

REVIEW ON THE DEVELOPMENT OF FUEL CELLS AND ITS FUTURE PROSPECTS

Thareny Ravichandran^{a,b}, Juhana Jaafar^{a,b*}, Hamid Ilbeygi^c, Mochammad Purwanto^d

^aAdvanced Membrane Technology Research Centre (AMTEC), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

^bSchool of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

^cFuture Industries Institute, University of South Australia Building X, Mawson Lakes Campus, Mawson Lakes SA 5095, Adelaide SA 5001

^dKampus Institute Teknologi Kalimantan Karang Joang, Jalan Soekarno Hatta KM 15 Karang Joang, Balikpapan 76127, Kalimantan Timur, Indonesia

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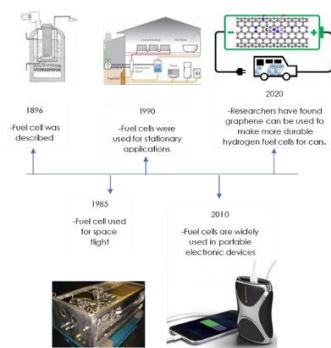
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*Corresponding author
juhana@petroleum.utm.my

Graphical abstract



Abstract

Fossil fuels are unsustainable energy storage medium with pollution problems. With the limitation of fossil fuels, fuel cells, which are known as effective electrochemical converters, has attracted much attention. Present review paper provides a complete information on fuel cell technology and history which includes competing technologies, current status of research-and-development and its future direction. Fuel cell plays an important role in stationary applications from 1990s till now due to its efficiency upon reducing emissions.

Keywords: Fuel cells, renewable energy, fuel cell applications, sustainable source, technologies

Abstrak

Bahan api fosil adalah medium penyimpanan tenaga yang tidak berkekalan dan mempunyai masalah pencemaran. Dengan keterbatasan bahan api fosil, sel bahan api, yang dikenali sebagai penukar elektrokimia berkesan semakin dikaji oleh ahli sains. Makalah ini mengulas maklumat komprehensif mengenai sains sel bahan api dan sejarahnya yang merangkumi teknologi bersaing, status terkini penyelidikan dan pengembangan dan sasaran masa depan. Sel bahan api memainkan peranan penting dalam aplikasi pegun dari tahun 1990-an hingga sekarang kerana dapat mengurangkan pelepasan.

Kata kunci: Sel bahan api; tenaga diperbaharui; aplikasi sel bahan api; tenaga berkekalan; teknologi

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1.0 INTRODUCTION

Natural resources can be categorized into renewable and non-renewable [68]. Renewable resources or clean energy includes wind, hydro, tidal, geothermal, biomass, and solar energy [69]. They produce lower emissions of carbon dioxide which can reduce the dependency on fossil fuels. Natural renewable resources are the predominant energy source that has been used throughout history. Biomass is the primary energy source that has been used widely in the developing country up to date. Non-renewable resources are those resources that are no longer available once the existing resources are exhausted. Fossil fuels are considered non-renewable although they renew themselves in a few millions of years. Humans extract them in various forms such as in gas, liquid, or solid which is then converted for their use, mainly related to energy [70-71]. According to World Wide Fund [1], 90% of the world's energy consumption is supported by fossil fuels. About every 20 years, the consumption of fossil fuels nearly doubles. As fossil resources are depleting, the world population is becoming concerned each day. Governments all over the world are considering alternative and sustainable sources of power. Fuel cell technology is gaining attention worldwide due to its renewable nature [2]. Owing to internal combustion-free operation, fuel cell technology is noise-free and low maintenance. With only water as the primary by-product of its exhaust stream, the fuel cell is a zero-emission technology.

