time until 650°C is attained and (d) impossibility to restart the cell stacks after shutting down the operating temperature. In spite of the all major demonstrations in various countries of the world, there is still an increasing demand for improving and developing these systems on commercial scale with the help of researchers, organizations and industrial companies. The central focus of all these researches is to improve the efficiency of cell and to increase the power density.

3.6. SOFCs characteristics and applications

The SOFCs are one of the most efficient and emerging technologies among all the FCs. Now-a-days, large number of SOFCs are available with high temperature programmed systems working with the approximate energy of 10 kilowatts. Recently, keen interest have been developed for the low temperature SOFCs to be used in automobiles [93]. In comparison with the all other FC technologies, these SOFCs are known to have number of advantages (i) high thermal and electrical efficiency among all the FCs (ii) no use of noble metals or any other expensive metal inside the cell as a catalyst (iii) use of cost-efficient hydrocarbons as a fuel such as natural gas, coal gas and biomass (iv) low rate of degradation and long operative life cycles (v) simpler structures and easy processing (vi) low emissions of oxides of nitrogen and sulphur in case of hydrocarbon fuels and (vii) less noise pollution [94].

Some of the major disadvantages of SOFCs are (a) long starting time is required as compared to the all other high temperature FCs (b) difficulties in the achievement of proper operating temperature (c) thermo-mechanical issues due to the coupling of materials having combination of different thermal expansion coefficients (d) poor thermal cycling of SOFCs (e) limitations of usage for the stationary applications only. However, environment friendly nature, low cost and highest efficiencies of SOFCs will enable it to replace PAFC technology for commercial scale applications. In the Europe and North America, high expectations are being associated with the stationary and mobile distribution power applications. The characteristic properties of SOFCs are also very suitable for the portable applications. Lots of research efforts are focused on the reduction of operating temperatures due to the huge energy expanse. The aim of all the research investigations is to reduce the temperature around 450°C and 600°C. Steady state progress is required for the development of auxiliary power sources to fuel the automobiles and to power the private homes.

3.7. Future directions of fuel cell science and technology

Implementation and future development of the FC technology is dependent on the upward growth of global oil prices, fall in oil recovery, depletion of already existing oil

wells and improvements in infrastructure of hydrogen based energy resources. Emerging environmental concerns and pollution problems arising from conventional coal and gas thermal power plants and the toxic exhausts emitting from automobiles and crude oil refineries are the major drivers in development of energy efficient, low cost and environment friendly energy technologies. The future energy concerns are dependent on the: (a) less emissions of toxic exhausts (b) low prices (c) maximum efficiency (d) appropriate profit for manufacturer and (e) easy availability for end users.

Development of infrastructure for hydrogen based energy resources encompasses the production methods, easy distribution and proper dispensing and safety regulations of fuels such as synthesis gas, naphtha gas, natural gas, ester, alcohol and hydrogen. All these advanced fuels are fed to fuel processors and FCs. Among these fuels, alcohols and hydrogen can be produced from renewable energy resources such as biomass gasification, biomass fermentation, solar power and wind energy. Both alcohol and hydrogen can also be produced from non-renewable fossil fuels. In case of renewable energy resources, toxic emissions of greenhouse gases are almost negligible in comparison with the non-renewable energy resources.

In all the advanced renewable energy processes, zero emissions of toxic exhaust gases and minimum air pollution can be ensured except for the biomass gasification. In case of non-renewable energy resources, air pollution will be produced in a centralized area and surrounding locations will be free of pollution. In some cases, internal combustion engines of automobiles release huge amount of pollutants in the city areas due to heavy traffic. Among all the advanced energy technologies, hydrogen based motor vehicles and hybrid electric vehicles are known to produce the minimum toxicants in environment. The fueling of motor vehicles with hydrogen based energy resources derived from natural gas produces more carbon dioxide and significantly increases the cost of entire process. Till date, SOFC based stationary power plants and PEMFC based automobiles are not very cost efficient due to the inadequate infrastructure but in near future, scientists do hope to achieve the maximum efficiency with minimum possible prices. In future, these emerging technologies will be more profitable and cause less damage to existing biota and human life [95].

Table 1: Different Types of FCs

Type of FCs	Operating Temperature (°C)	Power (kW)	Efficiency (%)	Applications
PEM	60-110	0.01-250	40-55	Portable, mobile and low power generation
AFC	70-130	0.1-50	50-70	Mobile, space and military
PAFC	175-210	50-1000	40-45	Medium to large scale power generation
MCFC	550-650	200-100,0000	50-60	Large scale power generation
SOFC	500-1000	0.5-2000	40-72	Vehicle auxiliary power unit

