LIMITATIONS OF COMMERCIALIZING FUEL CELL TECHNOLOGIES

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Limitations of Commercializing Fuel Cell Technologies

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Abstract

Fuel cell is the technology that, nowadays, is deemed having a great potential to be used in supplying energy. Basically, fuel cells can be categorized particularly by the kind of employed electrolyte. Several fuel cells types which are currently identified having huge potential to be utilized, namely, Solid Oxide Fuel Cells (SOFC), Molten Carbonate Fuel Cells (MCFC), Alkaline Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), Polymer Electron Membrane Fuel Cell (PEMFC), Direct Methanol Fuel Cells (DMFC) and Regenerative Fuel Cells (RFC). In general, each of these fuel cells types has their own characteristics and specifications which assign the capability and suitability of them to be utilized for any particular applications. Stationary power generations and transport applications are the two most significant applications currently aimed for the fuel cell market. It is generally accepted that there are lots of advantages if fuel cells can be excessively commercialized primarily in context of environmental concerns and energy security. Nevertheless, this is a demanding task to be accomplished, as there is some gap in fuel cells technology itself which needs a major enhancement. It can be concluded, from the previous study, cost, durability and performance are identified as the main limitations to be firstly overcome in enabling fuel cells technology become viable for the market.

Keywords: Fuel Cells, Polymer Electron Membrance Fuel Cell (PEMFC), Phosphoric Acid Fuel Cells (PAFC); Alkaline Fuel Cells (AFC); Molten Carbonate Fuel Cells (MCFC); Solid Oxide Fuel Cells (SOFC); Direct Membrance Fuel Cells (DMFC); Regenerative Fuel Cells (RFC)

1. Introduction

There is no doubt that today energy availability represents a key discriminator whereby to measure a society's well-being. Increasing of awareness towards environmental issues in respect to abate CO_2 emissions as well as to ensure the diversity of energy supply for not to be dependence on fossil fuels, therefore, some countries primarily industrialized and developed countries have moved forward in seeking new sources of energy. Previously, hydrogen (H_2) is only an abundant substance in the universe without any use, but for today, the scenario is changed. Realizing the potential of H_2 as a versatile energy carrier that can be utilized to power nearly every end-use of energy need, therefore, lot of efforts have yet been carried out to do evolvement in this particular domain. By meant to fully exploit the sources of H_2, the most recent technology with a huge potential and capability, fuel cells, are used. Fig. 1 illustrates the flow of H_2 being extracted for useful energy and in this context for using in transportation applications.

Fuel cells basically perform as energy conversion devices that can efficiently capture and use the power of hydrogen to generate electricity by electrochemical processes [1]. The operation of fuel cell is approvingly simple, clean and mechanically straight forward. Basically, a fuel cell acts like a battery, but, instead of a battery a fuel cell does not run out or require recharging as long as fuel is supplied. In extend to that, fuel cells harness the chemical energy of H_2 to generate electricity and heat without combustion or pollution. This is actually supporting the objective to reduce greenhouse gas emissions (GHGs). Besides that, energy efficiency can as well be increased by using fuel cells technology as much as two to three times the efficiency of traditional combustion [1].

Basically, a single fuel cell comprises an electrolyte between two electrodes (anode and cathode). Bipolar plates on either side of the cell help distribute gases and serve as current collectors. H_2 fuel is channeled into anode of the fuel cell, while oxygen enters to the fuel cell through cathode. Catalysts then encourage the chemical reaction until hydrogen atom splits into a proton and an electron. The proton passes through the electrolyte, whereas, the electrons create a separate current that can be utilized before they return to the cathode, to be reunited with the hydrogen and oxygen in a molecule of water.