Sir William Grove invented fuel cell in 1838. Later, in 1982, Francis Thomas Bacon created gas diffusion electrode. O.K Dartyan experimented with high and low alkaline hydrogen cell. During 1950s, fuel cell was being developed for space exploration. Many advancements in technology have led to the practical usage of fuel cell. Applications of fuel cell includes macro (e.g. bus) and micro scale (e.g. laptop). In United States, in 2019, the fuel cell market was estimated at over USD 3.5 billion, with annual installations expected to cross 400 thousand units by 2026 [74]. Fuel cell process comprises of converting chemical energy to electrical energy [72]. Typically, electrochemical reactions take place at electrodes with different charges named anode and cathode. The electrochemical reaction produces electric current when gaseous/liquid are fed as fuels to the electrode (anode) compartment, simultaneously, an oxidant is fed continuously to the cathode compartment. Figure 1 shows the basic mechanism of energy conversion [73]. Fuel cell have some disadvantages such as degradation and/or malfunction of specific components [3].

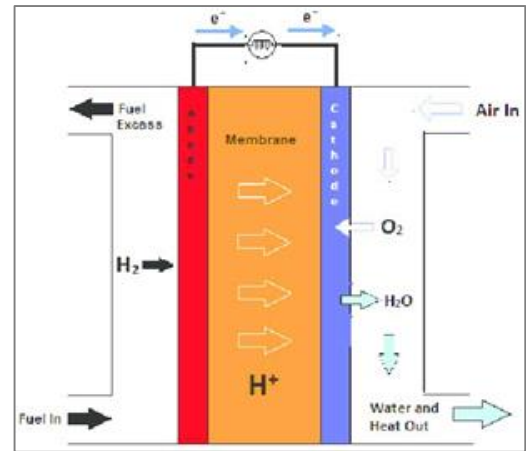


Figure 1 Basic mechanism of energy conversion [73]

There are variety of fuel cells which are being developed. There are different categorizations of fuel cells such as according to type of electrolyte, a combination of a type of fuel and oxidant, temperature of operation, whether the fuel is processed outside (external reforming) or inside. However, the widely use categorization of fuel cells are mainly according to its type of electrolyte. Under this categorization, the fuel cell can be divided into 5, namely: proton exchange membrane (polymer) electrolyte fuel cell (PEMFC), alkaline fuel cell (AFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), and phosphoric acid fuel cell (PAFC).

Fuel cells are used in military because of the high power and lighter in comparison to traditional portable applications [5,6]. The manufacturing of a portable fuel cells is costly. To manufacture 50,000 fuel cell stacks for portable system, \$166 kW/e to \$5,387 kW/e is needed for a 250 kW/e system, per year [7].

The fuel cell provides energy for future applications. It is now being used to replace the internal combustions engines that undesirably for environmental nurturing. The history of fuel cells can be found in the last two centuries. But its development and progress do not publish. Therefore, this review paper aims to show advancements of fuel cells in various sectors and future prospects of them.

2.0 CURRENT APPLICATIONS

Fuel cells have a large variety of approach in a number of markets. Its applications are ranging from small scale power supply such as gadgets to a larger level power supply such as power plants. Fuel cell applications are shown from the year 2014 to 2018 (Figure 2) [4].

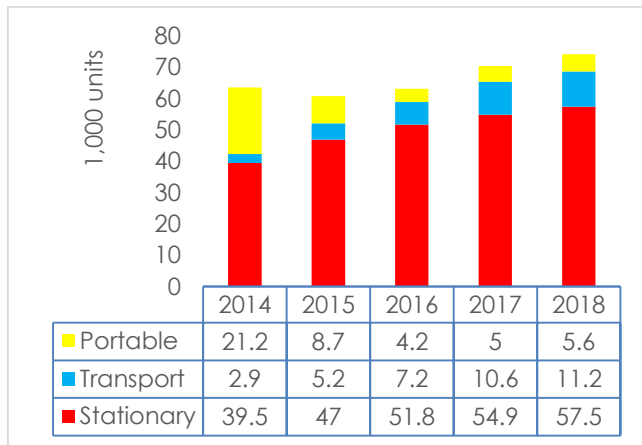


Figure 2 Fuel cell applications by category [4]

The graph shows the units of fuel cell used different applications. Number of fuel cells used for stationary is dominant in the range of years. Usage in portable has decreased noticeably. While, fuel cell applications in transport have been slightly increasing in the years.

