Research Article

A Comparative Study between the Seven Types of Fuel Cells

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Abstract
In the new era with advanced technologies, fuel cell has been widely used as source of power both for portable and stationary applications. The application has become more popular nowadays as it is an eco-friendly device and has no noise due to absence of rotating components. Fuel cells are designed with high efficiency compared to conventional energy sources. However, the benefits have come with weaknesses and threats that might deter its prevalent application. This paper is, therefore, aimed at comparing the seven mainly used fuel cells. The SWOT analysis of the fuel cells are also presented separately, and the pros and cons of each cell were summarized.

Keywords: Fuel cell, SWOT analysis, Hydrogen, Chemical energy, Electrical energy

1 Introduction

A fuel cell is an electrochemical device that produces electricity by transforming chemical energy into electrical energy without any combustion cycle [1]. The fuel cell converts hydrogen and oxygen into electrical energy and heat [1]. Therefore, the hydrogen gas could act as the fuel and the oxygen can be utilized as the oxidizer. Materials such as potassium, sodium hydroxide, to mention few, can be used as electrolyte. Several types of non-precious metals can also be utilized as a catalyst for the anode and cathode to accelerate the reactions and produce electricity.

A fuel cell generates direct current electricity that can be used in application such as lighting using light bulb or functioning as an electric engine [2]. There are mainly seven types of fuel cells: Direct Methanol Fuel Cell (DMFC), Polymer Electrolyte Membrane Fuel Cell (PEMFC), Reversible Fuel Cell (RFC), Alkaline Fuel Cell (AFC), Phosphoric Fuel Cell (PFC), Molten Carbonate Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC). These seven types of fuel cells have slight differences in their working principles. This paper presents comparison between the seven types of fuel cells through SWOT analysis as a method. This would help understand the differences among each other to promote a higher renewable energy utilization in the future.

2 Strength

2.1 *Direct Methanol Fuel Cell (DMFC)*

Methanol as a liquid fuel is denser and contains higher energy density compared to hydrogen gas, and it can be stored at ambient conditions. Hydrogen is preferred due to its high gravimetric energy; however, DMFC contains smaller flammability and is safe to use [3].

Sajgure *et al*. concluded that DMFC is considered as environment friendly technology, as it doesn't

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produce any toxic byproducts. However, they are not considered as emission-free since the carbon dioxide which is green-house gas would still be produced during operation [4]. Furthermore, due to its lower density, the design of DMFC is comparatively compact making the size small and light weight. Therefore, they can easily be transported from one place to another, reducing the expenses in the meanwhile. Moreover, it is simple and able to recharge instantaneously with long life designed [5].

2.2 *Polymer Electrolyte Membrane Fuel Cell (PEMFC)*

The Polymer Electrolyte Membrane Fuel Cell (PEMFC) has the highest demand among all the fuel cells since it has a lot of advantages such as high-power density, small footprint, fast start-up and shutdown, and quiet operation. It also operates at relatively low temperature, around 80°C, which allows them to start quickly and results in less wear on system components along with better durability [2], [6].

Besides, it is designed for easier installation due to its simple working principle, and requires low maintenance. PEMFC does not produce any noxious emission, and this is more efficient compared to the heat engine. The performance of PEMFC can provide clean, continuous power and light commercial application [7]. PMEFC was observed providing high efficiency for vehicles with fuel cell powered and low tail pipe emission. When applied to a vehicle, the hydrogen fuel can provide the highest conversion efficiency, and create Ultra Low Emission Vehicle (ULEV) [8].

2.3 *Reversible Fuel Cell (RFC)*

The reversible fuel cells were applied on the Solid Oxide Fuel Cell (SOFC) system which uses the energy generated from solar or wind turbine to generate the hydrogen gas [7]. Consequently, they are compressed and stored within the tank as shown in Figure 1.

The stored hydrogen is used in the SOFC system as a fuel for electricity generation whenever power is required. There is an output of 50 kW in fuel cell mode within a 20 ft container but the output power is predicted to be improved to around 200 kW to 250 kW in the future [9]. This is a comparatively new fuel cell technology being developed by NASA and other such laboratories [2].

Figure 1: Hydrogen storage tank [9].