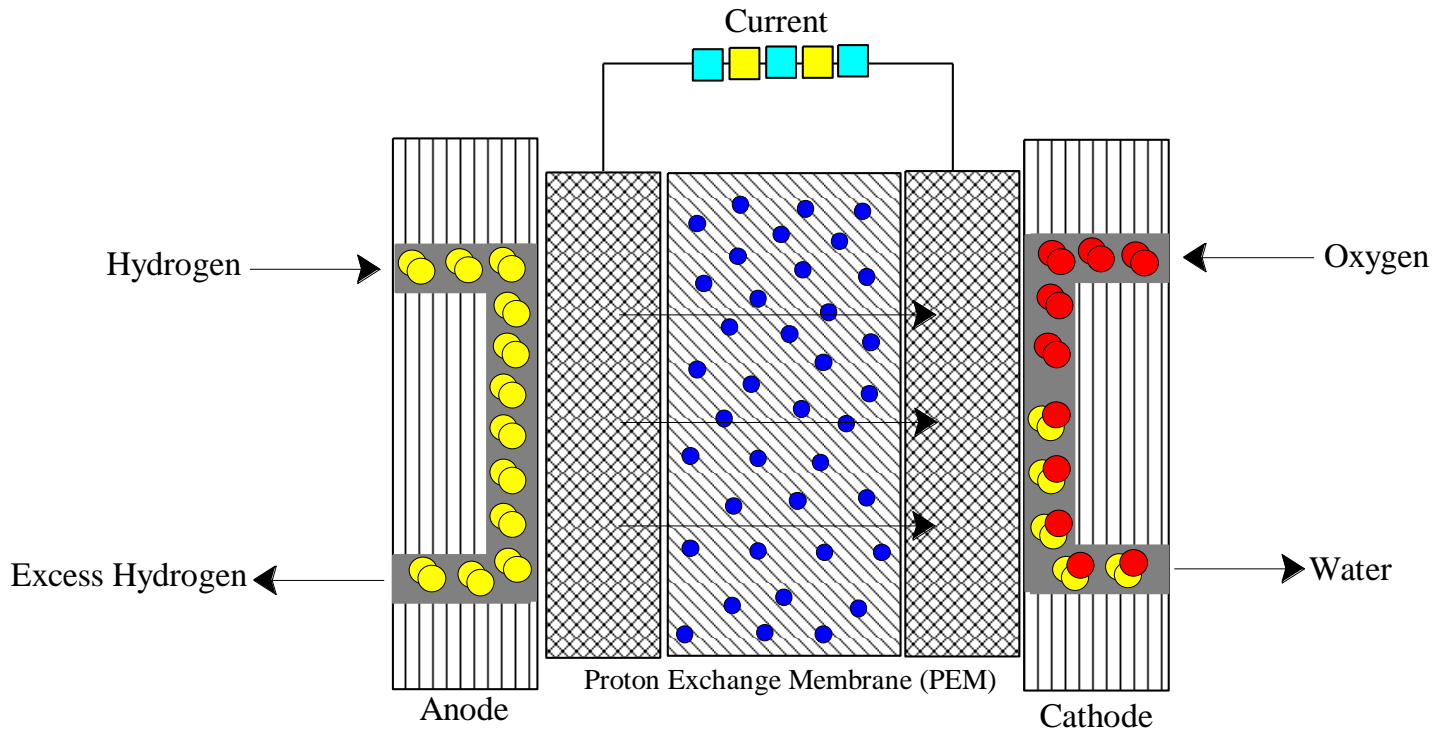


Figure 1: Schematic representation of PEMFC

Table 2: Comparison of Different Types of FCs

Components	Materials	Manufacturing Process
MEA membrane	Polymer matrix with attached sulfonic acid groups	Complex manufacturing process
Electrode substrate	Carbon paper PTFE	Attached to membrane through hot pressing
Catalyst	Pt (0.4–4 mg=cm ²)	Deposited between the electrode membrane and the electrode substrate
Other stack components Flow field plated (including cooling plates)	Graphite, stainless steel and carbon polymers etc.	Machined out of bulk material, stamped and injection molded
Non repeating components	Off the shelf components	Simple machining

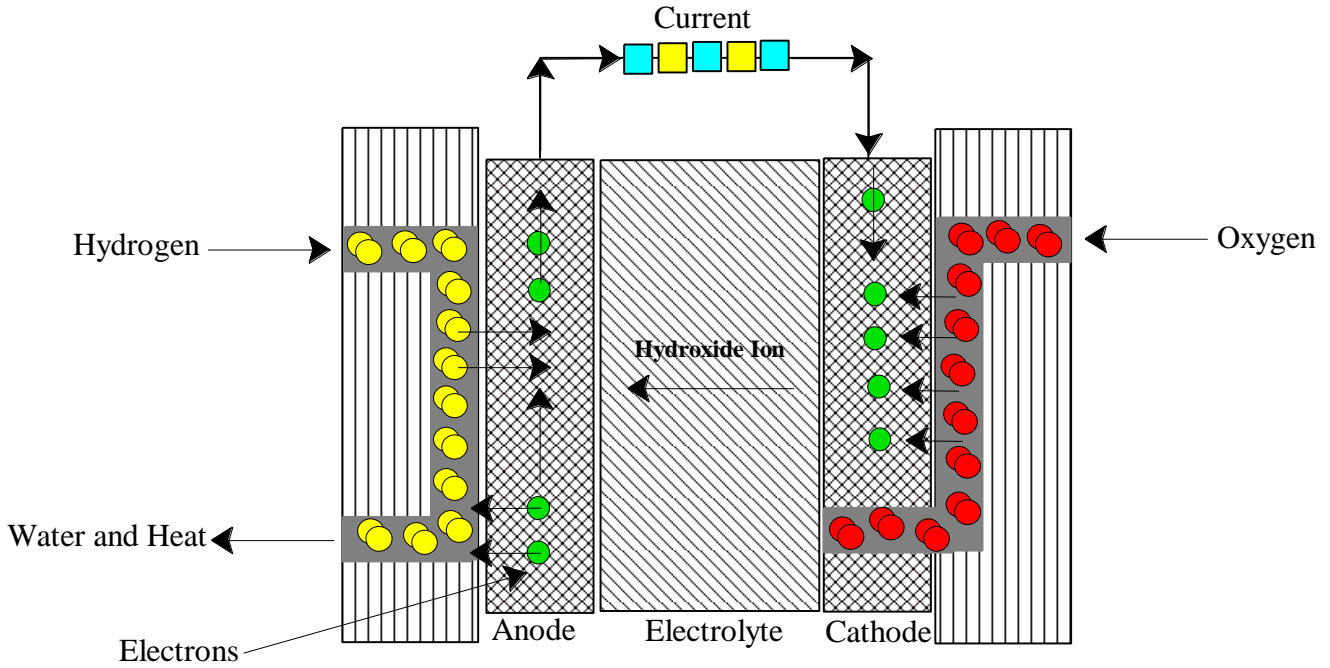


Figure 2: Alkaline Fuel Cell

Table 3: Components of AFC

Component	Material	Manufacturing Process
Anode	PTFE Powder, Graphite Powder, Catalyst (Pt or Pd 0.12–0.5 mg=cm ²) Ni–Al and Ag	Mechanical processes involving grinding, dispersion, filtering, rolling and drying
Cathode	PTFE Powder, Graphite Powder and Catalyst: (Pt or Pd 0.12–0.5 mg=cm ²) Ni–Al, Ag	Mechanical processes involving grinding, dispersion, filtering, rolling and drying
White Layer (For both Anode and Cathode)	PTFE Powder	Pre-forming and rolling
Module Current collectors	Nickle mesh	Pressed to black and white layers
Plastic frames	ABS Plastic	Injection molding and manual assembly with electrodes
Spacers	Unknown	-
Stack assembly	-	Plastic frames and friction-welded to module casing for sealing

