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Review

A feasibility study on direct methanol fuel cells for laptop computers based on a cost comparison with lithium-ion batteries

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Abstract

This paper compares the total cost of direct methanol fuel cell (DMFC) and lithium (Li)-ion battery systems when applied as the power supply for laptop computers in the Korean environment. The average power output and operational time of the laptop computers were assumed to be 20 W and 3000 h, respectively.

Considering the status of their technologies and with certain conditions assumed, the total costs were calculated to be US$140 for the Li-ion battery and US$362 for DMFC. The manufacturing costs of the DMFC and Li-ion battery systems were calculated to be $16.65 W^{-1}$ and $0.77 W h^{-1}$, and the energy consumption costs to be $0.00051 W h^{-1}$ and $0.00032 W h^{-1}$, respectively. The higher fuel consumption cost of the DMFC system was due to the methanol (MeOH) crossover loss. Therefore, the requirements for DMFCs to be able to compete with Li-ion batteries in terms of energy cost include reducing the crossover level to at an order magnitude of −9 and the MeOH price to under $0.5 kg^{-1}$. Under these conditions, if the DMFC manufacturing cost could be reduced to $6.30 W^{-1}$, then the DMFC system would become at least as competitive as the Li-ion battery system for powering laptop computers in Korea.

Keywords: Direct methanol fuel cells; Lithium-ion batteries; Manufacturing cost; Energy consumption cost; Specific energy; Energy density

Contents

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1. Introduction

In today's ubiquitous networked society, the market for portable and microelectronic devices such as laptop computers, cellular phones, and personal digital assistants (PDA) is certain to experience continued growth. In addition, new technologies regarding mobile communication and mobile internet are being developed very quickly and synergistically. For example, from the middle of 2006 Korea began to provide high-speed, wireless, commercial internet services in Seoul based on wireless broadband (WiBro) with speeds up to 1 Mb for devices traveling at up to 60 km h^{-1}. In addition, a digital multimedia broadcasting (DMB) service, consisting of technology that enables people on the move to enjoy crystal-clear video, CD-quality audio and data via cellular phones or laptop computers for free, has already been locally supplied.

In 2007, Korea has become the first country to establish a working commercial high speed data packet access (HSDPA) service, based on a platform similar to wideband-code division multiple access (CDMA), which allows download speeds of up to 14.4 Mb s^{-1} and upload speeds of 2.3 Mb s^{-1}. This service enables video conferencing between callers on the HSDPA phone.

However, the current power supply systems in portable or wireless appliances are mostly rechargeable lithium (Li) and nickel (Ni)-based battery systems. Especially with the rapid development of Li-based battery technology over the last decade, this system has succeeded in dominating supply applications in traditional markets such as laptop computers, mobile phones and PDAs, as well as in next generation portable electric devices. Indeed, it is estimated that about one billion packs of Li-ion batteries for powering cellular phones and laptop computers were sold worldwide in 2006, rising to expected sales of about 1.9 billion packs in 2008.

However, as aforementioned, the rapidly advancing needs for mobile communication and mobile internet services are increasing the consumer demand for portable appliances with even higher power output, longer operational time, smaller size and lighter weight. For example, faster CPUs, higher resolution displays, wireless connectivity and other advances all increase the demands on power supply. Li-ion or other rechargeable battery systems are not suitable for high power and long time span portable devices due to their lower energy density, shorter operational time and safety [1–9].

With these shortcomings, many fuel cell researchers have claimed that direct methanol fuel cells (DMFCs) have the potential to complement or substitute for Li-ion batteries and represent the future technology for portable-power supplies. However, Li-ion battery researchers might disagree with these predictions due to the likelihood of Li-ion battery technology keeping pace with the growing power demands, and various low-power-consuming electronic devices being introduced and developed for portable applications [10–12]. In addition, a lot of challenges remain to be overcome before DMFCs can economically complement or substitute for Li-ion batteries.

Nevertheless, DMFCs and Li-ion batteries have their own specific advantages and features with their own future potential, despite remaining competitors for application to portable electronic devices. Therefore, many papers [1,6–8,13,14] have reported valuable comparisons of their relative competitiveness in the portable application field since the late 1990s. However, none of these studies has quantitatively compared their competitiveness in terms of total cost including manufacturing and energy consumption cost.

Two difficulties arise in the quantitative and precise comparison of the total cost between the two systems. Both can be primarily ascribed to the difficulty in exactly estimating the manufacturing cost of the DMFC system. The current DMFC systems for powering laptop computers have only been introduced as prototypes or demonstration models. Therefore, few data and little information exist to estimate their manufacturing cost. Based only on the data from these prototypes or demonstration models, the real DMFC manufacturing cost has been considered to be even more expensive than that of Li-ion batteries.

Whereas ongoing development continues in various technologies to reduce the DMFC manufacturing costs, Li-ion battery technologies, despite also undergoing constant development, are sufficiently mature for their total cost to be analyzed on the basis of existing data.

Comparison of each system's total cost is also difficult due to the different environments and market conditions for portable electric devices. In other words, it is important to consider the price of the Li-ion battery and the energy consumption, as well as the status of the mobile application such as its market, availability and technological level. For example, Korea is recognized as one of the most developed countries in terms of portable applications, is considered to be a suitable test market for mobile communication, and is acknowledged to have a sufficiently expansive network for wireless internet service in the main cities.

While a comparison of the total cost between DMFC and Li-ion battery systems is difficult, it will nevertheless be very interesting and helpful for the many researchers and companies involved. Therefore, the present paper analyzes and discusses the relative competitiveness of the two systems in terms of total cost by applying them to 20 W laptop computers in the Korea environment, with consideration for the status of their technologies and the assumption of some generally accepted conditions. The total cost of each system, neglecting maintenance cost, comprises manufacturing cost and energy consumption cost for powering a 20 W laptop computer for a working life of 3000 h.