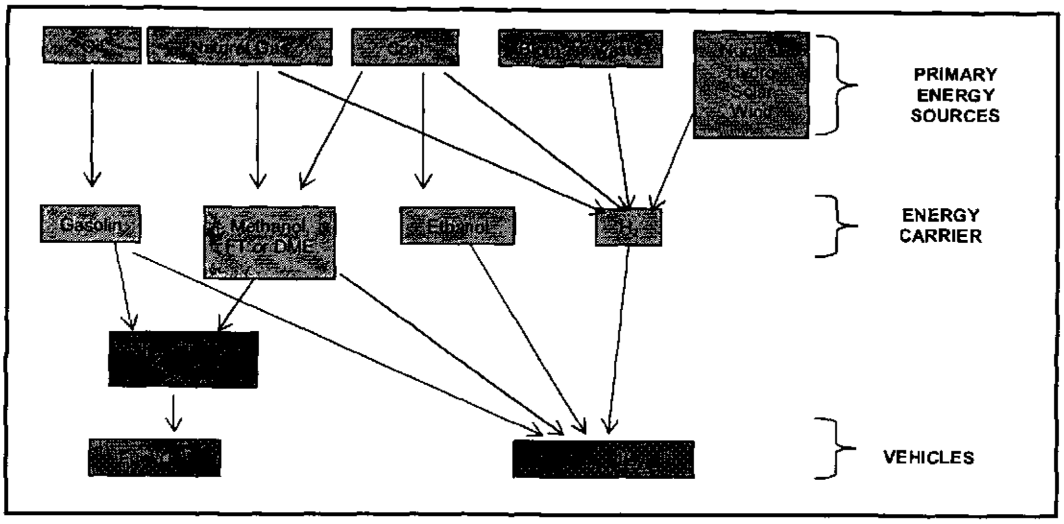

Fig. 1 Energy generation used H_2 for transport application [2]

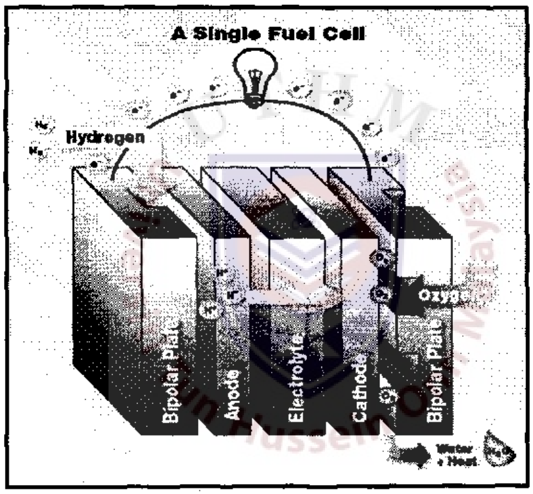

Fig. 2 Mechanism of fuel cell [1]

Principally, fuel cells can be divided according to the kind of electrolyte being used. Table 1 shows 5 basic types of potential fuel cells, which each of them has their on characteristics and specification to match with the market demands [1]. Besides these basic 5 types, as the strong determination of people around to acquire the great efficiency of fuel cells, the two more types of fuel cells are initiated Direct Methanol Fuel Cells (DMFC) and Regenarative Fuel Cells (RFC).

Fuel cells as a promising technology which is fully deemed have a great potential to be exploited. It can be significantly adopted for variety of applications from small to huge which is shown in Table 2. Of all these applications, stationary power generation and transport applications are emphasized in this case study because, instead of other applications, these two applications are seen having better prospects for fuel cells to be implemented. Indeed, for other applications, the fuel cells technologies are still at early stage of evolvement.

In stationary power generations, the efficiency of fuel cells is typically higher than conventional combustion plant in generating electricity which meets up to 60% relatively to only 33%-35% for conventional combustion plants [1]. On another application which is in transportation, the efficiency of gasoline engine in a conventional car is less than 20%, whereas for hydrogen fuel cell vehicles, the efficiency of 40%-60% can simply be achieved [1]. Nevertheless, in spite of positive and great evolvement of fuel cells technologies in both stationary power generations and transportation applications, there still have some barriers that should be firstly examined in route to excessively use these technologies. These mainly consist of cost reduction and durability. For competitive stationary and transportation fuel cells, the cost on the order of \$500-800k/W and \$50-100k/W are respectively required, whereas in terms of durability, the development goals are to achieve 40,000-50,000h lifespan between major maintenance process for stationary systems and 4,000-5,000h for automotive systems [2].