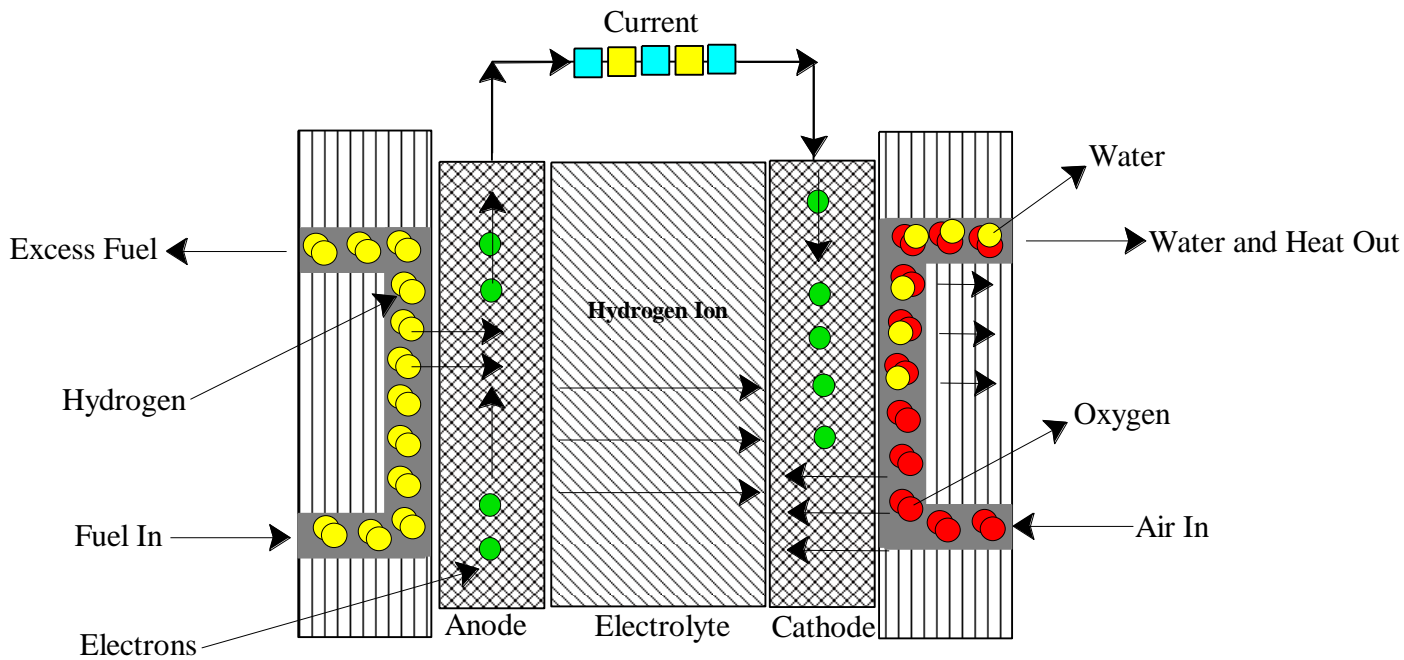


Figure 3: Phosphoric Acid Fuel Cell

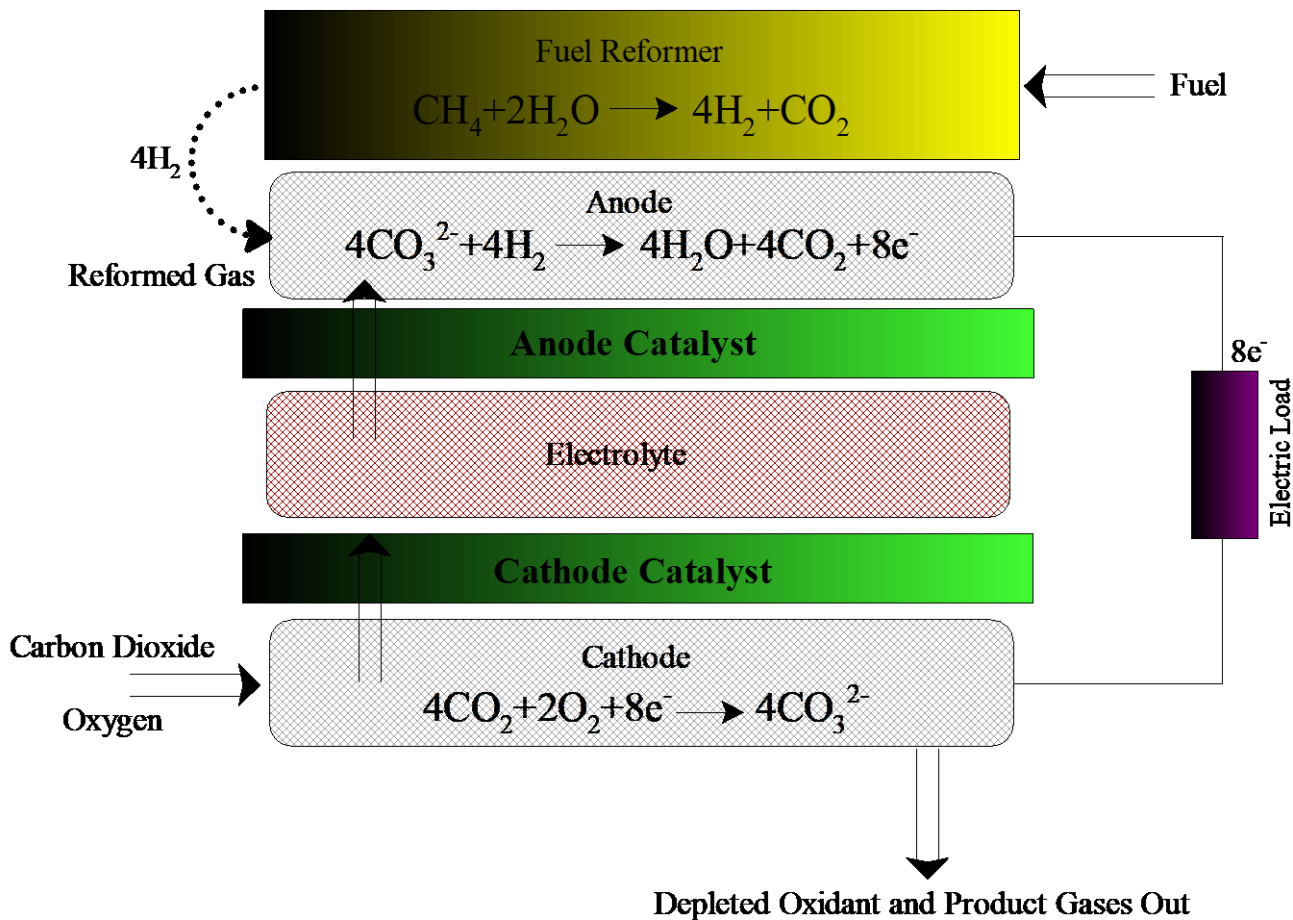


Figure 4: Schematic representation of molten carbonate fuel cell

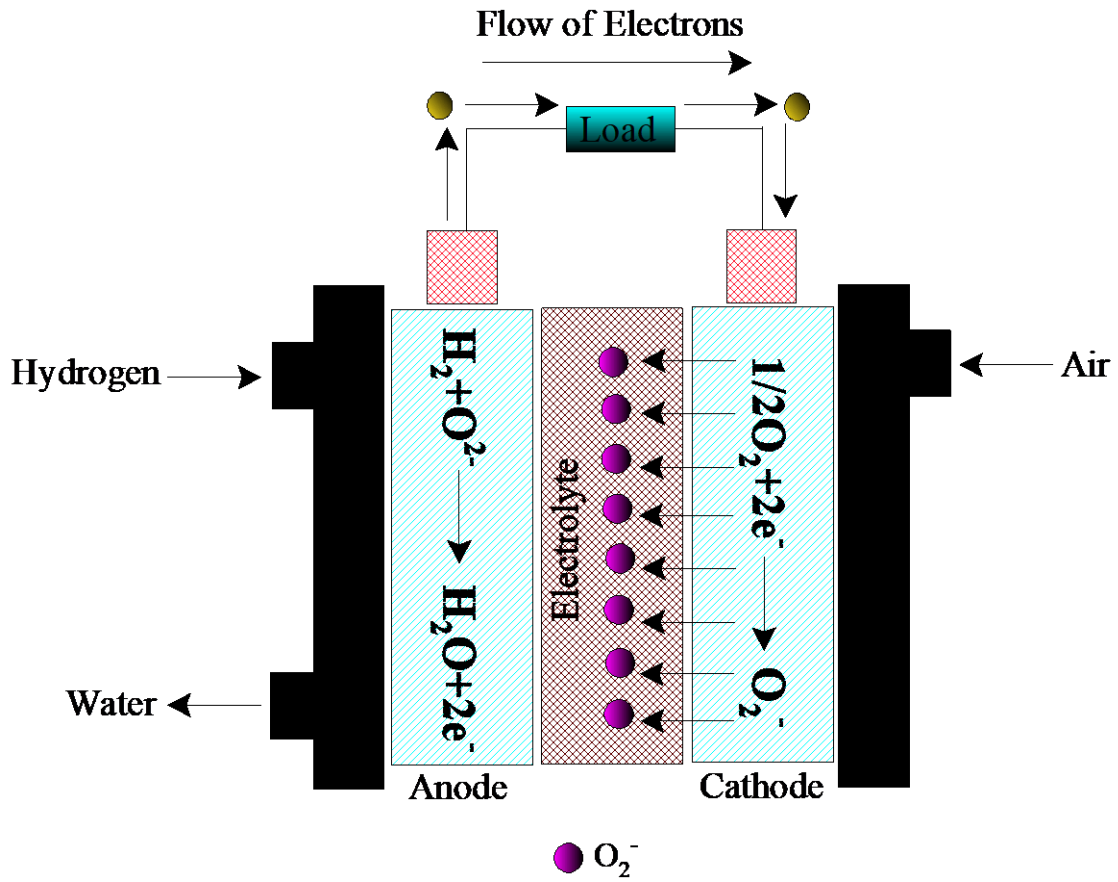


Figure 5: Solid Oxide Fuel Cell

Table 4: Potential performance of SOFC operating at 1000 °C

Design	Potential Difference	Power Density	Efficiency
Tubular	0.65 Joules/Coulombs	0.261 W/cm ²	50%
Planar	0.8 Joules/Coulombs	0.318 W/cm ²	61%