2.1 Portable Applications

Power for portable fuel cells ranges from 5 to 500 W and the power range could reach kW-level up to some of the demanding portable electronics. Portable fuel cells such as cellular phones, laptops, and battery chargers can be moved around and used for various activities. On the other hand, stationary fuel cells are immovable. The energy density of a typical fuel cell is 5-10 fold higher than that of rechargeable batteries. This makes fuel cell to be a more favorable option for portable devices. For instance, direct methanol fuel cells (DMFCs), reformed methanol fuel cells (RMFCs), and PEMFCs are being used for portable military. Table 1 shows the contrast between fuel cells and its portable technology opponents. By referring to the table, it is clear that fuel cells have high effectiveness and capacity.

2.2 Stationary Applications

Residential, industrial, and commercial sectors have high demands for fuel cells for both grid-assisted power supply and grid-independent fuel cells. Grid-independent fuel cell also known as stand-alone fuel cell. Table 2 shows the contrast between fuel cells and its stationary technology opponents. Based on the table, it is important to note that the fuel cells have high effectiveness and influencing factors in the stationary sector. Selamogullari *et al.* [9] has demonstrated that the light load efficiency can be increased by using an insulated gate bipolar transistor–metal oxide semiconductor field-effect transistor (IGBT–MOSFET) switch combination in a half-bridge inverter topology. Hydrogen usage can be reduced by utilizing the new inverter design in stand-alone operations. To connect the fuel cell-based Distributed Generation (DG) system to a utility grid,

output voltage, real and reactive power flow, phase, and frequency of the inverter has to be modified in order to be able to control between DG and grid [10–12].

Nelson *et al.* [13] demonstrated an energy storage system using a combination of a fuel cell stack, an electrolyzer, and a hydrogen storage tank. This configuration was used to compare a traditional hybrid energy system with battery storage. The study showed that an existing method is economical than using the conventional fuel cell.

Karakoulidis *et al.* [14] has discussed the advantages of standalone-based fuel cell systems in terms of technical and economical using simulations. The result indicates that diesel generators and batteries by hydrogen technologies decreased fossil fuel dependency

2.2.1 Large-scale Power Generation

Phosphoric acid fuel cell (PAFC) technology is playing a major role in the market. Since the 1970s, more than 500 PAFC power plants have been installed and tested around the world [15]. Molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), and polymer electrolyte membrane fuel cell (PEMFC) units have been established too. However, MCFC, SOFC, and PEMFC are accepted mostly in the market due to its cost which is lower than phosphoric acid. The PAFC is least preferable compared to other types of fuel cells due to the lack of progress towards the sustainable price. To provide higher efficiencies at higher power, MCFCs are used.

MCFCs are bound to be adopted at a higher power of above 250kW because of their higher efficiencies. Electrochemical reaction increases when current that can be obtained at a given voltage [16].

The major advantage of a fuel cell in large- and small-scale power generation is significantly more variable as compared to transportation and portable sectors. A few processes of industries produce a lot of waste biogas and it can be used with fuel cells to create power with ease.

2.2.2 Residential and Small Stationary Power Generation

Fuel cells that are used in residential have units of between 1 and 10 kW. Few studies suggest that a fuel cell should be able to provide electricity for the whole house [17]. Meanwhile, others suggest that fuel cells should only provide baseload. Although PEMFC and SOFC units are popular, more companies are working on PEMFC. Europe, North America, and Southeast Asia are the three main regions active in fuel cell development [18]. Fuel cells require significant development work in obtaining uninterrupted power supplies and to have the durability of >5 years which can encounter the real requirements of the world customers.

Table 1 Contrast among fuel cells and their portable technology opponents [8]

Portable technology	Gravimetric energy density (Wh/kg)	Volumetric energy density (Wh/L)	Power density(W/kg)	Capital cost (\$/kWh)
DMFC	>1000	700-1000	100-200	200
Lead-acid battery	20-50	50-100	150-300	70
Nickel-cadmium battery	40-60	75-150	150-200	300
Nickel-metal hydride battery	60-100	100-250	200-300	300-500
Lithium-ion battery	100-160	200-300	200-400	200-700
Flywheel	50-400	200	200-400	400-800
Ultracapacitor	10	10	500-10000	20000

