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Applications of proton exchange membrane fuel cell systems

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Abstract

Proton exchange membrane fuel cells (PEMFCs) have recently passed the test or demonstration phase and have partially reached the commercialization stage due to the impressive worldwide research effort. Despite the currently promising achievements and the plausible prospects of PEMFCs, there are many challenges remaining that need to be overcome before PEMFCs can successfully and economically substitute for the various traditional energy systems. With the many promising research efforts in overcoming these challenges, the most important tools for the commercialization of PEMFCs will be the technical data and information from a real PEMFC application test. For these reasons, this paper introduces and discusses the remaining challenges and some of the latest research on the application test of PEMFC to real systems such as transportation, residential power generation and portable computers. In addition, this paper describes and summarizes the relative prospects and the competitive force of PEMFCs in these fields.

These prospects primarily depend on stable and economical high-purity hydrogen supplies, the scale of application, the existence of more efficient competitive power sources and the social viewpoints such as the health and environment benefits as well as infrastructural aspects associated with traditional power supply and demand. The review shows that PEMFC have the most promising applications to buses, recreation vehicles, and lightweight vehicles. Without doubt, the technology

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for a stable supply of high-purity hydrogen along with the corresponding infrastructure is essential for the success of PEMFC in various application fields.

Keywords: Proton exchange membrane fuel cell; Application; Fuel cell vehicles; Stationary power supply; Portable computer; Hydrogen energy

Contents

1. Introduction

Since the applications of proton exchange membrane fuel cell (PEMFC) systems were initially reported in the New Generation of Vehicles program (PNGV) in the US in 1993 [1], it has taken more than 10 years to reach the current test-phase or partial commercializing stage. In April 2005 in Monaco, five kinds of powered cars with an on-board PEMFC system introduced by GM, Hyundai, Daimler-Chrysler, etc. ran in a road rally and covered a distance of approximately 410 km through Switzerland. In this rally, one re-fuelling stop was allowed for the fuel cell vehicles (FCV) and the journey time was approximately 6 h. The rally was successfully completed to a certain extent. This rally clearly showed the present status of the applications of PEMFC to the FCV field.

PEMFCs have a many advantages such as a low operating temperature, sustained operation at a high current density, low weight, compactness, the potential for low cost and volume, long stack life, fast start-ups and suitability for discontinuous operation [1–9]. These features make PEMFCs the most promising and attractive candidate for a wide variety of power applications ranging from portable/micropower and transportation to large-scale stationary power systems for buildings and distributed generation. For these reasons, many companies including fuel cell technology (Ballard, UTC, Nuvera, GE-FCS, Plug Power, Intelligent Energy, NovArs, Smart fuel cell, Toshiba, Sanyo, and Hydorgenics), automobile

(Daimler-Chrysler, Ford, Renault, Toyota, Nissan, GM, BMW, Hyundai), and electricity (NTT, Sanyo, Samsung and IBM) have announced various applications, new technologies, and prototype vehicles using on-board PEMFCs [10–15]. In addition, many technologies utilizing PEMFC for different applications are currently under development [7,16–18], and are soon expected enter the market in force worldwide [19,20].

However, despite the promising achievements and plausible prospects of PEMFCs, the remaining problems mean that it is still long way before they can successfully and economically replace the various traditional energy systems. Furthermore, despite the many promising results, the most important tools for the commercialization of PEMFCs are the technical data and information on a real PEMFC application test. Unfortunately, there is very little published data or information on the PEMFC in real application fields. Many fuel cell companies in the world have patented their accumulated experience and technologies for their own benefit. Because the world is faced with energy problems and environmental pollution, it is essential to share information and data regarding these technologies in order to bring on full commercialization quickly.

This review introduces and discusses some of the remaining challenges and some cases of the latest research on the application tests of small and middle ranged (power range from 30 to 50 kW) PEMFCs to real systems such as transportation, residential power generator (RPG), and portable computers. In addition, this paper describes and summarizes the relative prospects and the competitive force of PEMFCs in these fields. This review discusses the papers published since 2001, which is expected to provide useful and helpful information on the development of PEMFC technologies.

2. Review of the remaining challenges for the commercialization of PEMFC

PEMFCs have recently passed the demonstration phase and have partly reached the commercialization stage on account of the rapid development and an impressive research effort worldwide. However, the remaining challenges that need to be overcome mean that it will be several years before full commercialization can take place. While each challenge has been focused on differently according to each application, there are three main challenges that are common to each application. These are a stable supply of high-purity hydrogen, cost reduction of the system and various technological problems.

2.1. Stable hydrogen supply with high purity

For the full commercialization of PEMFC system, a stable supply of high-purity hydrogen is essential. However, this is little available today and it has been repeatedly disputed on this challenge for a long time. There may be two issues related to this problem. One is the technological (or economical) point and the other is the social.

Traditionally, hydrogen is technologically produced by the steam reforming of hydrocarbons such as natural gas or by coal gasification. However, these methods cause the inevitable CO_2 emission, which can lead to greenhouse effect. In addition the production of CO can cause serious poisoning of the anode electrocatalysts in PEMFC. It is also important to develop the safer and more efficient hydrogen storage system than the traditionally used systems such as tank, metal hydride and chemical hydride.