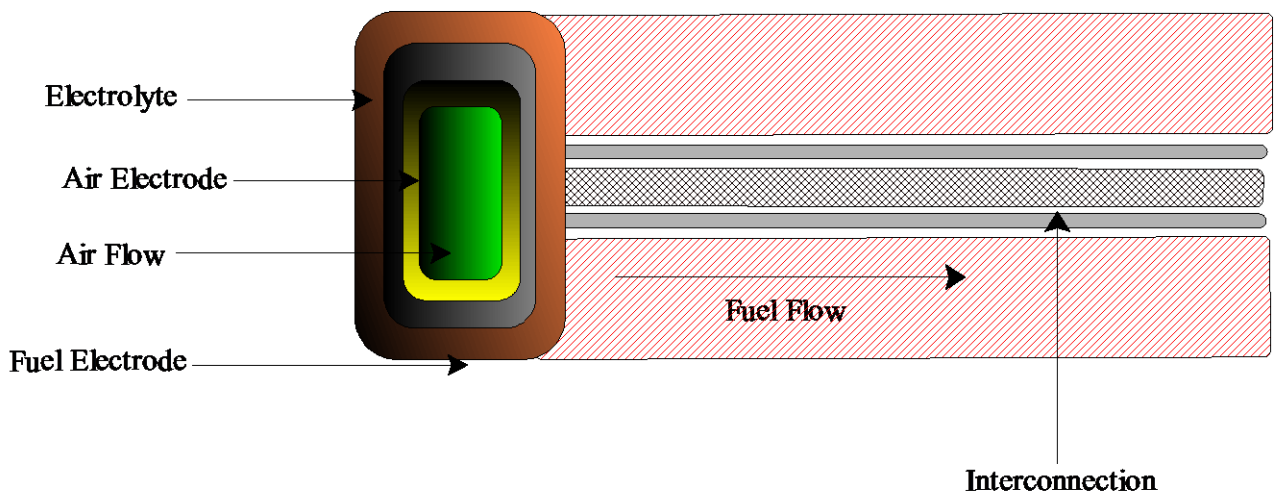


Figure 6: Tubular Solid Oxide Fuel Cell

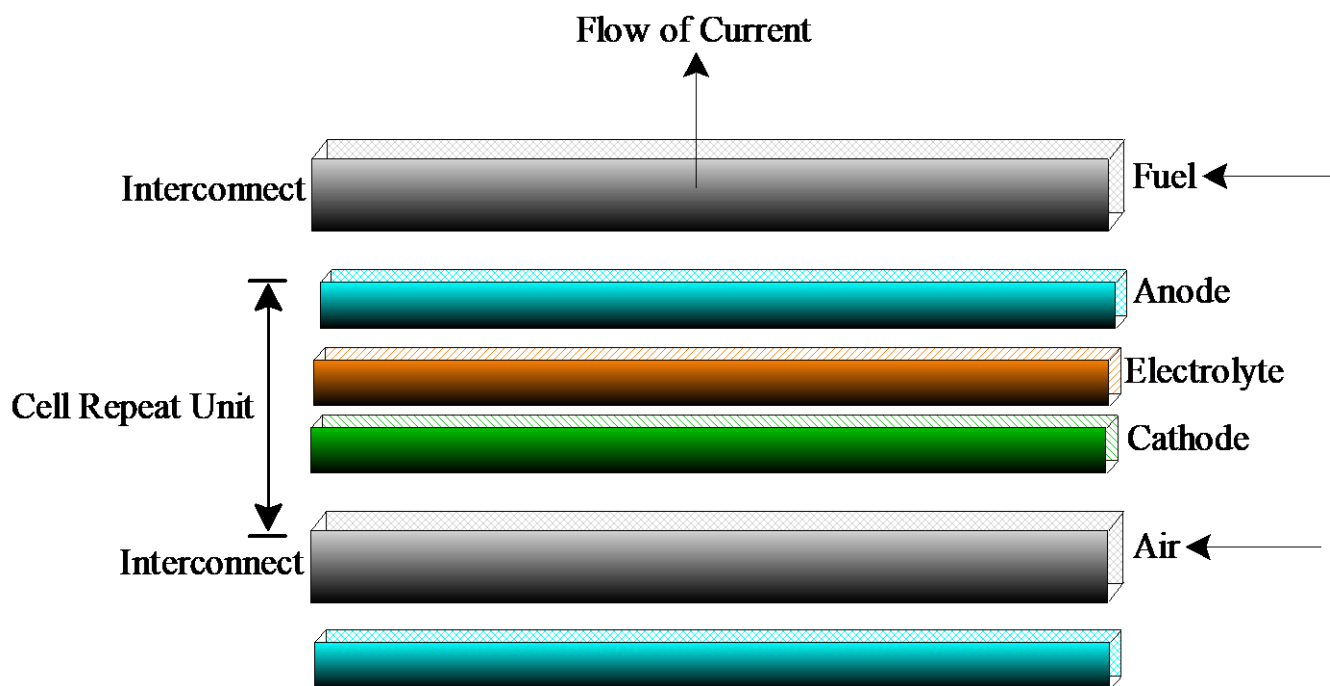


Figure 7: Planar Solid Oxide Fuel Cell Configuration

Table 5: Comparison between some properties of Planar and Tubular SOFC

Properties	Planar	Tabular
Ease of fabrication	Easy	Difficult
Cost of fabrication	High	Low
Ease of sealing	Difficult	Easy
Long-term stability	Fair	Excellent
Thermo-cycling stability	Fair	Good

Conclusions

Now-a-days, entire global world is trying to find out the several alternative methods for efficient production of electrical energy using advance cost-effective approaches. Production of electricity is the key factor in increasing the nation’s economy and to play a major role in developing a positive relationship amongst nature and society. Since past few decades, conventional fossil fuels have been playing a leading role in providing huge amount of energy along with release of toxic pollutants and greenhouse gases specially carbon monoxide and carbon dioxide. In previous decades, FC technology gained much attention due to the fact that this emerging technology can connect the two basic future energy carriers such as "hydrogen" and "electricity". This is the most efficient technology for the conversion of chemical energy of hydrogen into electrical energy using highly cost-effective approaches.

Moreover, it is now generally believed that we are going to witness the beginning of exciting time for FC technology and hydrogen based energy resources; primarily driven by three basic forces such as (a) commercialization of

fuel cell technology and implementation of FCs in the electric vehicles by the world’s leading automakers (b) the increased interest of world’s telecom owners in FC backup power and (c) recognition of hydrogen as a potential and attractive energy resource for long term storage and utilization. The day by day increasing number of global companies investing in FC technology is indicating the success and recognition of this technology on a commercial scale. With the slight improvements in supply chain, this technology will emerged as a miracle in fulfilling the passenger’s vehicular demands. In near future, this technology is going to become a well-aligned method of global success.

References

[1] W.-W. Li, G.-P. Sheng, X.-W. Liu, H.-Q. Yu. (2011). Recent advances in the separators for microbial fuel cells. *Bioresource technology*. 102(1): 244-252.

[2] P. Arora, Z. Zhang. (2004). Battery separators. *Chemical reviews*. 104(10): 4419-4462.