2. Direct methanol fuel cells (DMFCs) for laptop computers

2.1. DMFC system

Among several types of fuel cell systems, DMFC is the most promising candidate for portable applications and has consequently attracted worldwide research attention due to its many advantages [4,15–21]. Despite the many advantages of the DMFC system, relative to the Li-ion battery system, such as its higher energy density and grid independence, several obstacles such as its high manufacturing cost and methanol (MeOH) crossover (or permeation) need to be overcome before the widespread commercialization of the DMFC system is achieved. In addition, DMFC companies also face recently introduced regulations on the use of highly flammable MeOH fuel, which is generally prohibited on commercial airline flights.

In Korea, a lot of research on DMFCs is being actively conducted due to the ongoing development of portable electronic devices and wireless internet services in the country. My previous paper [22] already presented the general background and environment of DMFCs such as research history and technology status.

2.2. DMFCs commercialization and prototypes for powering laptop computers

While many obstacles remain in DMFC commercialization, the use of DMFCs for powering laptop computers has recently passed the demonstration phase. For example, many companies in fields including fuel cell technology (Antig, DMFC Corp., DTI energy, Energy Visions Inc., INI Power, MTI MicroFuel Cells, Neah Power, Plug power, and Smart Fuel Cell), communication and electricity (Fujitsu, IBM, LG, Motorola, NTT, Sanyo, Samsung, Sony and Toshiba) have announced various DMFC prototypes for laptop computer power supply [23–33]. In addition, these companies have also announced commercialization plans in the near future. The prototypes introduced by many companies worldwide are summarized below and their features are listed in Table 1.

In March 2003, Toshiba introduced the world's first prototype of a small DMFC for laptop computers with a claimed energy density up to five times that of a typical Li-ion battery and average and maximum power outputs of 12 W and 20 W, respectively. They also claimed significant advances in developing a system that allows a higher concentration of MeOH to be diluted by the water produced as a by-product of the power generation process [23].

In June 2003, NEC demonstrated a working laptop computer with an internal DMFC delivering average and maximum outputs of 14 W and 24 W, respectively. The company claimed that the size (or volume) of their DMFCs can be substantially reduced by the new technology which supports an increase of the power density up to 60 mW cm^{-2}; the highest in the industry, they claimed [24].

In January 2004, Fujitsu presented their DMFCs for laptop computers. The company claimed that their new DMFC membrane allows an increased fuel solution concentration of up to 30%, thereby leading to smaller and more efficient fuel cells. They claimed that the prototype had been slimmed down to 15 mm thickness, while delivering a power output of 15 W [25].

In June 2004, Samsung Advanced Institute of Technology (SAIT) together with Samsung presented a 100 W h laptop computer powered by a DMFC manufactured with nanomaterials technology. They claimed that the application of their nanotechnology supports a catalyst reduction of 50% and prevents MeOH crossover by more than 90%. The power density of the system approached about 100 mW cm^{-2} [26].

In March 2005, Antig Technology demonstrated a 10 W DMFC for laptop computers. The prototype DMFC system measured 190 × 128 × 30 mm and weighed 435 g. Its uniqueness is its component modularity which enables the DMFC module for portable PCs to fit into a standard laptop optical drive bay. The company, however, admitted that an additional power source is necessary due to the inadequacy of the 10 W power supply for modern laptop computers [27].

In April 2005, Sanyo Electric and IBM unveiled a prototype micro DMFC weighing 2 kg and able to supply about 8 h of power from a single 130 ml fuel cartridge containing pure MeOH. However, the fuel solution concentration was not indicated. Their system also contained a slim Li-polymer battery, built into the base of the unit under the laptop computer and charged by the fuel cell even as the fuel supplies power to the PC. While the fuel cell by itself supplies a maximum power of 12 W, the combination of the fuel cell with the polymer battery can supply a maximum of 72 W [28].

In September 2005, LG announced its own DMFC for laptop computers, with a claimed lifespan of more than 4000 h, size of less than 1 L in core volume and weight of less than 1 kg. Furthermore, the 200 ml fuel cartridge volume can power a 25 W laptop computer for more than 10 h. They have announced a plan to sell the product at about US$550 in the near future [29].

In January 2006, Panasonic introduced their prototype of a DMFC for laptop computers (Matsushita battery). They claimed that in conjunction with a standard laptop battery it can power a computer for about 20 h with 200 ml of MeOH fuel [30].

In September 2006, Antig demonstrated a DMFC system called "BEGINI" which was developed for power supplies for widely used portable applications from cell phones to laptop computers. According to the company, the external charger is safe and provides stable energy. Moreover, with the LCD display, the lightweight BEGINI is easy to use. This product is currently on the market at US$2000 [31,32].

The most recent DMFC prototype for powering laptop computers with a power of 1200 Wh was unveiled by Samsung

Table 1
DMFC prototypes and their features for powering laptop computers introduced by many companies worldwide

Companies	Announcing date (month, year)	Power output (W)	Specification (W: weight) (V: volume)	Concentration of fuel solution (wt.% of MeOH solution)	Impressive technologies
Toshiba	3, 2003	12 (ave) 20 (max)	W: 900 g (without fuel solution) V: 825 ml (275 × 75 × 40 mm)	3–6	Developing a system for fuel dilution using produced water
NEC	6, 2003	14 (ave) 24 (max)	W: 893 g (including 298 g of fuel solution) V: 2916 ml (270 × 270 × 40 mm)	10	Fuel cell's size reduction due to higher power density
Fujitsu	1, 2004	15	n.g.	30	Their new membrane help lead to smaller and more efficient fuel cells
SAIT (Samsung)	6, 2004	20	n.g.	n.g.	Applying nanomaterials technology
Antig	3, 2005	10	W: 435 g V: 730 ml (190 × 128 × 30 mm)	10–15	DMFC module fit into a standard laptop optical drive bay
Sanyo Electric and IBM	5, 2005	12 (DMFC only) 72 (combined with Li-polymer battery)	W: 2.2 kg V: 1218–4111 (270 × 282 × 16 to 54 mm).	n.g.	Docking bay type and hybrid with Li-polymer battery
LG Chem.	9, 2005	25	W: less than 1 kg V: less than 1 l in the core volume	n.g.	Lifetime of more than 4000 h
Panasonic	1, 2006	13 (DMFC only) 20 (combined with Li-ion battery)	W: 450 g (without fuel) V: 400 ml	n.g.	Hybrid with Li-ion battery
Antig and their partner	9, 2006	16 W (80 Wh)	W: 800 g (without fuel) V: 1527 ml (218 × 68 × 103	n.g.	Power supply for a wide range of portable applications
Samsung Electronics	12, 2006	20 (max)		n.g.	Docking station type and high power output

n.g.: not given.