Table 1 Specification of each fuel cells type [1]

Fuel Cell Type	Operating Temperature	System Output	Efficiency	Applications
Alkaline (AFC)	90–100°C 194–212°F	10kW–100kW	60–70% electric	• Military • Space
Phosphoric Acid (PAFC)	150–200°C 302–392°F	50kW–1MW (250kW module typical)	80–85% overall with combined heat and power (CHP) (36–42% electric)	• Distributed generation
Polymer Electrolyte Membrane or Proton Exchange Membrane (PEM)*	50–100°C 122–212°F	<250kW	50–60% electric	• Back-up power • Portable power • Small distributed generation • Transportation
Molten Carbonate (MCFC)	600–700°C 1112–1292°F	<1MW (250kW module typical)	85% overall with CHP (60% electric)	• Electric utility • Large distributed generation
Solid Oxide (SOFC)	650–1000°C 1202–1832°F	5kW–3 MW	85% overall with CHP (60% electric)	• Auxiliary power • Electric utility • Large distributed generation

Source: Argonne National Laboratory

**Direct Methanol Fuel Cells (DMFC) are a subset of PEMFCs typically used for small portable power applications with a size range of about a subwatt to 100W and operating at 60–90°C.*

Table 2 Application of Fuel cells [2]

Application	*Explanation*	*Total Energy*
Stationary power generation	Combined heat and power (CHP)	1kW-50MW
Transport	Utility vehicle, bus power systems and electric passenger car	20kW-250KW
Auxiliary power units (APU)	Auxiliary power units for cars, trucks, and motive power for scooters	3kW-5kW
Small consumer electronics	Power for portable electronic devices	5W-50MW
Others	Power for remote telecommunications applications	100W-1KW
	Power for consumption and outdoor recreational uses	1kW-3kW

Based on the current state, there are still a lot of improvements need to be done for fuel cells excessively penetrating the market. The most crucial task that must be firstly carried out is determining the practical limitations or barriers for each fuel cells type and finding the ways to solve. On the whole, this case study discusses all confronted limitations or barriers for each type of fuel cells and which of these limitations give the huge impact in enabling fuel cells to be viably commercialized. For this, there are several papers have been referred in order to justify all the given statement.

3. Limitations for Each Type of Fuel Cells

Realizing the promising potential of fuel cells to be as one of the vital sources for generating energy, therefore, something should be taken in route to tackling all the remain limitations. Cost, performance, and durability are generally looking as the key areas which need to be addressed. In parallel to this, there are multi of works on fuel cells being carried out. Most of these works focus on developing a new material for fuel cell component that have a high durability and more less-expensive. Based on the current markets particularly in transport applications and stationary power generation, the high efficiency, durability, and capability of fuel cells are required. Both of these application, for instance, operate at high temperatures which up to 120°C and above 120°C, respectively, therefore the fuel cells which are capable withstand at this temperature are needed and it definitely increase the capital cost [3]. In this case, even the high performance is the main goal for any particular application; but, it still must have a trade off with the overall cost running the fuel cells.

In order to reduce a cost, the significant improvement that can be made is in deciding the type of catalyst wanted to be employed. The most effective catalyst, nowadays, is platinum (Pt) which is costly. Therefore, finding and developing new materials that can replace this sort of precious metal would become the most valuable meant. There are varieties of fuel cells type available in market, which are divided based on their electrolyte types. Each of them has their own advantages, potential but as well as limitations. However, the limitations are the most important aspects that must be firstly examined before fuel cells technology can be further disseminated. The limitation(s) for each type of fuel cells are separately presented to recognize which of these fuel cells that has more promising potential to be exploited and what are the remarkable limitation(s) in route to commercialize fuel cell technologies.