The other issue is the social viewpoint. Hydrogen will not be accepted as an existing energy system by the end user due to the lack of infrastructure and uncertain safety regulations. This issue will only be a barrier to the application of RPGs. On the other hand, it would not be a primary issue in the automotives and portable application fields.

Therefore, some researchers are pessimistic about the future of the PEMFC technology. The technological issue needs to be addressed because this is a more important and decisive matter regarding the future of PEMFCs. If this not overcame, there is the probability that PEMFC will lose the various application fields to other types of the fuel cell systems such as a molten carbonate fuel cell (MCFC), a solid oxide fuel cell (SOFC), a direct methanol fuel cell (DMFC), and a direct borohydride fuel cell (DBFC) [21] as well as the battery systems.

To address the technological problem, there have been many studies on high-purity hydrogen producing technology including the water electrolysis using the electricity from wind turbines and solar cells. While this idea appears to be nonsense in the point of energy efficiency, Jacobson [22] reported the economical and social benefits on using the hydrogen fuel cell vehicles (HFCVs). In this report, the authors evaluated the cases where converting all US on-road vehicles to HFCVs might improve the air quality, health, and climate significantly, regardless of whether the hydrogen was produced by the steam reforming of natural gas, wind electrolysis, or coal gasification. According to the literature, HFCVs powered by hydrogen produced by electrolysis using the electricity from wind energy could offer the greatest potential health benefits and could save 3700–6400 US lives annually. Therefore, they claimed that the real cost of hydrogen production from wind electrolysis may be less than that of US gasoline. However, this result is available only for the FCV field within the US, and with the exception of health benefits, this technology is not practical.

Irrespective of these health benefits, Lee et al. [23] carried out an economic feasibility study of producing hydrogen using the excess electricity from wind turbines on the large Island of Hawaii. While it was technically feasible to produce hydrogen using wind energy in this area, wind-produced hydrogen was not cost competitive with gasoline or oil to-date in Hawaii, as shown in Table 1. The price of the hydrogen produced by this program was more than twice that produced by methane reforming.

Besides using wind turbines, recent developments in PEMFC are also beginning to produce hydrogen from solar electric power systems [24–28]. Shapiro et al. examined a PEMFC system with on electrolyzer activated by a solar electric power system [24]. Their system concept was shown in Fig. 1.

Table 1
Hydrogen cost comparison [23]

Process of hydrogen production	Hydrogen price ($/kg)	Hydrogen price ($/kWh)
DOE's goal (By 2010, at plant gate, untaxed, no compression, no storage)	2.5	0.075
Captive hydrogen from natural gas (at $5.00/MMBTU natural gas, no compression or storage)	1.67–1.93	0.05–0.06
Current wind-hydrogen costs on Big Island of Hawaii (at plant gate, untaxed, no compression or storage)	3.95–5.20	0.12–0.16
Hawaii's gasoline price (equivalent) (at $2.73/gal; including taxes and cost of delivery)	2.48 (equivalent)	0.075 (equivalent)

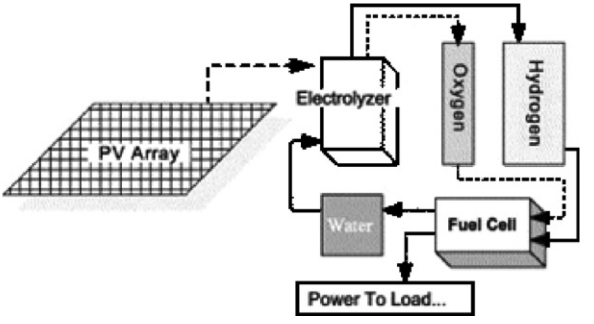

Fig. 1. Regenerative photovoltaic electrolyzer/fuel cell system [24].

According to this paper, further studies on areas such as the electrolyzer design and energy flow will be needed to develop a more efficient system. In these types of technologies, an efficient electrolyzer system would be the key factor. Therefore, recent developments towards a more efficient and economical electrolyzer system for PEMFCs have been made worldwide [29–33].

Finally, considering the social and health benefits on using PEMFC, it is desired that there should be more focus on developing hydrogen production technology such as electrolyzing water using excess electricity from wind turbines or solar cells.

2.2. Cost reduction of PEMFC system

Currently, the total cost of a PEMFC is approximately 500–600\$/kW [34]. When a car is made using this system, the total cost of the FCV is 10 times that of a traditional car with an internal combustion engine (ICE). The cost of a typical PEMFC is made up of the cost of the membranes, platinum, electrodes, bipolar plates, peripherals and the assembly process. Among them, the costs of the bipolar plate and the electrode including platinum make up approximately 80% of the total cost of a PEMFC. In order to reduce the cost, it is natural that there be a more efficient and economical development of each component in a PEMFC.