2.4 *Alkaline Fuel Cell (AFC)*

An alkaline environment can increase the efficiency due to its capability to flow oxygen better as contrasted with acidic electrolytes when oxygen was engaged with the electricity generation process. The alkaline electrolyte is useful to perform better in the room temperature to generate higher current densities with lesser voltage losses. Nevertheless, the initial cost to produce AFC system is cheaper compared to the other cells as the cells and electrodes used are made from low cost materials. Alkaline fuel cells have long lifetime that may reach more than 15,000 h since the squanders and electrodes can be removed easily with minimal corrosion as the electrolyte is less corrosive. A catalyst is needed in the electrolyte to accelerate the concerned reactions to allow the alkaline fuel cell to work in peak efficiency. The cost effectiveness and reliability rely upon the quantity of alternate catalysts present for the AFC [10].

2.5 *Phosphoric Acid Fuel Cell (PAFC)*

In the Asia and United State, Phosphoric Acid Fuel Cell (PAFC) had been proved to be used as robust on the medium capacity stationary application within 100 to

500 kW power generation. Phosphoric acid (H3PO4) fuel cell can function at high temperature (up to 200°C) without a problem as opposed to the PEMFC. This feature reduces the sensitivity to carbon monoxide poisoning and increases the reaction that takes place in the electrode. As the operating temperature of the system can be as high as 200°C, the waste heat can be used for space heating, and many PAFC systems are appropriate for combined heat and power plant facilities.

PAFC can be operated by using air rather than pure oxygen. Although phosphoric acid is a poor conductor the cell would not reduce electrochemically during operation compared to other electrolytes [11]. Furthermore, PAFC usually operates at both atmospheric and high pressures which enables to operate at increased overall efficiency. In a combined power and heat application system the overall efficiency can reach up to 87%. Besides, PAFC can be operated with a lifetime up to 40,000 h in a wide range of atmospheric conditions; with temperatures as low as –32°C and as high as 80°C [11].

2.6 *Molten Carbonate Fuel Cell (MCFC)*

Currently molten carbonate fuel cells are being developed for various power plants in the area of electricity generation, industrial applications and in the military applications using natural gas and coal as a fuel [2].

MCFC uses a ceramic matrix impregnated with carbonate-salt as an electrolyte suspended in a porous, chemically inert ceramic lithium aluminum oxide matrix. Its operating temperature is very high (450–650°C) in which precious metal catalysts are not required at the anode and cathode reducing the material cost for construction.

Their improved efficiency offers another reason for significant cost reductions over phosphoric acid fuel cells (PAFCs) when the system is applied only for electricity generation. Besides, high temperature operation facilitates the internal reforming process, eliminating the need for an external reformer as used in alkaline, phosphoric acid, and polymer electrolyte membrane fuel cells. In addition, MCFCs are not prone to carbon monoxide and carbon dioxide poisoning making them more attractive when gases produced from coal are used as a fuel [2].

2.7 *Solid Oxide Fuel Cell (SOFC)*

Solid Oxide Fuel Cells (SOFC) are best suited for large-scale power plants that could generate electricity to supply for grid system or factories. SOFCs use a prefabricated hard, non-porous ceramic compound as the electrolyte, sandwich between electrodes. The electrolyte can be manufactured in variety of geometries: tubular, plate or planar, corrugated plate, etc. SOFCs operate at relatively high temperatures around 1000°C, and are expected to be around 50–60% efficient at converting fuel to electricity [2].

SOFC systems are known as a high-performance system with low environmental pollution ratio among other fuel cells. Since all the SOFC components are solid, the problem of electrolytes loss and corrosion of electrodes is not significant [12]. As the SOFCs cell operates at high temperature, the presence of impurities is not a big concern.

The emission levels of SOFCs are negligible, and in addition the integration of the system with other thermal systems was found suitable. Precious metals are not required as a catalyst and hence the cost of constructing the cell would be reduced [13]. As these cells are functioning at high temperature, conversion of carbon monoxide and hydrogen is easier and internal reforming of gaseous fuel promotes rapid kinetics to produce high quality heat for energy conversion [14].

3 Weakness

3.1 *Direct Methanol Fuel Cell (DMFC)*

Methanol crossover (MCO) is one of technological challenges where it showed the unreacted methanol located at anode catalyst layer is able to permeate through the membrane to cathode. In DMFC system, the fuel diffuses through Nafion membrane [4]. MCO reduces the overall cell voltage, fuel efficiency and oxygen consuming as the permeated methanol gas created mixed potential with oxidization in cathode. With the effect of MCO, the cathode catalyst and membrane could be degraded [15]. As a result, severe flooding would take place in the cathode with the oxidation of permeated methanol. The water generated inside the cathode due to electrochemical reaction and oxidation of permeated methanol causes flooding. Water crossover (WCO - large fraction of unused water from anode permeates to cathode) has significant influence on cathode flooding where it was used to control the flooding [16].