Electronics in December 2006. The DMFC was set in the docking station with the laptop on top. Although the docking station was rather heavy weight, Samsung claimed that it was still very light compared with competing products and, unlike them, was more or less portable. They further claimed that the system can run for a month at a stretch without additional fuelling and can also reach an energy density of 650 Wh L^{-1}, which is, they claimed, four-fold higher than that of their rival companies. However, they did not describe the based volume of its energy density [33].

Considering the impressive features of these DMFC prototypes for laptop computers, the total system volume is one of the most important factors for their commercialization. This is directly related to the power density and energy density of the fuel cells, as well as the fuel solution concentration. Also important is the efficient integration of the DMFC system with the laptop. The DMFC prototype, like others announced by Japanese companies such as Toshiba and NEC, clips on the back of the laptop computer and wraps around underneath it. On the other hand, the prototypes announced by Sanyo and Samsung Electronics are set in the docking bay under the laptop. The method of DMFC attachment affects the level of power output and operation time span.

Despite such successful demonstrations of DMFC systems carried out by many companies world wide, the commercialization of DMFCs for laptop computers has been repeatedly delayed for two reasons. One is that current regulations prohibit the carrying of MeOH on board aircraft so DMFC-powered products could not be taken on planes [34]. The other is the very high manufacturing cost; at least 10 times more than that of Li-ion batteries. The aforementioned BEGINI DMFC power source costs more than most laptops it might power.

The regulations concerning MeOH safety are beyond the scope of the present paper, and its clearance is expected within the near future. However, the high cost of the DMFC system is more critical and this is the central focus of the present paper.

3. Lithium-ion batteries for powering laptop computers

3.1. Research history

Gilbert N. Lewis pioneered Li batteries in 1912, but it was not until the early 1970s when the first non-rechargeable Li batteries became commercially available. Attempts to develop rechargeable Li batteries failed due to safety problems. Because of the inherent instability of Li metal, especially during charging, research shifted to a non-metallic Li battery using Li ions. Although slightly lower in energy density than Li metal, Li ion is safe, provided certain precautions are met when charging and discharging.

In Japan, the Li-ion rechargeable battery was first developed by the Sony Corporation with high energy density and high discharge voltage (3.6 V) and commercialized as early as 1991. Although a cylindrical battery was used in the early stages, prismatic-shaped cells with aluminum laminated version and square-shaped cells have now flooded the market, in conjunction with the rapid spread of cellular phones and laptop computers [1,8,35].

3.2. Technology status

For the most widespread Li-ion battery system, which uses $LiCoO_2$ as the cathode and graphite as the anode, electricity is traditionally charged and discharged via the positive (cathode) and negative (anode) reactions. The current status of technologies on Li-ion battery system is well known and described in many papers [1,8,14,35].

Regarding operating safety and cycling stability, most current batteries are based on the $LiCoO_2$ cathode (positive electrode) in which Li ions are inserted or intercalated into the crystal structure. However, cobalt is quite expensive, possesses limited practical capacity and rates, and suffers from stability problems at elevated temperatures in the common electrolyte solutions so there is a considerable incentive for substitution of a cheaper and more stable material [36–38]. In the anodes made by using graphite, a single Li ion can be intercalated for each hexagon in the graphite's molecular structure, for a nominal composition of LiC_6 at full charge [39].

3.3. Safety and charging

Li-ion batteries are often assembled together with a safety protection circuitry into a "battery pack" (or called "battery module") to prevent polarity reversal, over-voltage and overheating, as well as to meet the specific requirements of the power and volumetric space of various electronic devices. Such a battery pack usually requires a specific charger that is controlled by a microprocessor with a pre-programmed charging algorithm. Normally, the charger is programmed to charge the battery pack through two continuous steps of constant-current/constant-voltage (CC/CV) charging. Most of the chargers are designed to provide about a 3-h charging time, during which the battery is first charged to 4.2 V at under 1 C to reach 60–70% of the capacity and then charged at the peak voltage to reach the rest of the capacity [40,41].

3.4. Li- ion batteries for powering laptop computers currently sold in the market

Generally, Li-ion battery systems for laptop computers have been developed together with the laptop system. Therefore, many international laptop manufacturing companies such as HP, IBM, LG, Sanyo, Samsung, Sony, and Toshiba have developed their own unique Li-ion battery systems and sold them for application only to their laptop computers, as part of their sales strategy. There is no commonly used, standardized, Li-ion battery for use with all laptops, irrespective or to the electronic companies.

Generally, Li-ion batteries for laptops consist of 6–12 single cells connected in series and parallel to each other. For example, when four single cells are connected in series and this pack is connected with the other one in parallel, this is called the 4S2P Li-ion battery system. Therefore, the output voltages and power output of Li-ion batteries are determined by the number of single cells and its connection method. Generally, their output voltages range from 7.2 V to 14.4 V and their current capacity from 1500 mAh to 8800 mAh. The traditional four types of Li-ion battery for laptop computers currently sold in Korea are listed in Table 2. Among them, Type II is the most widely used due to its optimality for the 12.1–15 in. display and one DVD drive in standard laptop computers.

Table 2
Four traditional types of Li-ion batteries for laptop computers currently sold in Korea

Type of Li-ion batteries for laptop	Configuration of the single cells (number of single cells)	Energy capacity (Wh) (output volts (V)/current capacity mAh)	Use (specification of laptop)	Currently average retail price in Korea (US$)
I	3P (3)	25.92 (10.8/2400)	Less 12.1 in. display, light weight, slim and mini laptop	80
II	3S2P (6)	51.84 (10.8/4800)	12.1–15 in. display, standard type (built-in one optical drive)	100
III	4S2P (8)	69.12 (14.4/4800)	Up to 15 in. display	140
IV	3S3P (9)	77.76 (10.8/7200)	Up to 17 in. display (option), long operating time	160

4. Comparison of total costs between DMFC and Li-ion battery systems for powering laptop computers

Firstly, to compare the total cost of the DMFC and Li-ion battery systems, the average power output and the operational time of laptop computers were assumed to be 20 W and 3000 h, respectively.