Tsuchiya et al. [34] reported the cost structure of PEMFC and the possibility of its reduction by mass production of PEMFC using the learning curve analysis Their references for analysis were based on the following case: the typical performance of a single fuel cell has a 0.6–0.7 V and 0.3–0.6 A/cm^2 cell current density, which equates to a power density of 2 kW/m^2 or more. However, the stack performance is lower than that of a single cell. If an automobile has a 50 kW rated output, then the cell area for 2 kW/m^2 of power density will need to be 25 m^2, i.e. 278 cell layers with 30 cm $\times$ 30 cm cell area. In this case, the power density is expected to increase to the level of 5 kW/m^2 or more. According to their analysis, cost reduction to the level of an ICE is possible with mass production. However, the analysis of cost structure showed that the bipolar plates and MEA still make up a large proportion of the stack cost even at the mass production stage. Therefore, there should be greater emphasis on research aimed at reducing the cost of these two components [35–45]. In addition, there should be more effort focusing on alternative proton-conducting membranes, which are less expensive but have similar proton conductivity to perfluorosulphonic acid membranes.

2.3. Remaining technological problem

Besides the aforementioned hydrogen supplies and the cost of PEMFC, there are still some technological problems remaining in a PEMFC system. They include water and thermal management, scale-up from single cells to cell stacks, flow fields, fuel processing, CO poisoning of the platinum anode electrocatalysts, the MEA structure and the overpotential of cathode electrocatalysts [1,5]. However, considering the status of PEMFC technologies, these technological problems are expected to be solved in the near future.

3. Review of PEMFC application and its prospect

Basically, fuel cells have been investigated as an innovative system that can be integrated with traditional electrical power plants or to supply electricity as on-site power generators [6]. However, according to the development of industrial and social structure, the diverse applications of fuel cells have been the main focus. While there are several fuel cell types with features applicable to certain fields, PEMFCs are the most promising system in terms of energy efficiency and compactness. Therefore, in recent years, many studies on PEMFC technology and its application have been worldwide.

Generally, there are three main application fields for a PEMFC system such as transportation, stationary and portable applications. The development direction of PEMFCs in each nation is bound up with their social and industrial environment as well as their structure of energy supply and demand. Therefore, the US and Japan have

Table 2
Various application test of PEMFC on-board reported since 2002

Application	Function	Power	Fuel	Comments	Reference
Hybrid power bus	Power supply	50 kW	Compressed hydrogen in cylinder	Efficiency: 40%, Mean power consumption: 17–24 kW	[50]
Powered bicycle	Power supply	300 W	Hydrogen stored in the metal hydrides	Efficiency: 35%, Distance-to-fuel ratio: 1.35 km/g	[51]
Lightweight powered vehicle	Power supply	5 kW	High pressure gaseous hydrogen in cylinder	Drive over a 100 km run at a speed of 18 km/h	[52]
Sailing yacht	APU (auxiliary power units)	300 W	Hydrogen produced by LPG via a series of processor on-board system	Used as auxiliary power units using bottled LPG as fuels	[53]
Stationary power generator	Power supply	5 kW	Commercially available 15 MPa hydrogen cylinder	Efficiency: more than 30% in fully loaded operation. Operated 3 h at 5 kW with two 50 liter hydrogen cylinders	[61]
Uninterrupted power supply	Power supply	2 kW	Hydrogen produced by methanol via fuel processing	Total cost was strongly dependent on the service time.	[62]
Portable computer	Power supply	46 W	Hydrogen stored in the metal hydrides	Trouble-free start-up of the portable computer	[68]

concentrated on the application field of FC cars, and the EU has directed their attention to the FC buses and trains. On the other hand, there have been RPG applications in Japan and the FC bicycle or lightweight FC car in China. Table 2 shows the advantages and disadvantages of PEMFC in each application as well as the results of the application tests carried out in the world since 2002.

3.1. Transportation

Among the many applications of PEMFCs, transportation is the most competitive and promising. In addition, people could easily see the potential of this promising alternative technology through the development of environment-friendly vehicles. Therefore, the success of PEMFC in this field might be the most important factor to provide an incentive for expanding their applications to the other fields. The development of a FCV requires the on-board integration of a fuel-cell system and electric energy storage devices, with an appropriate energy management system. In order to meet the future transportation needs, most major carmakers in the world are actively engaged in developing prototype FCVs and assessing their performance. In order to evaluate the FCV on-board PEMFC, it is important that their driving test be conducted according to a standard duty (driving) cycle, which includes reiteration such as stop, acceleration, cruising, start, and brake.

The most important factor for the success of a FCV is the success of the hydrogen economy and its related technology. McNicol et al. [46] reported that a FCV system equipped with direct-conversion fuel processor could compete successfully with conventional ICE vehicles because there is every prospect that the performance regarding hydrogen would exceed that of an ICEV in all aspects except for the initial cost. This report shows that the development of FCV should be currently carried out on buses, and recreation vehicles (RV), which have more space to house the fuel processor than passenger cars.

The present and future specifications of PEMFC for FCV can be explained by the technology roadmap [47], which was published by Ballard in May 2005. This roadmap set out trends and targets in four areas that are critical for the commercial adaptation of automotive PEM stack technology: durability, cost, freeze-start and volumetric power density. The main targets of the roadmap are:

- A lifetime of 5000 h by 2010. Ballard already demonstrated a durability of more than 2200 h in simulated testing.
- A stack cost of US$ 30/kWe net at a volume of 500,000 units.
- A freeze-start capability down to $-30\,^{\circ}C$, reaching 50% of the rated power in 30 s.
- A volumetric power density of 2500 W net/l.