3.1 Polymer Electrolyte Membrane Cells (PEMFC)

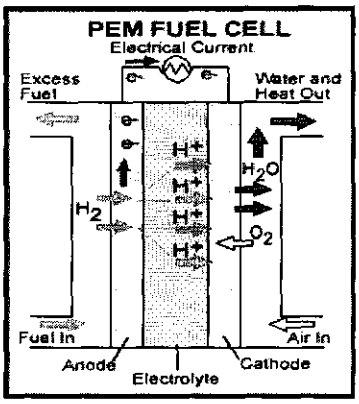

Fig. 3 PEMFC

In the turn of the centuries, there are lot number of researches on fuel cells already been carried out particularly in addressing the applications of PEMFC [4, 5, 6, 7, 8, 9]. These all researches were done by experimental and simulation model. In fact, PEMFC is characterized as the most promising candidates for future power generating devices in the automotive, distributed power generation and portable electronic applications [6]. However, there are several limitations that must be initially overcome in route enabling PEMC to be viably commercialized. The most crucial part is in developing or finding new material that can replace noble-metal catalyst (i.e. platinum (Pt)) which is currently used for separating H_2 to electrons and protons. To this age, the Pt is solely the one which has been identified can work efficiently in fuel cells. However, it is really expensive to be afforded and even also tremendously sensitive to CO which can cause poisoning.

US is among countries which is struggling enough towards adopting PEMFC systems in their transportation application. In the late 90's, for instance, there was a strong collaboration between US Department of Energy (DOE) and the US automotive industry in developing a six-passenger automobile that can achieve up to 80 miles/gal by using PEMFC system, under auspices of the Partnership for a New Generation of Vehicles (PNGV). Chalk et al. (2000) in their research claimed that, this program is targeting higher-risk development of high-temperature, inexpensive membranes, and O_2 catalysts PEMFC typically operates at 80°C. The large advantages would be obtained with having inexpensive membrane that can operate at 100°C-150°C; which are in context of sustainable current densities and does not require significant humidification [4].

On top of that, this particular membrane also can increase CO tolerance and reduce heat rejection permitting a dramatic reduction in the size of the condenser and radiator [4]. Apart from that, Chalk et al. (2006) emphasized that higher operating voltage are required to meet efficiency targets for fuel cell systems. Therefore, the development of improved O_2 reduction electrocatalyst with enhanced kinetics would be beneficial. Indeed, advanced O_2 Catalysts could reduce and eliminate the need for air compressor in fuel cell systems.

Besides that, the significant limitation in context of transportation application is in terms of hydrogen storage which according to [3] H_2 itself having the low energy density, consequently, it is difficult to store enough H_2 onboard to allow vehicles to travel the same distance as gasoline-powered vehicles before refueling, typically 300-400 miles. Whereas in stationary applications, the fuel cell types which are capable operating at temperature above 120°C are needed for better thermal management, however, it is not case for PEMFC which can operate at slightly lower temperature [3].

Liu et al. (2006) in their parametric study of PEMFC performances discovered that the cost of PEMFC is still too high for them to become viable commercial products. On top of that, the performance of PEMFC fuel cells is known to be influenced by many parameters, such as operating temperature, pressure and humidification of the gas streams. Therefore, in order to improve fuel cell performances, it is essential to understand these parametric effects on fuel operations.

3.2 Phosphoric Acid Fuel Cells (PAFC)

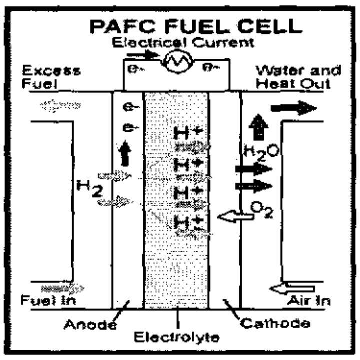

Fig. 4 PAFC

PAFC is the first fuel cell types which are commercially exploited. This fuel cell type is typically used for stationary power generation such as combined heat and power (CHP) plants and has several distinct which is used for power large vehicles such as city buses. Similar to PEMFC, according to EERE (2006) PAFC also uses platinum as its catalyst which expectedly raises the operating cost up to $4,000 and $4,500 per kilowatt. On top of that, comparing with other fuel cell types which have same size, PAFC is rather less powerful. As consequently, it becomes more bulky. The identification of the best PAFC plant size thus represents a key target resulting in significant economic savings [10].