While the current average power output of traditional laptop computers ranges from 12 W to 14 W, it is continuously increasing. Therefore, 20 W was assumed to be the average power output of future laptop computers and 8 h was the most favored operating time per day. This corresponds to an operational life of 3000 h for a 1-year lifetime.

Secondly, a DMFC system with an average power output of 20 W and a Li-ion, Type II battery with energy capacity of 51.84 Wh were selected as reference DMFC and Li-ion battery systems, respectively.

4.1. Total costs of Li-ion battery system for laptop computers

4.1.1. Manufacturing costs of Li-ion battery system

The retail price and component costs are well known for the Li-ion battery system. While the material cost according of each component may differ slightly, the traditional share of material costs comprises 40% for cathode ($LiCoO_2$), 15% for negative electrode (LiC_6), 18% for separator, 8% for electrode and 19% for others.

The estimation of the manufacturing cost of the Li-ion battery begins with its retail price and the various assumptions are listed in Table 3.

The Korean retail prices of traditional Li-ion batteries for powering laptops sold in the current market range from about US$80 to US$160, as listed in Table 2. Among them, the average retail price of the Type II with a power of 51.84 W h is about $100, equating to a retail price of about $1.93 Wh^{-1}. Considering that a formula for the evaluation of the manufacturing cost within the Korean Li-ion battery manufacturing industry is the one-third of the retail price, this suggests a Li-ion battery manufacturing cost of $0.64 Wh^{-1}, i.e., $33.33 for the 51.84 W h Type II battery. However, the current situation of Li-ion battery technologies is so mature and its current market so competitive that this estimated manufacturing cost is likely to be inaccurate.

While the average manufacturing cost of Li-ion batteries for laptop computers remains confidential, it was estimated to be about $0.5–0.6 Wh^{-1} before a global battery recall by Sony in late 2006. However, the manufacturing companies have suffered increased manufacturing costs due to heightened safety concerns about Li-ion batteries. Therefore, the assumed manufacturing cost of $0.64 Wh^{-1} for Li-ion batteries for laptops might be very reasonable.

The Li-ion battery has an average lifetime of 400 charge–discharge cycles with an average operating time of 2.5 h per cycle at a 20 W power output, equating to a total time span of 1000 h for a Type II battery. Therefore, three batteries are required for a 3000 h lifetime.

A CC/CV adaptor with a power range of 45–75 W is required for charging. These products are currently sold in Korea at a price of $45–80, suggesting a manufacturing cost of $20 and a total system cost for three batteries and one adaptor of $120.

4.1.2. Electricity consumption costs of Li-ion battery system

Currently, most of the electricity in Korea is generated and supplied by KEPCO (Korea Electric Power Corporation). KEPCO generated electric energy of 65,534 MW in 2006 and sold about 47,988 MW in the same year. While electricity pricing differs slightly, the average retail price for residence or household services is $0.00023 Wh^{-1} [42] and this is relatively cheap at about 60% of the OECD average.

To calculate the exact electricity consumption cost in using Li-ion batteries for laptop computers, the following total energy losses should firstly be considered: loss of energy

Table 3
Assumptions for total cost estimation of a Li-ion battery system for powering laptop computers at the average power output of 20 W

For manufacturing costs	
Selected Li-ion battery	3S2P (Type II in Table 1), $LiCoO_2$/graphite, prismatic type; energy capacity; 51.84 Wh
Assumed manufacturing cost[a]	$33.3/Type II ($0.64 Wh^{-1})
Average discharge–charge cycles or end of life	400 cycles; 1000 h
Number of Li-ion batteries working for operation time of 3000 h	3 packs of Li-ion battery (Type II)
Charging method	Via the CC/CV adapter, plugging into ordinary residence or household current
Assumed manufacturing cost of CC/CV adapter[a]	$20 (60 W)
Assumed total manufacturing cost[b]	$120
For electricity consumption costs	
Average battery efficiency (or energy capacity) according to repeated charge–discharging cycle	80% (from initial use to end of life) of energy capacity
Loss of electricity from the adaptor in charging process	10% of energy capacity
Average discharge/charge cycles or average time span	Neglected
Electricity costs for one charge	$0.0165 per charge

[a] Considering that a formula for the evaluation of the manufacturing cost within the Korean Li-ion battery manufacturing industry is 1/3 of the retail price and without considering the adaptor.

[b] Include three packs of Li-ion battery (Type II) and one CC/CV adapter for working at the power output of 20 W during 1000 h.

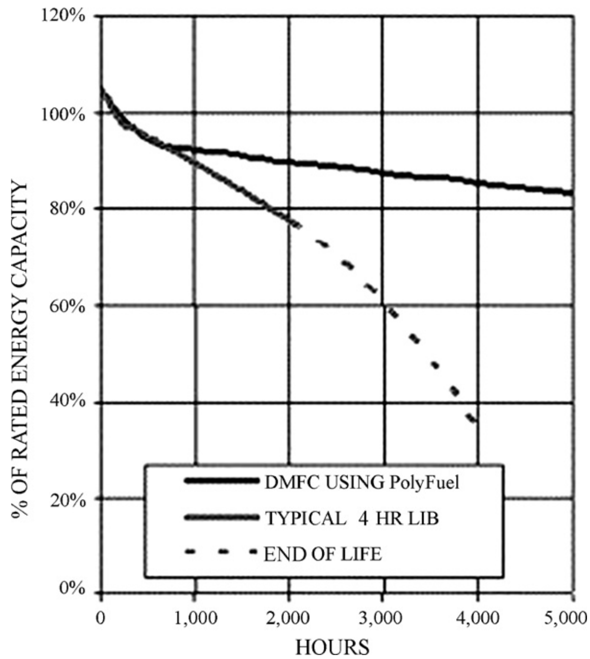

Fig. 1. Comparison of the energy capacity of Li-ion batteries vs. DMFCs built with PolyFuel's hydrocarbon DMFC membrane, over their respective operating lifetimes [13].

capacity according to repeating charge–discharging cycles (or charge–discharge efficiency), loss of electricity from the adaptor in the charging process and self-discharge of the batteries. These losses assumed are listed in Table 3.