Table 2 Contrast among fuel cells and their stationary technology opponents [8]

Stationary power	Power level (Mw)	Efficiency (%)	Lifetime (years)	Capital cost (\$/kW)	Capacity factor (%)
Phosphoric acid fuel cell	0.2-10	30-45	5-20	1500	Up to 95
MCFC/ags turbine hybrid	0.1-100	55-65	5-20	1000	Up to 95
SOFC/gas turbine hybrid	0.1-100	55-65	5-20	1000	Up to 95
Steam cycle (coal)	10-1000	33-40	>20	1300-2000	60-90
Combine gas turbine cycle (natural gas)	50-1000	45-60	>20	500-1000	Up to 95
Microturbine	0.01-0.5	15-30	5-20	800-1500	80-95
Hydroelectric	0.1-2000	65-90	>40	1500-3500	40-50
Solar photovoltaic	0.001-1	10-15	15-25	2000-4000	<25

2.3 Transportation Applications

The transportation industry aims to reduce the harmful emissions without compromising efficiencies. This is mainly because each year, the industry of transportation is accountable for 17% of the worldwide greenhouse gas (GHG) outflows [20]. Fuel cells offer near-zero harmful emissions and enhanced efficiencies than conventional internal combustion engines [21]. Fuel cells are being used in vehicles for the past few years [22]. Fuel cell voltage is stepped up by direct current-direct current (DC-DC) converters to the main DC bus voltage [23]. Since power management between battery and motor is the main problem with the fuel cell vehicle, hybridization is required with the energy storage unit [24].

The focus of automobile manufacturers is to determine some issues on the mass generation of FCVs. By 2030, it is expected that FCVs could replace traditional cars [25, 26].

Toyota Motor Corporation (TMC) started the fuel cell hybridization vehicles in 1992. In June 2005, TOYOTA had the first vehicle fueled by the fuel cell and acquire FCHV (Fuel Cell Hybrid Vehicle) certification [27].

2.3.1 Auxiliary Power Units (APUs)

PEMFCs, DMFCs, and SOFCs are being developed for APU applications. Fossils such as methanol, LPG, natural gas, gasoline, and diesel are possible fuels to develop fuel cells. Vehicles such as airplanes require fuel cells that operate at high-temperature such as MCFCs and SOFCs.

Non-propulsive power is produced by the on-board APU in vehicles. Unlike portable applications, the APUs are built in the vehicle. Heavy-duty trucks [28, 29]; leisure yachts, planes, and cars [30] are successful markets of APUs because of their high electrical energy demand [31-33]. By using a fuel cell as an on-board APUs, it could decrease NO_x emissions up to 95%, particulate matter-10 emissions by up to 65%, and CO₂ emissions by more than 60% [34].

2.3.2 Light Traction Vehicles (LTVs)

Some examples of light traction vehicles (LTVs) are scooters, airport tugs, and motorbikes. Generally, the highest positive use of the fuel cell is forklifts. Forklifts are extensively used in the warehousing and distribution industry, with nearly 2.5 million forklifts in operation in North America [35]. Conventional forklifts use rechargeable lead-acid batteries or combustion engines that use diesel, gasoline, LPG, compressed natural gas, or propane.

Approximately 1300 fuel cell-powered forklifts are functioning in the US market up to date [36]. Fuel cell forklifts normally use PEMFCs or DMFCs. Examples of LTVs are personal wheelchairs [37] and light carts [38]. Table 3 below shows the comparison of the conventional forklifts and fuel cell-based forklifts [8].

2.3.3 Light-duty Fuel Cell Electric Vehicles (L-FCEVs)

Light-duty fuel cell electric vehicles (L-FCEVs) provide fuel cell-based energy to the propulsion system. L-FCEVs provide noise-free operation, more efficient energy usage [39] compared to the current engine-based vehicles. L-FCEVs has a longer range, better acceptance of cold weather, refueling time, and lower weight compared to light-duty battery electric vehicles (L-BEVs).

The main common parts of an L-FCEV include high-pressure hydrogen storage tanks (stores hydrogen), fuel cell stack (generates electricity), supplemental Lithium-ion battery (stores electricity), power drive unit (governs electrical flow), and an electric drive motor (propels vehicle).