- [3] B. Zhu, L. Fan, P. Lund. (2013). Breakthrough fuel cell technology using ceria-based multi-functional nanocomposites. *Applied energy*. 106: 163-175.
- [4] H. Vaghari, H. Jafarizadeh-Malmiri, A. Berenjian, N. Anarjan. (2013). Recent advances in application of chitosan in fuel cells. *Sustainable Chemical Processes*. 1(1): 16.
- [5] F. Jaouen, E. Proietti, M. Lefèvre, R. Chenitz, J.-P. Dodelet, G. Wu, H.T. Chung, C.M. Johnston, P. Zelenay. (2011). Recent advances in non-precious metal catalysis for oxygen-reduction reaction in polymer electrolyte fuel cells. *Energy & Environmental Science*. 4(1): 114-130.
- [6] S. Bose, T. Kuila, T.X.H. Nguyen, N.H. Kim, K.-t. Lau, J.H. Lee. (2011). Polymer membranes for high temperature proton exchange membrane fuel cell: recent advances and challenges. *Progress in Polymer Science*. 36(6): 813-843.
- [7] V. Das, S. Padmanaban, K. Venkitesamy, R. Selvamuthukumar, F. Blaabjerg, P. Siano. (2017). Recent advances and challenges of fuel cell based power system architectures and control—A review. *Renewable and Sustainable Energy Reviews*. 73: 10-18.
- [8] P. Chaurasia, Y. Ando, T. Tanaka. (2003). Regenerative fuel cell with chemical reactions. *Energy conversion and Management*. 44(4): 611-628.
- [9] I. Sartori, A.G. Hestnes. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and buildings*. 39(3): 249-257.
- [10] I. Dincer. (2000). Renewable energy and sustainable development: a crucial review. *Renewable and Sustainable Energy Reviews*. 4(2): 157-175.
- [11] S.R. Bull. (2001). Renewable energy today and tomorrow. *Proceedings of the IEEE*. 89(8): 1216-1226.
- [12] D. Elliott. (2000). Renewable energy and sustainable futures. *Futures*. 32(3-4): 261-274.
- [13] W.C. Turkenburg, A. Faaij Renewable energy technologies; UNDP/UNDESA/WEC: Energy and the Challenge of Sustainability. World Energy: 2000.
- [14] F. Alcaide, P.-L. Cabot, E. Brillas. (2006). Fuel cells for chemicals and energy cogeneration. *Journal of Power Sources*. 153(1): 47-60.
- [15] O. Ellabban, H. Abu-Rub, F. Blaabjerg. (2014). Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews*. 39: 748-764.
- [16] G.J. Acres. (2001). Recent advances in fuel cell technology and its applications. *Journal of Power Sources*. 100(1-2): 60-66.
- [17] A. Arshad, H.M. Ali, A. Habib, M.A. Bashir, M. Jabbal. (2018). Energy and Exergy analysis of Fuel Cells: A Review. *Thermal Science and Engineering Progress*.
- [18] N.P. Brandon, S. Skinner, B.C. Steele. (2003). Recent advances in materials for fuel cells. *Annual Review of Materials Research*. 33(1): 183-213.
- [19] S. Wang, S.P. Jiang. (2017). Prospects of fuel cell technologies. *National Science Review*. 4(2): 163-166.
- [20] P. Chaurasia. (2000). Solar energy utilization technology through chemical reactions—A report. Indian Council of Agricultural Research, New Delhi. 3-20.
- [21] C. Berger. (1968). Handbook of fuel cell technology.
- [22] Y.-M. Lin, M.-H. Rei. (2000). Process development for generating high purity hydrogen by using supported palladium membrane reactor as steam reformer. *International Journal of Hydrogen Energy*. 25(3): 211-219.
- [23] V.S. Bagotsky. (2012). Fuel cells: problems and solutions. John Wiley & Sons: pp.
- [24] V.H.Y.V.K. Ebisu, V.S. Suzuki, V.N. Sawatari. (2005). Development of prototype micro fuel cells for mobile electronics. *Fujitsu Sci. Tech. J.* 41(2): 191-200.
- [25] S. Longo, M. Cellura, F. Guarino, M. Ferraro, V. Antonucci, G. Squadrito, Life cycle assessment of solid oxide fuel cells and polymer electrolyte membrane fuel cells: A review. In *Hydrogen Economy*, Elsevier: 2017; pp 139-169.
- [26] K.V. Kordesch, G.R. Simader. (1995). Environmental impact of fuel cell technology. *Chemical reviews*. 95(1): 191-207.
- [27] K.-D. Kreuer. (2012). Fuel cells: selected entries from the encyclopedia of sustainability science and technology. Springer Science & Business Media: pp.
- [28] S. Srinivasan, R. Mosdale, P. Stevens, C. Yang. (1999). Fuel cells: reaching the era of clean and efficient power generation in the twenty-first century. *Annual Review of Energy and the Environment*. 24(1): 281-328.
- [29] S.J. Peighambaroust, S. Rowshanzamir, M. Amjadi. (2010). Review of the proton exchange membranes for fuel cell applications. *International journal of hydrogen energy*. 35(17): 9349-9384.
- [30] O.T. Holton, J.W. Stevenson. (2013). The role of platinum in proton exchange membrane fuel cells. *Platinum Metals Review*. 57(4): 259-271.
- [31] G. Zhang, S.G. Kandlikar. (2012). A critical review of cooling techniques in proton exchange membrane fuel cell stacks. *International journal of hydrogen energy*. 37(3): 2412-2429.
- [32] S. Zhang, X.-Z. Yuan, J.N.C. Hin, H. Wang, J. Wu, K.A. Friedrich, M. Schulze. (2010). Effects of open-circuit operation on membrane and catalyst layer degradation in proton exchange membrane fuel cells. *Journal of Power Sources*. 195(4): 1142-1148.
- [33] N.G. Moreno, M.C. Molina, D. Gervasio, J.F.P. Robles. (2015). Approaches to polymer electrolyte membrane fuel cells (PEMFCs) and their cost. *Renewable and Sustainable Energy Reviews*. 52: 897-906.