The energy capacity of Li-ion batteries is reduced with repeated charge–discharge cycles from almost 100% initially to about 60% at the end of its life, i.e., an average of 80%. The lifetime of Li-ion batteries is strongly dependent on the working time and the number of charge–discharge cycles. It is known that Li-ion batteries have a lifetime of 2000–3000 h with 300–500 charge–discharge cycles, as shown in Fig. 1, based on an investigation by Polyfuel Inc. [13].

Despite the assumed lifetime of 1000 h for one Li-ion battery in the present paper, the 400 charge–discharge cycles should be required to supply the energy capacity of 51.84 Wh within 1000 h. This supports the reasonableness of the assumed 60% efficiency at the end of the Li-ion battery's life in present paper.

In addition, the loss of electricity due to heat loss from the adaptor in the charging process is assumed to 10% of the Li-ion battery capacity. Li-ion batteries have a self-discharge rate of approximately 4–5% per month. However, this is the energy loss from the unused, charged-state, Li-ion battery. Therefore, the energy loss due to self-discharge is neglected in the present paper. Therefore, the total electric energy loss of the Li-ion battery was calculated to be about 28% of the energy capacity, equating to a 72 Wh net electric energy requirement for a charge capacity of 51.84 Wh and a consequent cost of $0.0165 per cycle. Therefore, the average electricity cost for charging the Li-ion battery as the power supply for laptop computers is calculated to be $0.00032 Wh^{-1}$.

4.2. Total costs of the DMFC system for laptop computers

4.2.1. Manufacturing costs of the DMFC system

The DMFC manufacturing costs have traditionally been higher than those of any other fuel cell system, mainly due to the high costs of materials used in fabrication, especially the membrane electrode assembly (MEA) and platinum electrocatalysts. Furthermore, the DMFC system for laptops requires a complex cell structure to eliminate the CO_2 generated within the cell and a fuel solution concentration sensor, as shown in Fig. 2, which combine to further increase the costs. In addition, the non-passive (or active) DMFC system necessitates the pumps, fans, valves, and humidity regulators to supply, remove and treat the fluids.

However, it is very difficult to exactly and quantitatively estimate the manufacturing cost of the DMFC system due to the ongoing development of the technology and the substantial research on cost reduction. Furthermore, manufacturing costs remain confidential and sensitive issues for DMFC companies, which limit the available data. Dyer [6] reported a manufacturing cost for a DMFC system as high as $5 W^{-1}$, compared to another reported estimate of $3–5 W^{-1}$ [13]. The cost can be estimated considering the manufacturing cost of proton exchange membrane fuel cells, which are similar to DMFCs [14,43].

However, experts [44] in DMFC and Li-ion battery manufacturing companies in Korea recently claimed that the manufacturing cost of DMFCs was at least 10-fold greater than that of equivalent Li-ion battery systems. In addition, these experts claimed that the DMFC will retail at $540–1600 in the near future [44].

Therefore, according to this prediction, the manufacturing cost of a DMFC system with a power output of 20 W for powering laptop is estimated to be $333 in the present paper, which is obtained by multiplying the manufacturing cost of Li battery (Type II) by 10 and corresponds to $16.65 W^{-1}$.

4.2.2. Technological assumptions for calculation of the fuel solution consumption in DMFCs

The many assumptions in the calculation of the total DMFC cost assigned in the present paper are listed in Table 4.

The technological assumptions and their value for the calculation of fuel cost such as power density, concentration of fuel solution, operational voltage and temperature at atmospheric pressure are the same as mentioned in my previous paper [22]. These are assumed based on state-of-the-art DMFC technologies. However, in order to calculate the DMFC fuel cost more exactly, the deterioration of cell efficiency according to the operation time is considered first. Based on the results shown in Fig. 1, it is reasonable that the average cell efficiency between 0 h and 3000 h can be assumed to be 92%.

In addition, while the amount of MeOH crossover of the DMFCs was assumed to be 4×10^{-7} mol cm^{-2} s^{-1} in my previous paper [22], two values for the MeOH crossover are additionally assumed to be 4×10^{-8} mol cm^{-2} s^{-1} and 4×10^{-9} mol cm^{-2} s^{-1}. These two values are based on results from the papers [45,46] and these can be accepted as the state-of-the-art values for near future applications given the

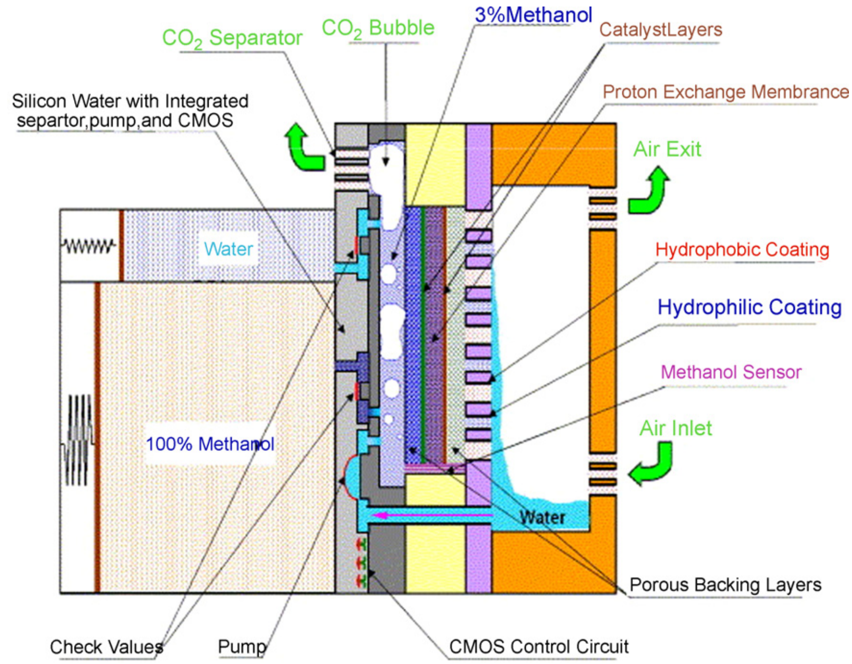

Fig. 2. Schematic diagram of micro DMFC system for laptop (a cut view) [52].

rapid development of current DMFC technology. In addition, the total cost of the DMFC system based on these two additionally assumed lower values of crossover might be informative for finding the best conditions for the DMFCs to be able to compete with the Li-ion batteries in terms of fuel cost.