L-FCEVs are not used commercially because of its lifecycle costings and drawbacks in its durability in fuel cell stack. The most commonly used fuel cell in L-FCEVs is hydrogen PEMFCs. Honda, Nissan, and other major vehicle producers are in the effort of utilizing L-FCEVs as the main propulsion system using the fuel cell system connected to an electric motor [40].

L-BEVs are the main competition for L-FCEVs with nickel-metal-hydride (NiMH) batteries being used in the L-BEVs market. In the future, NiMH will be replaced by lithium-ion (Li-ion) batteries in L-BEVs. L-BEVs and L-FCEVs have pros and cons that are highly dependent on the main energy source (biomass, renewable, or fossil), energy conversion chain (e.g., transport, hydrogen production, and storage mechanisms), and design requirements (driving range, maximum speed, or passenger capacity) [8].

Campanari *et al.* [41] found a temporary result for light-duty hybrid electric vehicles (L-HEVs) by using both batteries and fuel cells to merge their strengths. When biomass or natural gas are used as an energy source for a distance more than 160 km, Thomas [42] found L-FCEV has some advantages over L-BEV by referring to the mass of the vehicle, the volume of storage, GHG emissions, and well-to-wheel energy efficiency. Compared to other technologies, vehicles that use batteries, corn ethanol, hydrogen fuel cells, and cellulosic ethanol release less GHG. Due to constraints of hydrogen storage, hydrogen fuel that is needed to operate an L-FCEV is usually generated off-board [43].

2.3.4 Heavy-duty Fuel Cell Electric Vehicles (H-FCEVs)

Heavy-duty fuel cell electric vehicles (H-FCEVs) uses fuel cell for the electric propulsion system include buses, vans, heavy-duty trucks, etc. In 2012, Western Europe had 30 fuel cell buses while the United States had 25 [44]. Fuel cell electric buses (FCEBs) release very low emissions compared to conventional buses that use diesel. This makes FCEBs become the public's favorite.

Other vehicles that are powered by fuel cells are different compared to buses. This is because infrastructural requirements of hydrogen for buses is simple due to the fixed routes. In addition, these buses have flexible mass and size limitations for hydrogen storing system in comparison to traditional buses.

Few governments who have deployed FCEBs are the US, Canada, Japan, Australia and China. There are a few programs that are being carried out in different countries. For example, Sustainable Transport Energy Program (STEP) in Australia [45], the Clean Urban Transport for Europe (CUTE) and HyFLEET: CUTE project in Europe [46], Hydrogen Fuel Cell Demonstration Project in Canada, Urban-Route Buses Trial Project [47] in China and Zero Emission Bay Area (ZEBA) demonstration [48] and the Brazilian Fuel Cell Bus Project in California [49]. Figure 3 shows few important components in a FCEB [50].