On the other hand, the membrane would swell from absorbing water during fuel cell operation due to the delamination of electrode from the membrane. This phenomenon is called interfacial degradation which could decrease the conductivity of electron and proton and increase the over-potentials afterward. The degradation in catalyst layers called ruthenium crossover can diffuse through the membrane to cathode, reducing anode kinetics of oxygen reduction reaction and carbon monoxide (CO) resistance capacity [17].

3.2 *Polymer Electrolyte Membrane Fuel Cell (PEMFC)*

Water management is the most hindering issue on the performance of PEMFC. The membrane requires enough hydration level for conducting the proton efficiently. In contrast, an excessive liquid water floods the pores of the catalyst layer (CL) and the gas diffusion layer (GDL) which result in resistance for mass transportation. Hence, the water management requires a subtle equilibrium condition between membrane drying and liquid water flooding to guarantee a high performance level and prevent fuel cell degradation [18].

Heat management is also considered as one of the significant influences on the performance. Due to the restriction of electrochemical kinetics of oxygen reduction, the additional losses could be enhanced in the fuel cell stack. Moreover, the ohmic resistance and mass transport losses are able to deviate the operating voltage from the theoretical cell voltage. All these losses are acting as heat release to the surrounding [19].

3.3 *Reversible Fuel Cell (RFC)*

Hydrogen storage is a significant issue because of the gas state characteristic. The gas is required to be stored in a chamber tank to prevent any reaction with the surrounding. Abdalla *et al*. discussed that the material used for hydrogen storage must not have chemical reaction with hydrogen and other materials. They mentioned that the reversibility of the uptake and release of the gas is the key to store hydrogen since it would only be released when heating temperature is above 800°C, or else the carbon will be oxidized (Table 1).

Table 1: Progress and problems in hydrogen storage method

Type of Storage	Progress	Problems
Compression	Compress and store hydrogen in a cylinder of pressure up to 20 MPa.	Achieving a high tensile strength, low density, non-reactive with hydrogen & non-diffusive storage cylinder
Liquefaction	A process enables to store hydrogen in liquid phase at –253°C.	The process is intensive energy and time consuming.
Physisorption	Reversible hydrogen release upon physical absorption.	Dependent on absorbent geometry and absorption temperature.
Hydrides	Make use of metal for absorption of hydrogen to form hydrides.	Dependent on the type of metal properties.

Generally, the main challenges of hydrogen storage are weight, volume, cost, codes, standards for different applications. For instance, for on board application of hydrogen in vehicles, the weight, volume and cost are very high that make the hydrogen fueled vehicles incompetent to the petrol or diesel fueled vehicles. The use of compressed hydrogen in a pressurized cylinder has also problem as the density is low and at high pressure the cost is very high. Application of liquid hydrogen is acceptable if only the cost unit is comparable with gasoline. However, the inevitable boiling off liquid remains as a concern in the application [20].

3.4 *Alkaline Fuel Cell (AFC)*

AFC system is vulnerable to be affected by carbon dioxide. Little amount of CO_2 in the air can affect the cell operation adversely. Hence, purifying of hydrogen and oxygen that are used in the fuel cell makes AFC costlier. CO_2 can combine with KOH to form potassium carbonate which increases the resistance. Susceptibility to poisoning of AFC by CO_2 also affects the cell's lifetime (the amount of time before it must be replaced) further adding to cost. The chemical reactions that are responsible for poisoning of the AFC are the following [21].

$CO_2 + 2OH^- \rightarrow CO^2_3 + H_2O$ and/or
$CO_2 + 2KOH \rightarrow K_2CO_3 + H_2O$

This affects the hydroxyl ions available and therefore reduces the conductivity of ions of the electrolyte solution. In addition, it may affect the porosity of the electrode and block the movements or may stay as a liquid and reduce the conductivity of the ionic conductivity of the electrolyte [21].

3.5 *Phosphoric Acid Fuel Cell (PAFC)*

Similar with DMFC, the water is produced at the cell cathode and this must be removed to prevent the water from dissolving in the electrolyte and affecting cell performance. Removal is achieved by passing excess air through the cathode to carry the water away as water vapor [22]. As mentioned in previous section, since it is operated by using acid at high pressure with a favorable efficiency, the acid reaction is high, and this leads higher expenses due to the high cell component corrosion rate.