4.2.3. Fuel consumption costs with consideration for MeOH crossover in DMFC systems

The current market CFR (cost and freight) price of industrial-grade MeOH is approximately $0.3 kg^{-1}. The average MeOH price in bulk quantities was sold in the US at the CFR price of $0.95 per gallon (Methanex, March 2005). In Korea, the current CFR price of MeOH is about $300 per ton, with a bulk quantity retail price of $0.5 kg^{-1} (MeOH purity: 99.85%), rising to $0.6 kg^{-1} with packing. High-grade MeOH has a retail price of $1.6 kg^{-1}.

Table 4
Assumptions for total cost estimation of a DMFC system for powering laptop computers at the average power output of 20 W

For manufacturing costs	
Assumed manufacturing cost[a]	$333 (20 W); $16.65 W^{-1}
For fuel consumption costs	
Power density	80 mW cm^{-2} [47]; cell area of 250 cm^2 is required to generate 20 W
Concentration of fuel solution	2 M of MeOH solution
Operational voltage	0.5 V
Number of single cells for output voltage of 10.8 V	22
Operating temperature	~60 °C
Average cell efficiency for 3000 h	92%
Amount of fuel crossover (mol cm^{-2} s^{-1})	4×10^{-7}; 4×10^{-8}; 4×10^{-9}

[a] Estimated to be 10 times more than that of the Type II Li-ion battery.

None of the many research papers has clearly reported the effect of MeOH purity on the cell performance because the fuel solution typically used is optimally composed of 3–6 wt.% MeOH in distilled water. Therefore, many DMFC manufacturers and researchers have claimed that industrial-grade MeOH can be used as the fuel. However, the MeOH quality is probably directly related to cell performance in active DMFC system.

Considering the assumptions listed in Table 4, the amount of pure MeOH to generate a 1 Wh power output and the amount of distilled water for dilution of pure MeOH to 2 M fuel solution are listed in Table 5.

A total of 0.398 g of pure MeOH is required to generate 1 Wh, without considering the decrease of cell efficiency with operation time. However, considering the assumed average cell efficiency of 92% for 3000 h, this amount rises to 0.433 g. In addition, 6.263 g of distilled water is added to adjust the fuel solution to a MeOH concentration of 2 M, i.e., 6.696 g (or 6.763 ml) of fuel solution.

The price of distilled water can be neglected because it can be reused by recycling in the DMFC. Therefore, the net cost of MeOH needed to generate 1 Wh is $0.00022 Wh^{-1} and 0.00026 Wh^{-1} at a MeOH price of $0.5 kg^{-1} and $0.6 kg^{-1}, respectively, rising to $0.00069 Wh^{-1} at the high-purity MeOH price of $1.6 kg^{-1}, as listed in Table 6.

The additional loss of MeOH due to MeOH crossover is unavoidable in the DMFC system. At an assumed crossover level of 4×10^{-7} mol (MeOH) cm^{-2} s^{-1} and power density of 80 mW cm^{-2}, the MeOH loss due to crossover is 0.576 g Wh^{-1}, an excessively large value that even exceeds the MeOH consumption for generating power, 0.433 g Wh^{-1}, by 33%. However, if the order of magnitude of the crossover level

Table 5
Amount of fuel and fuel solution to solely generate a 1 Wh power output and the additional loss of fuel and fuel solution due to MeOH crossover according to the order of magnitude of MeOH crossover at the same power output (fuel solution concentration, 2 M MeOH; average cell efficiency according to the operation time to 3000 h, 0.92; power density, 80 mW cm^{-2})

Fuels and fuel solution	Net consumption of fuel solution to generate 1 Wh	Additional loss of fuel solution due to crossover according to the order of magnitude of crossover at power output of 1 Wh		
		Amount of fuel crossover (mol cm^{-2} s^{-1})		
		4×10^{-7}	4×10^{-8}	4×10^{-9}
Pure fuel (g or (ml) of pure MeOH)	0.433 (0.548)[a]	0.576 (0.729)[a]	0.058 (0.073)[a]	0.006 (0.007)[a]
Water for fuel solution (g)	6.263	8.340	0.834	0.083
Total amount of fuel solution (g or (ml))	6.696 (6.763)[b]	8.926 (9.006)[b]	0.892 (0.900)[b]	0.089 (0.090)[b]
Fuel cartridge volume[c] (ml of pure MeOH)	0.548	0.729	0.073	0.007

[a] Specific gravity of pure MeOH = 0.79 [48].
[b] Specific gravity of 1 M and 2 M MeOH solution = 0.99 [49].
[c] The DMFC cartridge volume was calculated when the cartridge-held pure MeOH was injected into the DMFC as the fuel.

could be reduced to −8 and −9, the MeOH loss due to crossover would be reduced to 10% and 1%, respectively. The losses of MeOH and fuel solution according to the crossover level are listed in Table 5. If the order of magnitude of the crossover level could be reduced to −9, the loss of MeOH due to crossover is calculated to be 0.006 g Wh^{-1}. This value corresponds to about 0.36 kg of MeOH over an operation time of 3000 h at a power of 20 W, which is negligible compared to the 26 kg of MeOH to solely generate power at the same power output and the same operation time.

The additional costs of MeOH loss due to the crossover are listed in Table 6 in the subsequent section.

4.3. Comparison of energy costs between DMFC and Li-ion battery systems

Based on the aforementioned calculations, the comparative energy costs between DMFC and Li-ion battery systems to generate a 1 Wh power output are listed in Table 6. These results clearly show the range of MeOH price and the level of MeOH crossover at which the DMFC system competes with the Li-ion battery in terms of energy cost.