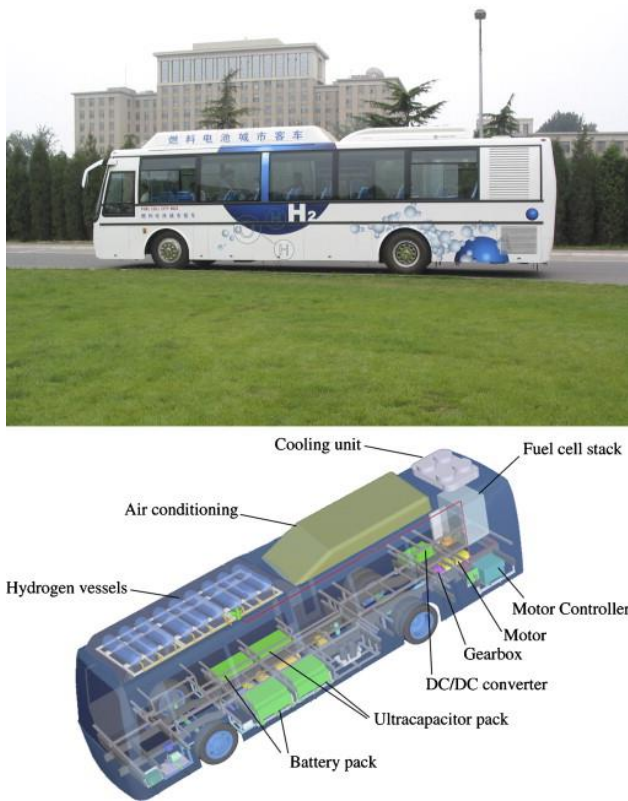


Figure 3 Components in a FCEB

The main components in FCEBs are auxiliary components, transmission, electrical motor, fuel supply unit, fuel cells, air condition and hydrogen tank which are mostly similar to L-FCEVs. PAFCs and PEMFCs are the most frequently utilized types for the stack and high-voltage batteries used for regenerative braking energy recovery and an improved dynamic response. The under-developed fuel cell technologies and the absence of mass production causing FCEBs to become unable to compete in terms of economy with

traditional buses and other competing novel innovations. This is more obvious for FCEBs than L-FCEVs because of the increasing demonstration programs' number and the endeavours by bus and fuel cell developers such as Hydrogenics, Ballard, and Daimler AG. A few noteworthy, milestones and demonstrations have been accomplished for H-FCEVs.

Table 3 Comparison of the conventional forklifts and fuel cell-based forklifts [8]

Conventional forklifts	Fuel cell-based forklifts
Harmful emission	Less-harmful emission than conventional
Most of the forklifts operates outdoors only	Can operate indoors or outdoors
Larger space for battery changing and charging	Less space for a refueling station
Longer time to recharge or changing batteries	Less time to refuel
Sensitive to the ambient temperature	Low sensitivity to the ambient temperature
Shorter operational cycles	Longer operational cycles
Less operational efficiency	More operational efficiency

In Germany, a hybrid waste disposal truck had been developed. The truck uses a hybrid diesel engine and a fuel cell system. The fuel cell system in the truck can use to collect, manage and dispose of waste. Meanwhile, the use of a diesel engine is for propulsion. Guo *et al.* [51] designed and used a power system for rail systems which will meet the locomotive's power demand with high effectiveness. The power system is a hybrid switcher locomotive that uses a SOFC power plant, ultracapacitors and lead-acid batteries. Miller *et al.* [52], on the other hand, found that a fuel cell yard switcher locomotive is better than using a hybrid fuel cell design. There is a low potential for recovery of regenerative braking energy and hybrid designs would be difficult.

2.3.5 Aerial Propulsion

Fuel cells are used in space and aeronautics sectors in small unmanned aerial vehicles (UAVs). UAVs are usually used for observation purposes. UAVs are widely preferred in the military sectors. PEMFCs are usually ideal for powering UAVs. Static operation and low heat emission are the benefits of UAVs over the internal combustion engine. One of the major advantages of fuel cells that makes it a good candidate to be able to use in a small-scale application is that its modularity. Bradley *et al.* [53] determined five different potential small-scale UAV propulsion systems. Kim *et al.* [54] concluded that for a long flight, UAVs is more efficient than battery- and combustion-based battery. The space industry is among the earliest to implement the fuel cell. In Japan, the fuel cell-powered high-altitude balloon was successfully tested [55]. During the 1960s, NASA

utilized PEMFCs and AFCs in their operated space explorations. Fuel cells are widely being used in space explorations because of the numerous advantages. The most attractive advantage is water being generated as a by-product of the electrochemical reactions where in space, air, water, and food are important [56, 57].

2.3.6 Marine Propulsion

APUs on-board boats and yachts are the most common fuel cell that is being used in the current marine propulsion market. There is a promising future for the fuel cell market in marine propulsion that still exists in marine transports such as submarines, boats, underwater vehicles, and cargo ships. For marine vehicles, low release, high productivity, and immobile operation are the benefits of fuel cells. On the other hand, problems related to reliability, wave resistance, life-span, and resilience to the salt present in the sea air need to be reviewed.