Moreover, flooding would happen in PAFC, where the water could affect the efficiency on dissolving the electrolyte. While starting PAFC requires preheating, on the other hand after starting, and when it reaches to the required temperature, regulating the temperature by removing the excess heat is required. [11].

3.6 *Molten Carbonate Fuel Cell (MCFC)*

For the long-term operation of MCFC, the efficiency would be affected by handling problem of the liquid due to the electrolyte configuration. The other challenge is depletion of liquid electrolyte caused by leakage, metal reaction and evaporation. Apart from that, the tolerance to sulfur in anode is very low which is no more than 1–5 ppm and this situation (sulfur poisoning) leads to performance loss of the fuel cell. The performance loss of the fuel cell will become obvious gradually when there is 1–5 ppm of the sulfur in the anode. MCFC is suitable for continuous power supply that requires large-scale and needs a big hydrogen tank to produce electricity, while the application is in less economic category among other fuel cells [23].

3.7 *Solid Oxide Fuel Cell (SOFC)*

One of the weaknesses, as similar with PAFC, is that SOFC would be degraded due to carbon deposition and sulphur poisoning. SOFC also requires an elevated temperature for effective operation. However, the high-temperature operation has some disadvantages. It results in a slow startup and requires significant thermal shielding so as to retain heat and protect personnel, which may be acceptable for utility applications but not for transportation and small portable applications. The high operating temperatures also place stringent durability requirements on materials, and the development of low-cost materials with high durability is a key technical challenge facing this technology. The current research emphasis is on exploring the potential for developing lower-temperature SOFCs operating at or below 800°C that have fewer durability problems and cost less [2], [12], [24].

4 Opportunity

4.1 *Direct Methanol Fuel Cell (DMFC)*

In a contrast to the micro fuel cell, DMFC provides better services in combination with the thin firm batteries, which creates a hybrid power system with rechargeable features. By applying DMFC in the mobile phones, the period of usage can be improved to readily available electrical power to at least 5 to 10 times greater energy densities than rechargeable batteries, and less costly compared to the alternative battery technologies [25].

DMFC can also be used in the stationary electric generation application more efficiently than producing electricity directly from fuel using internal combustion engine. DMFC can be applied to residential, commercial and industrial sectors for electricity as well as for heat production. As DMFC do not need any reforming of methanol, there are no losses in the reformer [26].

4.2 *Polymer Electrolyte Membrane Fuel Cell (PEMFC)*

PEMFC is very functional and provides a lot of convenience to the society. The major application includes mainly transportation sector as it is environment

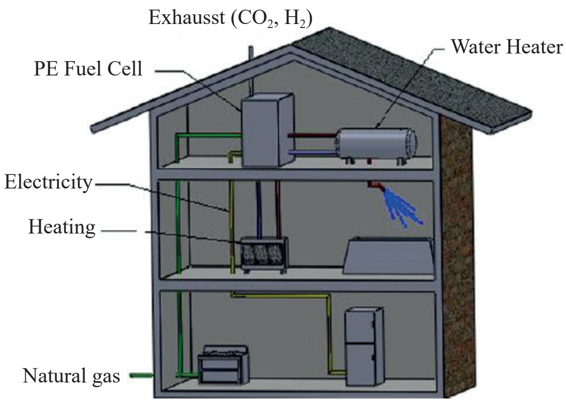

Figure 2: Schematic diagram of co-generation system.

friendly due to emission of the greenhouse gases (GHG) is not a problem. Vehicle companies are mostly applying this technology on their product due to the high-power density, and the heat and power can be utilized with higher efficiency. Unlike internal combustion engine, PEMFC is not operating in Carnot Cycle. Hence, the efficiency is higher since the loss in converting mechanical energy to electrical energy is avoided [6].

Furthermore, for the stationary power generation application, PEMFC can be wisely utilized and the waste heat can be efficiently used. It is also favorable to overcome the power losses during transmission in the case of long-distance energy transportation. Figure 2 shows the smaller scale stationary power generation, which can produce higher electric power efficiency with minimal noises [6].

4.3 *Reversible Fuel Cell (RFC)*

Harun *et al*. proposed a poly-generation plant combining reversible solid oxide fuel cell (SOFC) and biomass gasification. Their concept is to store electricity through the production of bio–SNG from syngas generated from biomass gasification and electrolytic hydrogen when the electricity demand/price is low and resume electric production when electricity demand/price is high. Their results showed that both the electricity and bio-SNG production efficiency are high at 46 and 69% each and with the condition of coproduction at district heat, the total efficiency was able to rise to 85 and 90%, respectively. This system allows operation at a constant manner throughout the year with their advancement using reversible fuel cell in conjunction with the consideration of the demand/price of electricity [27].