- [34] A. Baroutaji, J. Carton, M. Sajjia, A. Olabi. (2016). Materials in PEM fuel cells. Reference module in materials science and materials engineering. 1-11.
- [35] L.J. Blomen, M.N. Mugerwa. (2013). Fuel cell systems. Springer Science & Business Media: pp.
- [36] J.A. Asensio, E.M. Sánchez, P. Gómez-Romero. (2010). Proton-conducting membranes based on benzimidazole polymers for high-temperature PEM fuel cells. A chemical quest. *Chemical Society Reviews*. 39(8): 3210-3239.
- [37] T. Maiyalagan, S. Pasupathi In Components for PEM fuel cells: An overview, Materials science forum, 2010; Trans Tech Publ: 2010; pp 143-189.
- [38] S. Sharma, B.G. Pollet. (2012). Support materials for PEMFC and DMFC electrocatalysts—a review. *Journal of Power Sources*. 208: 96-119.
- [39] R. Fiala, M. Vaclavu, A. Rednyk, I. Khalakhan, M. Vorokhta, J. Lavkova, V. Potin, I. Matolinova, V. Matolin. (2015). Pt–CeOx thin film catalysts for PEMFC. *Catalysis Today*. 240: 236-241.
- [40] E.I. Santiago, M.S. Batista, E.M. Assaf, E.A. Ticianelli. (2004). Mechanism of CO tolerance on molybdenum-based electrocatalysts for PEMFC. *Journal of the electrochemical society*. 151(7): A944-A949.
- [41] G. Kim, S.-H. Jhi. (2011). Carbon monoxide-tolerant platinum nanoparticle catalysts on defect-engineered graphene. *ACS nano*. 5(2): 805-810.
- [42] Y.-C. Hsieh, Y. Zhang, D. Su, V. Volkov, R. Si, L. Wu, Y. Zhu, W. An, P. Liu, P. He. (2013). Ordered bilayer ruthenium–platinum core-shell nanoparticles as carbon monoxide-tolerant fuel cell catalysts. *Nature communications*. 4(1): 1-9.
- [43] M. Tanni, M. Arifujjaman, M. Iqbal. (2013). Dynamic modeling of a phosphoric acid fuel cell (PAFC) and its power conditioning system. *Journal of Clean Energy Technologies*. 1(3).
- [44] E. Proietti, F. Jaouen, M. Lefèvre, N. Larouche, J. Tian, J. Herranz, J.-P. Dodelet. (2011). Iron-based cathode catalyst with enhanced power density in polymer electrolyte membrane fuel cells. *Nature communications*. 2(1): 1-9.
- [45] J.K. Nørskov, J. Rossmeisl, A. Logadottir, L. Lindqvist, J.R. Kitchin, T. Bligaard, H. Jonsson. (2004). Origin of the overpotential for oxygen reduction at a fuel-cell cathode. *The Journal of Physical Chemistry B*. 108(46): 17886-17892.
- [46] S. Chen, H.A. Gasteiger, K. Hayakawa, T. Tada, Y. Shao-Horn. (2010). Platinum-alloy cathode catalyst degradation in proton exchange membrane fuel cells: nanometer-scale compositional and morphological changes. *Journal of The Electrochemical Society*. 157(1): A82-A97.
- [47] J. Greeley, I. Stephens, A. Bondarenko, T.P. Johansson, H.A. Hansen, T. Jaramillo, J. Rossmeisl, I. Chorkendorff, J.K. Nørskov. (2009). Alloys of platinum and early transition metals as oxygen reduction electrocatalysts. *Nature chemistry*. 1(7): 552.
- [48] D. Banham, F. Feng, T. Fürstnhaupt, K. Pei, S. Ye, V. Birss. (2015). Novel mesoporous carbon supports for PEMFC catalysts. *Catalysts*. 5(3): 1046-1067.
- [49] S.L. Gojković, B.M. Babić, V. Radmilović, N. Krstajić. (2010). Nb-doped TiO₂ as a support of Pt and Pt–Ru anode catalyst for PEMFCs. *Journal of Electroanalytical Chemistry*. 639(1-2): 161-166.
- [50] K. Gong. (2009). F. du, Z. Xia, M. Durstock and LM Dai. *Science*. 323: 760.
- [51] J.-P. Shim, C.-S. Han, H.-J. Sun, G.-S. Park, J.-J. Lee, H.-K. Lee. (2012). Preparation and Characterization for Carbon Composite Gas Diffusion Layer on Polymer Electrolyte Membrane Fuel Cells. *Transactions of the Korean hydrogen and new energy society*. 23(1): 34-42.
- [52] E. Misran, W.R.W. Daud, E. Majlan. (2010). Review on serpentine flow field design for PEM fuel cell system. *Key Engineering Materials Vols*. 447-448.
- [53] G. McLean, T. Niet, S. Prince-Richard, N. Djilali. (2002). An assessment of alkaline fuel cell technology. *International Journal of Hydrogen Energy*. 27(5): 507-526.
- [54] M.L. Perry, T.F. Fuller. (2002). A historical perspective of fuel cell technology in the 20th century. *Journal of the electrochemical society*. 149(7): S59-S67.
- [55] E. Gülzow. (1996). Alkaline fuel cells: a critical view. *Journal of Power Sources*. 61(1-2): 99-104.
- [56] K. Kordesch. (1983). The choice of low-temperature hydrogen fuel cells: acidic—or alkaline? *International Journal of Hydrogen Energy*. 8(9): 709-714.
- [57] K. Kordesch, V. Hacker In *Fuel Cells with Circulating Electrolytes and their Advantages*, Power Sources Conference, 2000; 2000.
- [58] K. Kordesch, G.R. Simader. (1996). Fuel cells and their applications.
- [59] K.V. Kordesch, Power sources for electric vehicles. In *Modern Aspects of Electrochemistry*, Springer: 1975; pp 339-443.
- [60] P. Michael. (2000). An assessment of the prospects for fuel cell powered cars. Harwell Laboratory, Energy Technology Support Unit: pp.
- [61] J. Larminie, A. Dicks, M.S. McDonald. (2003). Fuel cell systems explained. J. Wiley Chichester, UK: pp.
- [62] T. Burchardt, P. Gouérec, E. Sanchez-Cortezon, Z. Karichev, J.H. Miners. (2002). Alkaline fuel cells: contemporary advancement and limitations. *Fuel*. 81(17): 2151-2155.
- [63] K.V. Kordesch. (1978). 25 years of fuel cell development/1951-1976. *Journal of the electrochemical society*. 125: 77C-91C.
- [64] H. Van den Broeck, Research, development, and demonstration of alkaline fuel cell systems. In *Fuel Cell Systems*, Springer: 1993; pp 245-269.
- [65] B. Gou, W. Na, B. Diong. (2009). Fuel cells: modeling, control, and applications. CRC press: pp.
- [66] P. Stonehart, D. Wheeler, Phosphoric acid fuel cells (PAFCs) for utilities: Electrocatalyst crystallite design, carbon support, and matrix