In the marine fuel cell market, PEMFCs, SOFCs, and MCFCs hold the most promising future. The first-ever certified hybrid PEMFCs/lead-gel batteries system for APU and propulsion were introduced and put in service in Germany in 2003. As compared to the conventional diesel-based ship, this ship has twice the efficiency. Adding to that, in 2009, a hydrogen fuel cell boat was established in Austria. The boat has a four-part propulsion system which are photovoltaic panels, an electrolyzer, a high-pressure hydrogen storage system, and a fuel cell. Water is broken down into hydrogen and oxygen in an electrolyzer using solar energy. In order to propel the boat, hydrogen is fueled into the fuel cell system.

In order to apply fuel cell system in marine environment, first, there are several challenges to overcome. For example, high power demand of the ships and salt water tolerance [58].

2.4 Micro Power

The fuel cell can be applied in mobile appliances such as phones and laptops, which help to increase battery life [60]. Direct methanol battery will opt for mobile appliances. Fuel cell is popular in telecommunication systems [61]. Some telecommunication companies such as Sony [62] have shown that fuel cells can enhance telecommunication equipment. As an example, they proved that equivalent sized phones that are powered with fuel cell has twice the capacity of a lithium battery. Fuel cell-powered laptops can operate 5 hours without recharging.

Telecommunication companies are using fuel cell energy as a back-up supply. In Indonesia, 400 fuel cell supplies have been set up. In Caribbean, 60 fuel cells have been set up. These actions are in order to provide green energy and to obtain advantages from the fuel cell system [61].

3.0 FUTURE TARGETS

The key targets of the fuel cell industry and solutions in achieving more advanced fuel cells that meet future targets are as follows:

- Encourage academic communities and industrial personnel to do research and development.
- Reduce the degradation of MEA.

Surprisingly, potential reason that cause corrosion of cathode catalysts layers are discovered and may be attenuate by ever-changing the planning of anode catalyst. By as well as further chemical element evolution reaction practicality into the catalyst layer, anodes may be protected from corrosion by cell reversal. Through such changes, Petch *et al.* [63] have exhibited large enhancements to the steadiness and sturdiness of MEA. Specifically, vital enhancements within the tolerance of cell reversal of MEAs with novel anodes are described.

- Electrolyte material that can conduct and stable over a wide range of temperature and humidity.

To produce stable electrolytes from rare earth elements doping has been done [64-66].

- No or little catalysts PGM loading.

A kinetic model of autocatalytic degradation for PGM-free catalysts was proposed by Shao *et al.* [67]. They observed a quicker current density drop at 0.84 V if a lower cell voltage of 0.7 or 0.4 V was first used in their study. This observation was caused by the effect of H₂O₂/radicals on catalyst stability.

- Membrane and catalyst that can tolerate impurities.

For hydrogen separation, catalytic membrane reactors were studied to identify hydrogen separation rates and separation factors because of its ability to be able to compare to those of Pd-based membranes. The membrane had a high resilience toward CO₂ and H₂S impurities [68].

- Design a bipolar plate with the reduced weight

To decrease the weight and size of a PEMFC, a new plan was used [69]. As compared to the metallic bipolar plate, graphite bipolar plates were used in the conventional types of PEMFCs. This is because graphite bipolar plates are weightier and larger than the latter.

The as-proposed novel cooling design can decrease the size of the cell by up to 75%, in addition, to efficiently cool the PEMFC than the graphite bipolar plate.

4.0 CONCLUSION

The overview paper presents an updated record of the fuel cell, specially specializing in its competing technology and its future targets. The latest records from enterprise and academia were used as a reference for the paper. Although there are boundaries, the enterprise will have the ability to conquer those and make certain the gasoline cells may be commercialized into the industrial marketplace.

The advancement of fuel cells has largely increased over the previous few years with an increment in intrigued through governments and a higher profile in terms of public intrigued. A supply chain is starting to improvement with a number of corporations working on the large-scale manufacturing of fuel cells and its components. A few have definitely opened factories dedicated entirely to fuel cells. But, the maximum brilliant highlight of the company is the kind of companies involved. Whether they see fuel cells as an opportunity for upcoming development or as a chance to their modern-day commerce, numerous researches have decided the case for fuel cells to be correctly compelling to begin making a funding with.

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