Despite the positive prospects of this FCV field, some analyses indicate the hybrid car, which is a PEMFC-based Ni-MH battery or Li-ion battery system, is more efficient than a pure FCV [48]. Demirdöven et al. [49] compared the energy efficiency of hybrid and FCV as well as conventional ICE vehicles in 2004. They reported that FCV using hydrogen from fossil fuels offered no significant energy efficiency advantage over hybrid vehicles operating in an urban drive cycle. They also claimed that it is unclear if the efforts made to develop economic FC power plants for passenger cars would be successful. Therefore, they suggested that priority be placed on deploying hybrid cars than an exclusive FCV.

Considering the current status of PEMFC technology, this may be true to some extent and a PEMFC-based hybrid car could be main area of the transportation market in the future.

3.1.1. Powered buses

In 2003, Folkesson et al. [50] evaluated hybrid urban FC Buses achieved by the Clean Urban Transport for Europe (CUTE) project, and addressed the questions regarding the necessary infrastructure. The aim of this project was to design and build a demonstration vehicle in the shape of a hybrid FC Bus. The project was supported by funds from the EU's Non-nuclear energy (Joule) program with several companies and institutes being involved as partners or participants. The fuel cell system had a designed maximum power output of 50 kW. The fuel was compressed hydrogen and the oxygen used in the fuel cell was compressed ambient air. An integrated dc/dc converter adjusted the fuel cell output voltage with the voltage of a common power bus (600 V). The bus was 9.2 m long, 2.5 m wide and 3.2 m high and had capacity for 15 seated and 37 standing passengers. The propulsion system was located in the rear end of the bus, as shown in Fig. 2.

The whole system, including the fuel cell system, battery, wheel motors and power electronics and auxiliaries could be easily removed from the rest of the bus. They claimed this simplified the servicing and other work on the system. The heart of the fuel cell system was a stack module containing two PEMFC stacks. Each stack contained 105 cells. The stack assembly components were metallic. Its dimensions were 58 cm height, 42 cm width and 57 cm length, giving a total volume of 139 l. This system had a power density of approximately 0.2 kW/l.

The performance of their FC was tested on the road in northern Spain. All the tests were performed with the bus loaded with external weights making a total weight of 12,500 $\pm$ 25 kg. As a result, the mean power consumption was approximately 17–24 kW during the test duty cycles. They claimed that this performance meant that a fuel-cell system with a nominal power output of approximately 35–50 kW is adequate for a full size (12 m) hybrid electric city bus, even with a 20–25 kW air conditioning system installed. The net efficiency of the fuel-cell system was approximately 40% and its fuel consumption was between 42% and 48%, which is lower than a standard Scania ICE bus. In addition, bus subsystems such as the pneumatic system for door opening, suspension and brakes, hydraulic power steering,

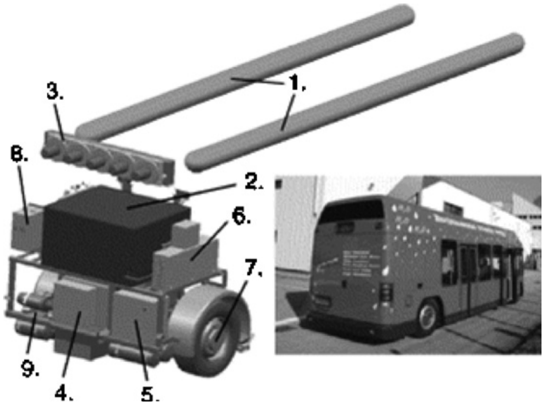

Fig. 2. The propulsion system located in the rear of the bus [50].

water pump and cooling fans consumed approximately 7% of the energy in the fuel input or 17% of the net power output from the fuel-cell system. From these results, the authors claimed that FC Buses have great potential. However, but there are still many issues to consider before the full-scale commercialization of this technology, which are related to durability, lifetime, costs, vehicle and system optimization as well as subsystem design.

3.1.2. Electric powered bicycle and lightweight vehicle

In 2004, Hwang et al. [51] published the test results of a prototype of electric bicycle powered by a PEMFC. The motive of their research target was that powered bicycles are commonly used on a daily basis for commuting in Taiwan and China. The fuel cell system consisted of a fuel-cell stack, metal hydride canisters, air pumps, solenoid valves, cooling fans, pressure and temperature sensors, and a microcontroller (Fig. 3).