"The more the proper sizing is carried out in search of the highest environmental and energy benefits, the higher financial returns will be"

[10]

3.3 Alkaline Fuel Cells (AFC)

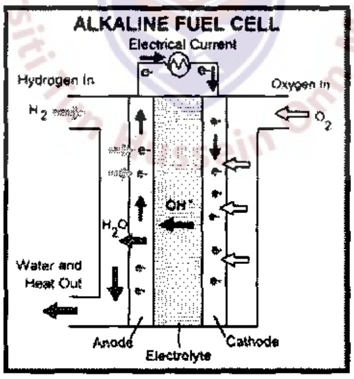

Fig. 5 AFC

The great thing about AFC is it can use a variety of non-precious metals as a catalyst. This absolutely reduce the cost, however, this fuel cells type is easily poisoned by CO_2 which it then can affect the cell's operation [3]. Due to the poisoning, a purification process needs to be implemented and it is costly. Indeed, the durability of AFC itself also affected by this poisoning.

Besides that, the material durability is also become a big issue in enabling AFC to be commercialized. AFC stacks have been shown to maintain sufficiently stable operation for more than 8,000 operating hours. To be economically viable in large-scale utility applications, these fuel cells need to reach operating times exceeding 40,000 hours, something that has not yet been achieved due to the limitation of material durability [3].

3.4 Molten Carbonate Fuel Cells (MCFC)

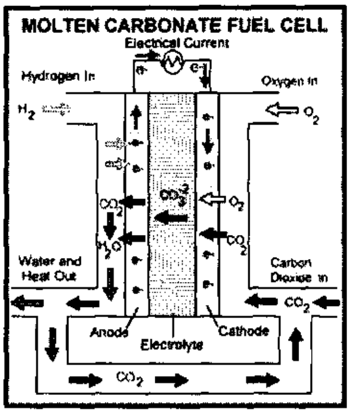

Fig 6. MCFC

MCFC is the only type of hydrogen-oxygen fuel cells which employs a molten salt electrolyte. It operates at high temperature up to 650°C and above, and this gives an advantage to MCFC, which is, in this particular case, non-precious metals can be utilized as catalysts; thereby it certainly reduces the cost. Nevertheless, there is still having a limitation in this type of fuel cell in terms of its durability. As these fuel cells types operate at relatively high temperature, it might cause corrosion; hence, it affects the durability and cell's performance. As to solve this problem, research has currently been carried out in developing corrosion-resistance materials. Apart from that the design of these fuel cell types are as well examined in order to improve the durability without affecting the cell's performance.

In comparison to other fuel cells, the MCFC operates with the lowest current densities due to limited zones of electrode reactions and low solubilities of O_2 and H_2 in molten carbonates; also it has a thickest electrodes-electrolyte assembly. As a result, the applications of MCFC are almost limited to stationary power generators [11]. However, even the MCFC stationary power generators have now approached high technological level of pre-commercialization, in the future they may face a serious challenge from PEMFC and SOFC, for which improvement of operational parameters is believed to be achieved easier [11].