4.4 *Alkaline Fuel Cell (AFC)*

The operation of AFC is limited in an environment without carbon dioxide in order not to affect the electrolyte. Carbonates are formed when carbon dioxide is in contact with alkaline as the carbonates are a kind of insoluble salt which can stop the permeable electrodes and obstruct the hydrogen and oxygen flow causing power failure [28]. Therefore, the input gases need to undergo purification in order to remove the carbon dioxide. Nowadays, the technology of carbon dioxide removal is completely developed and available. The cell life may ultimately be longer than acid fuel cells because of greater compatibility of alkaline electrolytes with practical cell materials. With the long cell life advantage, NASA and UTC had achieved over 15,000 h on space shuttle and Apollo-series mission in mid 1960s [29].

4.5 *Phosphoric Acid Fuel Cell (PAFC)*

PAFC was observed robust on the medium capacity stationary application within 100 to 500 kW. Their silent operation and low emissions make PAFC more preferable in sensitive urban areas where other types of generator might be less suitable [10]. Particularly for terrestrial stationary power application PAFC retains important market share. Small commercial organization such as hospitals and universities are the main targets since both of heat and power can be utilized wisely with economical unit size of 100 to 400 kW [28].

As mentioned previously, the additional heat that is produced when the cell reaches to operating point should be removed during operation [30]. In the commercial field, the waste heat can be captured and sent for heating and used to drive the reformer that produced hydrogen for the fuel cell [31].

4.6 *Molten Carbonate Fuel Cell (MCFC)*

MCFC is very ideal for powering large-scale and stationary applications with more than 45% energy conversion. The entire process could be very stable with the longer warm-up period to reach the operating temperature and also it has slow response to changing power demands [23]. With the ideal temperature of 650°C from system design perspective, most of the catalysts are suitable to be used under this temperature and internal reforming could be carried out under this condition. MCFC has sufficient capacity to generate the high-grade waste heat since its scale is very huge. It was observed that MCFC has the steepest polarization curve compared to other fuel cell, resulting in low current density operation.

4.7 *Solid Oxide Fuel Cell (SOFC)*

The systems of SOFC provide a cleaner environment compared to other systems. Apart from that, it provides a completely new businesses and employment areas with the realization of economic independence. With the latest breakthroughs in the automotive industry, electric cars are being considered as the ways for the future. Nevertheless, they found that electric car is taking time to charge, and this hinders their growth. Therefore, the invention of SOFC would be one means to solve the prolonged charging time [12].

5 Threat

5.1 *Direct Methanol Fuel Cell (DMFC)*

When bad methanol is mixed with oxygen during cross-over section, the methanol concentration would be reduced, and this leads to slower reaction rate. The oxygen flow rate would affect the fuel cell performance, where sufficient amount of oxygen with extensive flow rate is able to dry the membrane efficiency, and this could reduce the overall conductivity simultaneously. The lower the oxygen flow rate, the lower the cell voltage and power density [32].

5.2 *Polymer Electrolyte Membrane Fuel Cell (PEMFC)*

The ambient temperature is playing a significant role on the performance of PEMFC. The flow velocity of air reduces with temperature gradient. As a result, the mass transfer increases and the oxygen transfer would decrease which affects the water removal rate in the cathode that would cause flooding [33].

Besides, if the thermal conductivity is too low, the fuel cell temperature would be high that adversely affects in use of the cell portably. Lesser water content is able to result in higher membrane resistance to proton, and this reduces the PEMFC performance [34].

5.3 *Reversible Fuel Cell (RFC)*

For reversible fuel cell, the operation is safe with almost zero threat to the surrounding. The only threat exists is on the hydrogen storage itself, especially the storage in pressurized cylinder tank. Hydrogen is a non-toxic compound, but it is flammable, especially in a highly pressurized condition in a cylindrical tank. From the International Consortium for Fire Safety, Health and Environment (ICFSHE), hydrogen would have high burn and explosive velocity whenever the concentration is high [27].

With this regard using RFC in fuel cell vehicle car system could create trouble with the ignition source especially during starting up of the engine. Fuel cell vehicles have installed ultra-capacitor for storing electrical energy under high voltage for rapid release upon usage whereby this ultra-capacitor retains the risk for critical undesired electrical discharges [20].