For example, at a crossover level of 4×10^{-7} mol cm^{-2} s^{-1}, the total DMFC energy consumption cost is greater than that of the Li-ion battery, irrespective of the energy price, even at the currently lowest price of \$0.5 kg^{-1}. However, at a MeOH cost of under \$0.7 kg^{-1} and a crossover level at an order of magnitude of −9, the DMFC energy consumption costs become competitive with those of Li-ion batteries.

4.4. Comparison of total costs between DMFC and Li-ion battery systems

The total cost comprises the manufacturing cost and energy cost. Therefore, based on the results presented above, the total cost of the Li-ion battery system for powering a 20 W laptop in Korea is calculated as listed in Eq. (1):

$$\$_{\text{total, Li-ion battery}} = \$120 + \$0.00032\,(\text{Wh}) \tag{1}$$

The first term is the manufacturing cost of three Type II Li-ion batteries and one standard CC/CV adaptor. This value corresponds to \$0.77 Wh^{-1} and is slightly larger than the manufacturing cost of only the Li-ion battery estimated in the previous

Table 6
Comparative energy consumption cost between DMFC and Li-ion battery system to generate (or supply) a 1 Wh power output

DMFC				
MeOH prices (\$ kg^{-1})	Cost of fuel consumption to generate 1 Wh (\$ Wh^{-1})	Additional costs of MeOH loss due to crossover (\$ Wh^{-1}) (total fuel cost)		
		Amount of fuel crossover (mol cm^{-2} s^{-1})		
		4×10^{-7}	4×10^{-8}	4×10^{-9}
0.5[a]	0.00022	0.00029 (0.00051)	0.00003 (0.00025)	0 (0.00022)
0.6[a]	0.00026	0.00035 (0.00061)	0.00003 (0.00029)	0 (0.00026)
0.7[b]	0.00030	0.00040 (0.00070)	0.00004 (0.00034)	0 (0.00031[b])
1.6[a]	0.00069	0.00092 (0.00161)	0.00009 (0.00078)	0.00001 (0.00070)
Li-ion battery				
Average electric price in Korea (\$ Wh^{-1})	Cost of electricity consumption to charge or supply 1 Wh (\$ Wh^{-1})			
0.00023	0.00032	–	–	–

[a] Price of MeOH currently sold in Korea.
[b] Same or more competitive price of MeOH in DMFCs than the current electricity price for charging of Li-ion batteries in Korea.

section, 0.64 Wh^{-1}. The second term is the electricity cost consumed in charging the Li-ion battery at the charging capacity of 1 Wh.

In the DMFC system, the total cost is as listed in Eq. (2). This is derived from the results of the assumed DMFC system manufacturing cost of \$333 for a 20 W power output. In addition, Eq. (2) is based on the pure MeOH price of \$0.5 kg^{-1} and the state-of-the-art order of magnitude for MeOH crossover of −7.

$$\$_{\text{total, DMFC}} = \$333(20\,W_{\text{fixed}}) + \$0.00022\ \text{(Wh)} + \$0.00029\ \text{(Wh)} \quad (2)$$

The second and the final term in Eq. (2) is the fuel cost to generate the 1 Wh power output and the additional cost of MeOH due to crossover at the same power output. If the order of magnitude of the crossover were reduced to −9 due to technology improvement, the final term in Eq. (2) could be neglected, as listed in Eq. (3)

$$\$_{\text{total, DMFC}} = \$333(20\,W_{\text{fixed}}) + \$0.00022\,\text{(Wh)} \quad (3)$$

Fig. 3 shows the total cost of each system to supply the 20 W laptop computer for about 1 year (or 3000 h).

This figure represents a substantial difference in total cost between the two systems and provides useful information about the crossover effect on the total cost. Based on Eq. (1), the total cost of the Li-ion battery system was \$140 per year, compared to \$362 for the DMFC system, based on the lowest MeOH price and a MeOH crossover level at the order of magnitude of −7. The DMFC system is 2.6-fold more expensive, and its cost only falls to \$346 (based on Eq. (3)) even if the MeOH crossover level is reduced to an order of magnitude of −9, which renders the cost of this loss as negligible. Reducing the MeOH crossover level by 99% only reduces the total cost by 4.4% at the currently low MeOH market price. However, if the manufacturing cost of the DMFC system can be reduced to a competitive level with the Li-ion battery, this small fuel cost saving due to the reduction of MeOH crossover will increase the total cost competitiveness with Li-ion batteries. In addition, the reduction of MeOH crossover is essential to increase the stable cell performance and system durability.

Therefore, as noted in many previous papers, the most significant factor for reducing the DMFC total cost is lowering the manufacturing cost. If so, how much should the DMFC manufacturing cost be reduced to compete with Li-ion batteries as the power supply for laptop computers in terms of total cost? Fig. 4 answers this question. At given conditions, the manufacturing cost of a DMFC system with an average power output of 20 W should be reduced to \$126 (or \$6.30 W^{-1}) represented as the total cost at time 0 day as shown in Fig. 4.

The present study results indicate that the fuel cost of the DMFC system with a crossover level at an order magnitude of −7 is always less competitive than that of the Li-ion battery even at the lowest MeOH price. Therefore, to compete with the Li-ion batteries the manufacturing cost of the DMFC system needs to be reduced to even below that of Li-ion batteries, as shown in Fig. 4, which is absolutely impossible under any foreseeable DMFC technology.