- materials challenges. In *Modern Aspects of Electrochemistry*, Springer: 2005; pp 373-424.
- [67] R. Drmanac, A.B. Sparks, M.J. Callow, A.L. Halpern, N.L. Burns, B.G. Kermani, P. Carnevali, I. Nazarenko, G.B. Nilsen, G. Yeung. (2010). Human genome sequencing using unchained base reads on self-assembling DNA nanoarrays. *Science*. 327(5961): 78-81.
- [68] H. Sotouchi, A. Hagiwara. (2009). Phosphoric acid fuel cells. *Energy Carriers And Conversion Systems With Emphasis On Hydrogen-Volume II*. 8: 333.
- [69] J. Tollefson, R. Monastersky. (2012). The global energy challenge: Awash with carbon. *Nature News*. 491(7426): 654.
- [70] R. Slade, R. Saunders, R. Gross, A. Bauen. (2011). Energy from biomass: the size of the global resource.
- [71] T.M. Gür. (2013). Critical review of carbon conversion in "carbon fuel cells". *Chemical reviews*. 113(8): 6179-6206.
- [72] I. Ganesh. (2014). Conversion of carbon dioxide into methanol—a potential liquid fuel: Fundamental challenges and opportunities (a review). *Renewable and Sustainable Energy Reviews*. 31: 221-257.
- [73] M. Aresta, A. Dibenedetto, A. Angelini, The changing paradigm in CO₂ utilization. *J. CO₂ Util.* 3-4, 65-73. In 2013.
- [74] Y. Delimarskiĭ, V. Shapova, V. Vasilenko, V. Grishchenko. (1975). *Otkrytiya, Izobret. Prom. Obraztzy, Tovarnye Znaki*. 52: 176-177.
- [75] L.-X. Yuan, Z.-H. Wang, W.-X. Zhang, X.-L. Hu, J.-T. Chen, Y.-H. Huang, J.B. Goodenough. (2011). Development and challenges of LiFePO₄ cathode material for lithium-ion batteries. *Energy & Environmental Science*. 4(2): 269-284.
- [76] Y. Ito, T. Nohira. (2000). Non-conventional electrolytes for electrochemical applications. *Electrochimica Acta*. 45(15-16): 2611-2622.
- [77] Y.J. Kim, M.C. Lee. (2017). Comparison of thermal performances of external and internal reforming molten carbonate fuel cells using numerical analyses. *International Journal of Hydrogen Energy*. 42(5): 3510-3520.
- [78] M.D. Lukas, K.Y. Lee, H. Ghezel-Ayagh. (2002). Modeling and cycling control of carbonate fuel cell power plants. *Control Engineering Practice*. 10(2): 197-206.
- [79] S. Frangini, S. Scaccia. (2004). Sensitive determination of oxygen solubility in alkali carbonate melts. *Journal of the electrochemical society*. 151(8): A1251-A1256.
- [80] F. Yoshiba, H. Morita, M. Yoshikawa, Y. Mugikura, Y. Izaki, T. Watanabe, M. Komoda, Y. Masuda, N. Zaima. (2004). Improvement of electricity generating performance and life expectancy of MCFC stack by applying Li/Na carbonate electrolyte: Test results and analysis of 0.44 m²/10 kW-and 1.03 m²/10 kW-class stack. *Journal of Power Sources*. 128(2): 152-164.
- [81] M.M.H. Bhuiya, A. Kumar, K.J. Kim. (2015). Metal hydrides in engineering systems, processes, and devices: a review of non-storage applications. *International Journal of Hydrogen Energy*. 40(5): 2231-2247.
- [82] M. Irshad, K. Siraj, R. Raza, A. Ali, P. Tiwari, B. Zhu, A. Rafique, A. Ali, M. Kaleem Ullah, A. Usman. (2016). A brief description of high temperature solid oxide fuel cell's operation, materials, design, fabrication technologies and performance. *Applied Sciences*. 6(3): 75.
- [83] W. Zhang. Simulation of solid oxide fuel cell-based power generation processes with CO₂ capture. University of Waterloo, 2006.
- [84] O. Devisch. *Participatory Design Theory*.
- [85] A. Hawkes, P. Aguiar, B. Croxford, M. Leach, C. Adjiman, N. Brandon. (2007). Solid oxide fuel cell micro combined heat and power system operating strategy: Options for provision of residential space and water heating. *Journal of Power Sources*. 164(1): 260-271.
- [86] O. Okada, K. Yokoyama. (2001). Development of polymer electrolyte fuel cell cogeneration systems for residential applications. *Fuel Cells*. 1(1): 72-77.
- [87] S. Bhatt, B. Gupta, V. Sethi, M. Pandey. (2012). Polymer exchange membrane (PEM) fuel cell: a review. *International Journal of Current Engineering and Technology*. 2(1): 219-226.
- [88] F. Barbir. (2012). *PEM fuel cells: theory and practice*. Academic Press.
- [89] J.-H. Wee. (2007). Applications of proton exchange membrane fuel cell systems. *Renewable and Sustainable Energy Reviews*. 11(8): 1720-1738.
- [90] M. Ronchetti. (2008). Celle a combustibile: stato di sviluppo o prospettive della tecnologia. *Enea*.
- [91] R.J. Remick, D. Wheeler, P. Singh. (2010). MCFC and PAFC R&D workshop summary report.
- [92] R. Bove, A. Moreno, S. McPhail. (2008). International status of molten carbonate fuel cell (MCFC) technology. *JRC Scientific and Technical Report*.
- [93] C. Sun, U. Stimming. (2007). Recent anode advances in solid oxide fuel cells. *Journal of Power Sources*. 171(2): 247-260.
- [94] A.B. Stambouli, E. Traversa. (2002). Solid oxide fuel cells (SOFCs): a review of an environmentally clean and efficient source of energy. *Renewable and Sustainable Energy Reviews*. 6(5): 433-455.
- [95] J.M. Ogden, R.H. Williams, E.D. Larson. (2004). Societal lifecycle costs of cars with alternative fuels/engines. *Energy policy*. 32(1): 7-27.