3.5 Solid Oxide Fuel Cells (SOFC)

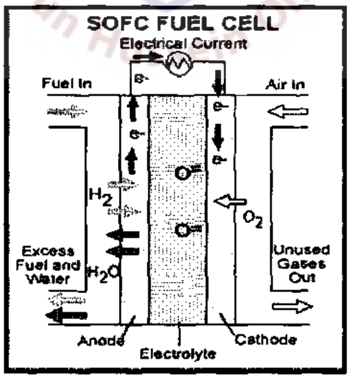

Fig 7. SOFC

SOFC operates at very high temperature which is at range 1,000°C. Similar to MCFC, this gives a key advantage to SOFC which it can use non-precious metal for replacing Pt as catalyst, thereby reduce the cost. Beside that, SOFC can internally reform fuels, hence reduce the cost associated with adding a reformer to the system [3]. However, this high temperature also has drawbacks particularly in terms of durability which it can affect cell components and accelerate corrosion. Extend to that, the SOFC technology might solely suitable for stationary power generation application and not for transportation application. This is because, SOFC itself has slow startup and requires significant thermal shielding to retain heat and protect personnel.

There must have a trade off in dealing with this technology between durability and cost. Developing economical fuel cells having a high durability and can operate efficiently within cell operating temperature is the most significant task that must be carried out. In context of SOFC, there are many researches have been implemented in way to explore the potential of SOFC operating at or below 800°C. Fundamentally, the durability can be increased if cells operate at low temperature; hence, cost can be reduced. However, according to [3] the lower the temperature of SOFC, the less electrical power can be produced. Indeed, till now, there is no stack materials have been identified can operate in this lower temperature range. Basically, in order to develop a high performance SOFC, the selection of a particular cell component as the support/substrate of the fuel cell can be the determining factor [12]. Chan et al. (2006) have claimed via their study that the performance of an anode-supported cell is superior to that of an electrolyte-supported cell or a cathode-supported cell for the same materials used, same electrode kinetics and same operational constraints.

3.6 Direct Membrance Fuel Cells (DMFC)

DMFC is considered as a new fuel cell technology which is powered by pure methanol. Unlike other fuel cell types, DMFC does not have a problem regarding the storage, delivery and supply of fuel, as it is used methanol as fuel. Methanol which has energy density higher compare to H_2, is absolutely seen more convenience and efficient to be used as fuel. However, DMFC is still new; in fact, its research and development is just only started compare to other fuel cell type, therefore, there still have lots of gaps for doing enhancement for this particular area specifically in terms of performance.

Because of advantages such as easily transported and stored, relatively cheap, no production of NO_x, and operates at low temperature, then, DMFC is very attractive to be used as a portable power source for small mobile devices such as cell phones and notebooks [13]. However, Reshetenko et al. (2006) justified that there is still certain problems happen when operating DMFC which are methanol crossover and low reaction rate. Despite the thermodynamic cell voltage corresponds to 1.21V, DMFC generally show a much lower value due to methanol crossover. Besides that, the low reaction is also identified as a major barrier for performance improvement.

3.7 Regenerative Fuel Cells (RFC)

RFC have the potential of achieving much higher specific energy densities than any of the advanced battery systems [14]. Therefore, according to Barbir et al. (2005) this technology is suitable for applications where relatively large amounts of energy must be stored such as for remote off-grid power sources, emergency, or backup power generation, zero emission vehicles, hybrid energy storage/propulsion systems for space craft, and high altitude long endurance solar rechargeable aircraft.

In optimizing RFC systems for a given application, the operating efficiency of both the fuel cell and electrolyzer may be traded against the stack mass [14]. The results of this trade-off analysis indicate that RFC may be viable option for energy storage in solar energy power systems where weight is important (such as in aerospace applications).

4. Remarkable Limitation

In chapter 3, the limitations are separately presented according to the fuel cell types. In this chapter, discussion are made to clearly justify which of all these limitations giving remarkable results in enabling each fuel cells type to be commercialized. From discussions that are made in chapter 3, it can be concluded that fuel cells technology can be exploited into two main applications namely stationary power generation and transportation. However in a route to use this fuel cells technology, there have certain limitations which can be initially examined and overcome. Table 3 specifically summarizes the limitations of each fuel cell types. Basically, there are two major subsystems that cause limitations which are either from fuel cell itself or from fuel handling which in this context the fuel used is H_2. In respect to fuel cell itself, there are four (4) limitations; cost, durability, size and weight, thermal and water management, whereas in hydrogen handling there are there (3); hydrogen production, hydrogen delivery and hydrogen storage.