The stack consisted of 40 cells with a nominal and peak power of 303 W (0.7 V) and 378 W (0.66 V), respectively. The stack not only drives the electric motor of the bicycle but also powers other sub-systems. With this powered bicycle, two types of tests were undertaken, the roller-stand test and the road test. In the roller-stand test, the maximum speed was approximately 25.2 km/h and the stack temperature varied from 30.0 to 31.9 °C. In general, the system displayed reliable operation without failure during the 1-h test. In the road-test, the bicycle underwent a 2.5 km run with a maximum speed of 16.8 km/h. According to the authors, the efficiency of the fuel-cell system reached up to 35%, which was significantly higher than that of an ICE, and a total of 6.8 g hydrogen covered the driving distance of 9.18 km, meaning that this electric bicycle has a distance-to-fuel ratio of 1.35 km/g. Based on these results, they are ready to commence the development of a two-seater, lightweight FCV. Despite their successful work, they did not address the economic and technological problems.

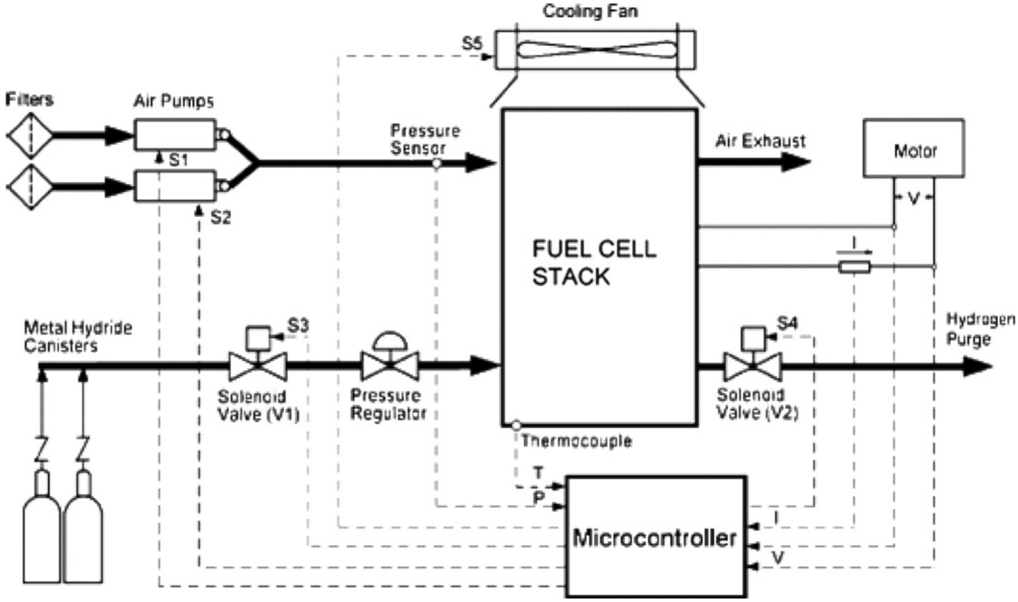

Fig. 3. Fuel cell systems for an electric powered bicycle [51].

Fig. 4. Driving test for a lightweight vehicle [52].

In 2005, the same working group also published a paper [52] describing the development of a lightweight vehicle on-board a 5-kW PEMFC. This vehicle was made by applying their accumulated technology from earlier work. Therefore, the structure and the characteristics of the system were similar to those of their earlier work. The authors conducted a road test involving a 1.6 km-run with this vehicle, as shown in Fig. 4.

The speed was kept to approximately 18 km/h without any failure during the 1-h test. They claimed this indicated the satisfactory stability and reliability of the present system to some extent. However, they claimed additional research would be needed to improve the performance such as speed enhancement, acceleration and fuel efficiency or hybridizing with a battery pack.

3.1.3. *Powered leisure yachts*

In 2005, Beckhaus et al. [53] evaluated a 300 W PEMFC system for liquid gas-powered operation with their main focus on leisure yachts. They specifically focused their application to sailing yachts because the consumption of electrical power is quite restricted during long cruises due to the low battery capacities. In this case, an additional power supply based on noiseless fuel cell technology promises an essential increase in comfort without any disturbing emissions. In addition, they claimed that most auspicious and promising markets for fuel cells are the leisure range and hobby applications. In these markets, they also suggested that the end user would be willing to spend more money for modern technologies giving him additional value, higher comfort or increased enjoyment. In the field of leisure applications, the use of bottled liquid petroleum gas (LPG) is widespread. Consumers use LPG mainly for camping, caravanning, sailing, yachting and other remote applications. This means that there is outstanding infrastructure for this fuel worldwide. Therefore, the authors concentrated their efforts on the development of small power supplies for leisure applications such as auxiliary power units (APU) running on liquid gas. This is the most important concept in this paper.

Their APU consists of a multi-stage gas processor to produce a hydrogen-rich gas such as a de-sulphurization unit, reformer, shift reactor, CO-purifier, a fuel cell stack, and the necessary peripheral components, as shown in Fig. 5.