5.4 *Alkaline Fuel Cell (AFC)*

Similar with the reversible fuel cell (RFC), the hydrogen is a safe element to be used in various experiments or even equipment as it is not toxic and not carcinogenic. However, a proper mixture ratio of hydrogen with oxygen has a likelihood to be ignited by a spark which consider as high energy source. Furthermore, static electricity is a good possibility for sparks as it ignited a leakage of hydrogen which can cause the hydrogen storage tanks to burst into flame. Cell could get irreparable damage when trace amounts of carbon dioxide react with the electrolyte [34].

5.5 *Phosphoric Acid Fuel Cell (PAFC)*

The pure hydrogen is required to be supplied at anode of PAFC, since most of them rely on providing their fuel by reforming natural gas. The overall efficiency could be reduced during this energy intensive process since some parts of them must be used to drive the reformation reaction [35].

On the other hand, the significant amount of carbon dioxide would be produced and released to the surrounding when the gas burns in a gas or steam turbine [10]. Hence, the extra procedure has to be taken to capture CO_2 after reforming hydrogen. In order to protect the lifetime of platinum catalyst, the sulfur compounds have to be removed to avoid sulfur emission poisoning on platinum catalyst [35].

5.6 *Molten Carbonate Fuel Cell (MCFC)*

Production of the carbon dioxide is always the threat to the MCFC. Although certain amount of the carbon dioxide is recycled but there is still small amount of it being flushed out together with the water and this leads to water pollution. Users will rather choose other fuel cell while considering the impact to the environment.

5.7 *Solid Oxide Fuel Cell (SOFC)*

There are only few threats in SOFC. One of the threats is that the systems are risky to be used and it is costly. It also requires exotic materials such as ceramic which is costly [13]. The complexity for manufacturing and its exaggerated cost are considered as a challenge in using the cell.

6 Discussion and Conclusions

In this paper seven types of fuel cells were considered, and their strength, weakness, opportunities and threats (SWOT) were investigated. Based on the study it was found that the choice of the cell mainly depends on the intended application. List of fuel cells appropriate for various applications, i.e., for portable use, stationary use and transportation use, are shown in Table 2.

Table 2: Application of fuel cell

Application	Portable	Stationary	Transportation
Typical power range	1 W–20 kW	0.5 W–400 kW	1 kW–100 kW
Typical technology	PEMFC, DMFC	PEMFC, SOFC, MCFC, PAFC, AFC	PEMFC, DMFC
Examples	• Non-motive auxiliary power units (campervans, boats, lighting) • Military applications • Portable products	• Large stationary combined heat and power (CHP) • Small stationary • Uninterruptible power supplies (UPS)	• Materials handling vehicles • Fuel cell electric vehicles (FCEV)

On top of that, from the previous section the pros and cons of different fuel cells can be summarized as:

- PAFCs are relatively matured as they have been used to power buses as well as stationary applications. Nevertheless, the cost is still high, and efficiency is relatively low.
- MCFCs are high efficiency, resistant to contamination and can run on hydrocarbon fuels. They run at high temperatures and are being developed for utility applications. Because of high temperatures, durability is often an issue.
- SOFCs use ceramics in their electrodes. For their operation catalyst is not required as they can work at very high temperatures. Although the efficiency of SOFCs is good, the startup time is slow, and hence they are not suitable for vehicle applications.
- PEMFCs are commonly used in vehicle applications with their fast response time characteristic. However, the cost is the main concern since platinum is used as catalyst and it is not cheap.
- AFCs are applicable for potential production of current and power density. However, alkaline electrolyte could absorb carbon dioxide and forms insoluble carbonate.
- RFCs are producing the electricity using hydrogen which is generated from solar or wind turbine.
- DMFCs use liquid methanol as a fuel. It is being developed mainly for small portable applications such as laptop and cell phone batteries.

Although the preference of a specific fuel cell depends on the type of application, Molten Carbonate Fuel Cell (MCFC) appears to be the best option when there is a high energy demand. In addition, MCFC is a matured technology compared to other fuel cells. It is also suitable for manufacturing industry which involves many types of machineries in the production line that need to operate all day long. Indeed, the release of carbon dioxide to the surrounding cannot be neglected and needs further improvement to minimize its setback. Fuel cells that can be operated at high temperatures are well-suited for combined heat and power (CHP) applications as the overall efficiency is better than to that of fuel cells used for power applications only.

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