Table 3 Summary of limitations for each type of fuel cells

Limitations	PEMFC	PAFC	MCFC	SOFC	AFC	DMFC	RFC
Fuel Cells Handling							
Cost	/	/					
Durability	/		/	/	/	/	
Size & weight		/					
Thermal&water management	/	/	/	/	/		
Hydrogen Handling							
Hydrogen production	/	/	/	/	/	x	x
Hydrogen delivery	/	/	/	/	/	x	x
Hydrogen storage	/	/	/	/	/	x	x

The most significant limitations in fuel cells handling are *cost and durability* [3, 4, 7, 15, 16]. It is generally accepted that, in whatever type of energy supply systems, there must have a balance between the performance and overall cost systems. Development of fuel cells consumes lots of money especially if the systems use noble-precious material (i.e. typically platinum (Pt)) as their catalyst. In this context, PEMFC and PAFC are more expensive compare others since it uses Pt as its catalyst. Basically, there are lots of researches been carried out in addressing this particular problem. The most recent electrolyst developments have shown that Pt alloy catalysts have increased activity and greater durability than Pt catalyst [4]. Since the durability is increased, it simultaneously reduces maintenance cost. Besides that, the durability of conventional fluorocarbon membranes is improving, and hydrocarbon-based membranes have also shown promise of equaling the performance of fluorocarbon membranes at lower cost [4]. Chalk and Miller (2006) also claimed that fuel cells can start from freezing conditions without significant deterioration.

Size and weight of fuel cells is often considered when dealing with applications that have a restriction in these both factors. PAFC, for instance has a huge size and weight due to their less powerful compare to other fuel cell types. Therefore, its applications solely limited to the huge scale application. *Thermal and water management* processes include heat and water use, cooling and humidification [3]. Water and thermal management is essential for the proper operation of PEMFC, which the polymer membrane in the PEMFC must be in a hydrated state to facilitate proton transport [9]. Liu et al. (2006) also emphasized that if there is not enough water, the membrane becomes dehydrated and resistant to proton conduction increases sharply. On the other hand, if too much water is present, flooding may occur. Water flooding often acts as the main cause of serious performance drop at high current densities.

In *hydrogen production* the greatest and most challenging task is cost reduction [1]. This is important to be considered in matter making H_2 to be competitive with other conventional fuels such as oil and gasoline.H_2 contains a relatively small amount of energy by volume compare to other fuels such as natural gas and gasoline [1]. Therefore, there are stringent cost and energy efficiency in *hydrogen delivery*. The cost in this case is primarily related to cost developing high performance pipeline, which can channel H_2 to end-use energy need without too much energy losses.

In context *hydrogen storage,* the characteristics of H_2 itself, having a low volumetric energy density, is actually become as the major obstacle in enabling H_2 to be stored. This then becomes really matter to be considered primarily for transportation applications. Nevertheless, H_2 storage systems for vehicles are practically identified inadequate to meet customer driving range expectations (>300 milesor 500 km) without intrusion into vehicle cargo or passenger space [4].

For that, DMFC and RFC are initiated for meant to solve this problem. DMFC basically uses methanol whereas RFC can use other alternatives such as solar power to generate electricity. Hence, there is no problem in terms of storage for these two applications.

5. Conclusion

Generally, fuel cell is one of potential and promising technologies available nowadays for generating electricity and heat. It can be used for small scale applications or even large scale applications. Stationary power generation and transportation application are the two applications which can fully exploited the advantages of this technology. However, there still have several limitations that must be initially overcome in order to viably commercialize this technology. The most significant limitations that are identified in enabling fuel cell become more competitive than other current technologies are in terms of cost reduction, performance and durability. Developing low cost membrane and catalyst with high performance and durability is the most relevant key to solve this problem.

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