In this paper, they also described the technological aspects of their system such as the system concept, installation, structure, and components. However, they did not describe

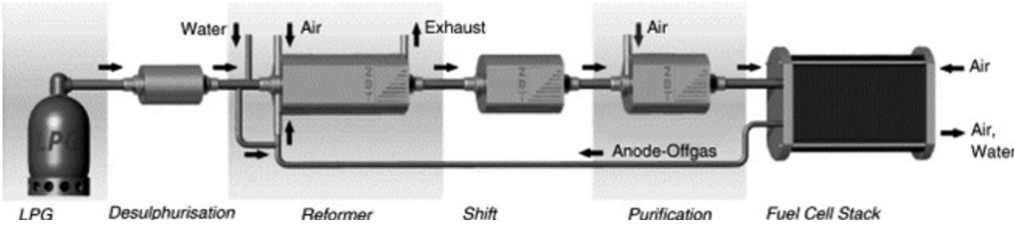

Fig. 5. Fuel cell systems for a leisure powered bicycle [53].

the detailing performance of their system. Instead, they claimed it would be conducted via a real cruise with a technical consortium in the near future.

3.2. Stationary application

In general, due to aforementioned advantages of PEMFC, it is known that PEMFC technology is one of the more favorable candidates for a main or APU in the field of a stationary power plant or RPG. However, this application of PEMFC appears to be even less promising and more restricted than the field of FCV applications. Besides the challenges of high-purity hydrogen and its supplies and storages systems, this could be also attributed to the features and quick development of other types of the fuel-cell systems such as a MCFC [54–56] and a SOFC [57–59]. Despite their low energy efficiency, MCFC or SOFC are currently believed to be one of the best technologies for stationary applications for reasons such as the use of a more available fuel such as methane than pure hydrogen [6,60]. Their development has improved as much as the PEMFC system. However, current research into PEMFC is aimed at producing an even higher electric conversion efficiency, compactness and lightweight. Therefore, considering the present status and technology on various fuel cell type, research on PEMFC in this field should be concentrated on small power range (1–5 kW) uninterrupted power supplies (UPS) or APU systems than can be used for middle or large-scale powered applications. However, if the economical and efficient technology for stable hydrogen supplies with a high purity can be achieved, the PEMFC system would be the most promising candidate irrespective of scale due to their even higher energy efficiency.

3.2.1. Stationary power system

In 2005, Wang et al. [61] reported the development of the key components, specifications, configuration and operation characteristics of a 5 kW H_2/air PEMFC system for a stationary power generator. The specification of their PEMFC system was similar to traditional PEMFC systems. They consisted of a 5 kW stack consisting of 56 cells with an active area of 250 cm^2 per cell. The MEA was comprised of a Nafion membrane with a catalyst layer containing 0.4 mg/cm^2 platinum loading on each side. Membrane electrode assemblies were made by using a hot press method at 135 °C. Bipolar plates were made of graphite plates with a modified surface. An external humidification system was used. The cooling system comprised of a number of cooling plates through which water was circulated. The current was drawn from the stack at two metal plates placed at opposite ends of the stack. Two-glass epoxy plates bolted together with tie rods held the stack together. Fig. 6. shows the appearance of their stationary power system. The

Fig. 6. Appearance of the 5 kW PEMFC stationary power system [61].

system comprised of a fuel cell module, water management, heat management, reactant gas feeder, power converter (which converts the DC power generated by the fuel cells to an AC output), and a controller, which controls the system as a whole.

With this system, they carried out a performance test under various conditions. The startup at room temperature was less than 1 min. The operating time at 5 kW output with two 50 l hydrogen cylinders was approximately 3 h. The generation efficiency in a fully loaded operation was $>30\%$. In addition, the authors reported that, as anticipated during the design stage, the power source has a superior performance than conventional ICE generators. However, the authors also reported that future studies should be aimed at developing the traditionally known as problems such as CO tolerant anode electrocatalysts with low Pt loadings, an increased cell operating temperature and improved exhaust gas quality.

3.2.2. UPS system in mobile phone station

In 2005, Lin et al. [62] described the application of a 2 kW PEMFC to a UPS system used in a mobile phone base station. According to the authors, there are more than 25,000 base stations constructed by six local telecommunication companies in Taiwan. Interruptions of the electricity supply due to typhoons, earthquakes, and floods, which frequently occur in Taiwan, are a severe threat to the uninterrupted service of mobile phones. Telecommunication companies usually use lead-acid batteries to extend the service time during blackout periods. However, these battery systems make it impractical to extend the UPS service time from currently 2 or 4 to 8 h. Therefore, they attempted to apply a PEMFC as UPS system fueled by methanol processing. They evaluated the performance of their system by comparing the device cost, the module weight, module volume and energy expense of both the battery and PEMFC system, as shown in Fig. 7.

According to the paper, the difference in the total cost of both systems was strongly dependent on the service time. This means that the fuel cell model was more expensive than

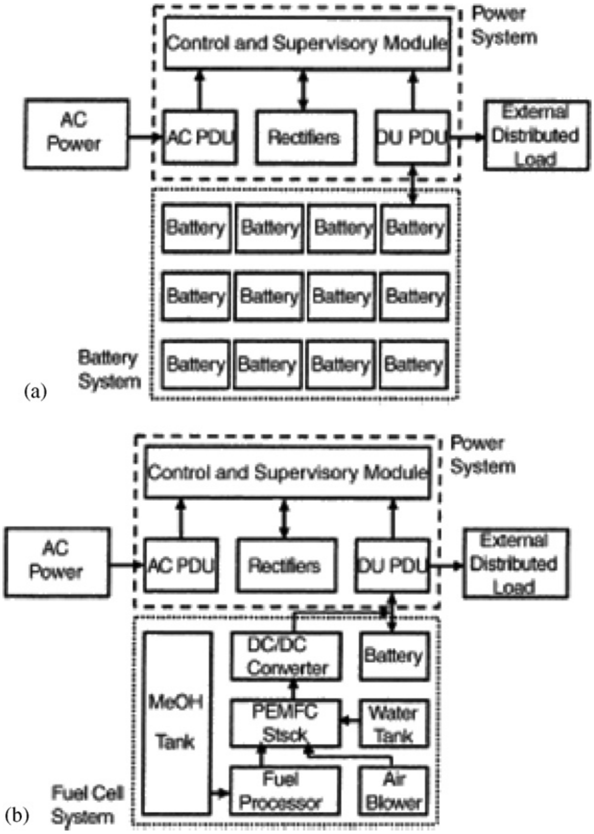

Fig. 7. Simplified schematic diagrams of the energy system used in mobile phone base stations: (a) conventional battery model; (b) fuel cell model [62].

a battery model within 2 or more service time. However, they claimed if the service time was 24 h, then the total device costs of both systems were almost identical. At a longer service time, the fuel cell model becomes cheaper. However, they did not describe the detailing methanol reforming and the deterioration of the cell performance during operation.

3.3. Portable communication

Because of the aforementioned features of PEMFC, it is well known that a PEMFC system has the potential to complement or to substitute for batteries and would be a future technology for a mobile or potable power supply [63]. However, there are a few negative opinions regarding the competition of PEMFC with traditional batteries in this market. These opinions are primarily attributed to two reasons. One is the challenge of a safe hydrogen supply used as liquefied fuel for portable applications. The PEMFC, the alkaline fuel cell (AFC) and the phosphoric acid fuel cell (PAFC) require gaseous hydrogen as a fuel. However, hydrogen storage technologies are required to match practical needs as described earlier. Compressed hydrogen is believed to be a feasible solution to vehicle applications but is not suitable for portable devices on account of its lower volumetric energy density and insufficient space to store it. Moreover, it is generally not possible for user to carry it.

Therefore, the use of liquid or solid fuel is believed to be the solution. However, liquid or solid fuels usually require a fuel modification process, which makes the systems more complicated. A DMFC, using methanol as the fuel, is believed to be a promising candidate for portable and mobile applications. However, its low performance and the methanol crossover are the hurdles for its practical uses. The DBFC is also believed to be a potential system for this field but it also has problems such as the high cost of borohydride and the treatment of by-products during the operation in an anode electrode.

Another reason for the negative opinion is perhaps due to the rapid development of Li-based battery technology and its current success in powering laptop computers, mobile phones, etc. The requirement for a higher energy density, higher specific energy or longer operational time between recharges is generally well served by Li-ion and Ni-based batteries especially those based on metal hydrides. Many researchers involved in the development of fuel cells should focus on this battery technology.

On the other hand, there are also many positive opinions for the PEMFC prospects in this field. According to these opinions [63], in the current portable appliance market, there is growing pressure on battery manufacturers to further increase the energy density for the next generation of portable electronic equipment, which will require a much higher energy density in order to make the equipment conveniently portable. This is not just due to marketing and product differentiation. It is a technological requirement for high bandwidth applications that demand much more power. The situation becomes critical as mobile phones and laptop computers merge to provide users with broadband wireless and multifunctional portable computing capability. Although battery researchers will disagree, battery technology is unlikely to keep pace with these growing power demands, and laptop equipment manufacturers are already being faced with the need to introduce various power-down options to save battery energy. In addition, according to various reports [63,64], the potential growth rate and an annual market size for portable electronic equipment with a high power source is expected to reach up to a 40% per year and in excess of $10 billion, respectively. While I partly agree these viewpoints, there is another important factor to be considered. That is the rapid development of various low-power-consuming electronic devices and more energy-saving equipment in portable applications [65–67].

3.3.1. Portable computer

In 2002, Tüber et al. [68] evaluated a PEMFC power system for a portable computer, as shown in Fig. 8. The systems consisted of four-cell PEMFCs, a six-phase DC/DC-converter, an air pump, two cylindrical metal hydride storage tanks, a valve and a pressure sensor to adjust the hydrogen flow and a control unit to manage the whole system.

The main characteristics of the system were a flat, large area and self-humidifying stack consisting of four cells and a directly integrated, high-efficient six-phase DC/DC-converter for low input voltages. This structure is quite efficient for portable computers. The system was operated using ambient air, dry hydrogen supplied by metal hydride storage tanks, and there was no active cooling. A control unit regulated the airflow rate and the hydrogen pressure during operation, and realized a controlled start-up and shutdown of the fuel cell. The air pump that feeds the cathode with air could provide a gas flow rate of up to

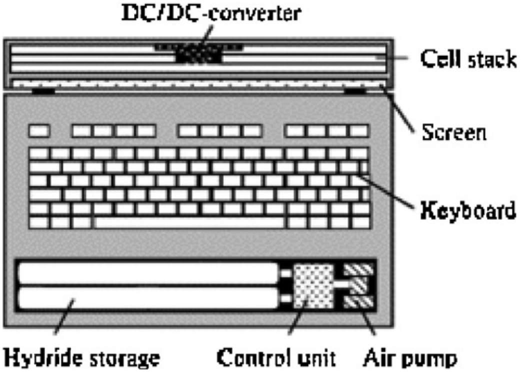

Fig. 8. Schematic top view of the PEM fuel cell power system [68].

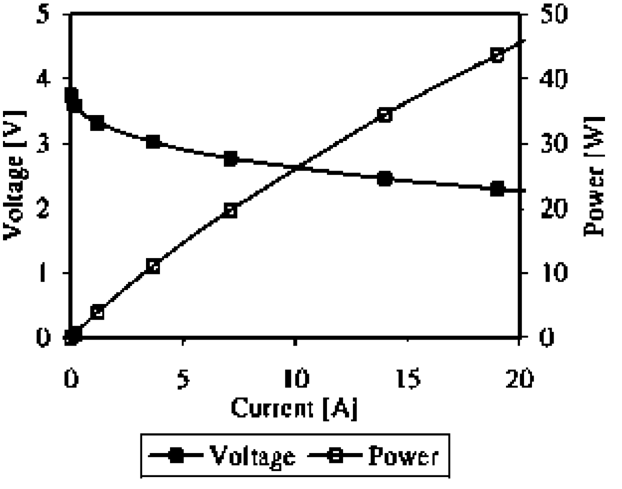

Fig. 9. Polarization characteristics of the PEMFC system for a portable computer [68].

5000 ml/min depending on the voltage applied (0–12 V). The two cylindrical metal hydride storage systems had a total capacity of 46 standard liters of hydrogen corresponding to an electrical energy output of approximately 70 Wh (assuming a system efficiency of 50%). In comparison with the original lithium-ion-battery module, this would result in a 50% increase in operating time. Prior to applying their system to a portable computer, the experimental measurements such as the effects of the flow field design and flow field combination as well as the effects of the relative humidity of the air and air flow direction were examined. As a result, the use of meandering flow fields with an outwards-vectored flow direction was found to be the optimum condition. The PEMFC system was then connected to the external power input of the laptop and the computer was used. Their system performances are shown in Fig. 9.

The open-circuit voltage of the four-cell stack was approximately 3.8 V and the polarization slope declined in a characteristic way down to approximately 2.3 V where a maximum current of 20 A of the electric load was reached. The power obtained at this stage was approximately 46 W. With an efficiency of more than 90% of the realized six-phase step-up DC/DC-converter, this was equal to a power output >42 W at 12 V. They claimed that subtracting the additional power required for the peripheral devices such as the pump and control unit (maximum 4 W), the total PEMFC system ensured a trouble-free start-up of the portable computer. In addition, they also reported that further steps should to be taken to miniaturize the peripheral system components (This appears to be most important issue for the success of this project), improve mechanical compression to minimize the electrical resistance of the fuel cell stack, directly integrate the electrical conversion into the internal power supply structure of the computer, and improve the long-term operation to examine the life cycle of a PEMFC system.

4. Conclusions

Table 3 summarizes the prospects of PEMFC technology considering their current status and a review of the latest research on their applications.

There are several issues to be solved before PEMFC can be properly commercialized. The first is the stable and economical supply of high-purity hydrogen. The second is on the scale of the application object, i.e. whether there is sufficient space for satisfying the first issue. The third is the existence of more efficient competitive power sources than the PEMFC system. The fourth is social viewpoints such as the health and environmental benefits as well as the infrastructural aspects of traditional power supply and demand.

Table 3
Relative prospects of PEMFC in various applications based on the current status of PEMFC technology

Application	Prospect	Main reason	Competition	Comments
Transportation				
Bus, RV, Lightweight vehicle	The most positive	More space for equipment of the fuel processor	None	PEMFC-based hybrid system desired
Passenger car	Positive	Health benefits for people	ICE-based hybrid system without PEMFC	PEMFC-based hybrid system desired
Powered bicycle	Less positive	Inconvenient for hydrogen supplies	Battery	Batteries or hybrid system desired
Leisure applications, (Sailing yacht)	Positive	Bottled LPG is wide spread	DMFC, DBFC	Used as a APU
Stationary				
Stationary power generator (middle scale)	Less positive	Challenge of stable hydrogen supplies with high purity	MCFC, SOFC	MCFC, SOFC desired
Uninterrupted power supply (small scale)	Positive	Possible for long blackout periods	Battery	Hybrid system desired
Portable				
Portable computer	The least positive	Impossible hydrogen supplies as the liquid	Batteries, DMFC, DBFC	DMFC or DBFC desired

In conclusion, considering these issues, buses, RV, lightweight vehicles powered by PEMFC are the most promising applications. Without doubt, the technologies of a stable supply of high-purity hydrogen and their associated economical system are a prerequisite to any other challenge. However, because this is not yet available, a PEMFC-based hybrid system should be used as the main substitution for traditional power sources in the near future due to their unique and relative advantages.

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