Therefore, the best conditions for competitive DMFC manufacture are a MeOH price of \$0.5 kg^{-1} and a crossover level at an order magnitude of −9. Under these conditions, a 62% reduction in the presently calculated DMFC manufacturing cost of \$16.65 W^{-1} down to \$6.30 W^{-1} would raise its competitive

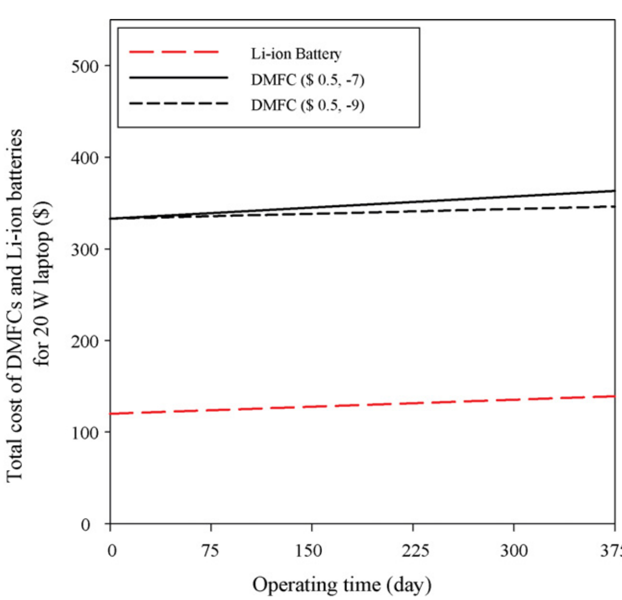

Fig. 3. Total cost of DMFC and Li-ion battery systems operating as power supplies for a 20 W laptop over a 3000 h operational year in Korea considering the status of their current technologies. DMFC (\$0.5, −7) and DMFC (\$0.5, −9) are the total DMFC cost based on the order of magnitude of crossover of −7 and −9, respectively, and the MeOH price of \$0.5 kg^{-1}.

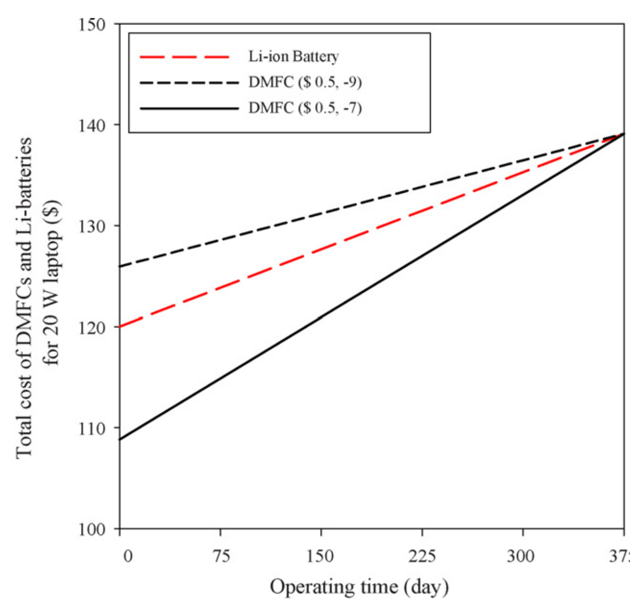

Fig. 4. DMFC manufacturing cost to compete with the Li-ion batteries and the total cost of each system operating as power supplies for a 20 W laptop over a 3000 h operational year. Total cost at time 0 day represents the manufacturing cost; DMFC (\$0.5, −7) and DMFC (\$0.5, −9) are the total DMFC cost based on the order of magnitude of crossover of −7 and −9, respectively, and the MeOH price of \$0.5 kg^{-1}.

level equal to that of the Li-ion battery system, for an operation time of 3000 h, as shown in Fig. 4.

5. Other comparative features between DMFC and Li-ion battery systems

5.1. Volume and weight

The specific energy and energy density based on the system weight and volume are very important factors to compare their competitiveness in terms of total weight and volume.

The specific energy and energy density of Li-ion batteries are conventionally indicated and calculated based on the weight or volume of the battery (or pack) itself. Advanced rechargeable Li-ion batteries have a specific energy ranging from 0.15 Wh g^{-1} (prismatic type) to 0.2 Wh g^{-1} (cylindrical type) and an energy density from 250 Wh L^{-1} (prismatic type) to 530 Wh L^{-1} (cylindrical type) [5,37]. Therefore, the total volume and weight of prismatic Li-ion batteries with an energy capacity of 51.84 Wh, equivalent to the standard Type II battery, are 207 ml and 346 g, respectively. Li-ion batteries with these specifications are easily available in the market.

On the other hand, it is not easy to exactly estimate the specific energy and energy density of the DMFC system because the fuel is continuously consumed for power generation. One of the advantages of DMFCs over Li-ion batteries in portable-power applications originates from the high specific energy (or energy density) of the pure fuel. However, this advantage disappears when the total system volume and weight are considered.

The theoretical DMFC specific energy is 6.08 Wh g^{-1} for pure MeOH, which equates to 4803 Wh L^{-1} considering the MeOH specific gravity of 0.79. These values are even larger than those of Li-ion batteries, as listed in Table 7, when based on $LiCoO_2$ and neglecting the weight and volume due to the electrolyte, battery case, and all other battery components.

Table 7
Specific energy and energy density of each system

Specific energy and energy density	DMFCs	Li-ion batteries
Based on the pure fuel[a]		
(Wh g^{-1} of pure MeOH or $LiCoO_2$)	6.08	0.55–0.58 [50,51]
(Wh L^{-1} of pure MeOH or $LiCoO_2$)	4803	1810 [51]
Based on the pure fuel[b]		
(Wh g^{-1} of pure MeOH)	2.51	–
(Wh L^{-1} of pure MeOH)	1983	–
Based on fuel solution[b]		
(Wh g^{-1} of 2 M MeOH solution)	0.16	–
(Wh L^{-1} of 2 M MeOH solution)	160	–
Based on total system		
(Wh g^{-1} of system or pack)	0.08	0.15[c]
(Wh L^{-1} of system or pack)	54	250[c]
Total weight and volume of system at power output 51.84 Wh		
(g)	646	346
(ml)	960	207

[a] Theoretical value at a voltage of 1.21 V.
[b] Operational value at a voltage of 0.5 V.
[c] Prismatic type Li-ion battery.

However, assuming that the maximum power densities could be delivered at the DMFC operational voltage of 0.5 V, their operational values are reduced to 2.51 Wh g^{-1} and 1983 Wh L^{-1} of pure MeOH, respectively, and further reduced to 0.16 Wh g^{-1} and 160 Wh L^{-1} based on the weight and volume of the fuel solution with the 2 M MeOH solution, respectively. In addition, the specific energy and energy density based on the DMFC total system are further reduced to even less than 0.16 Wh g^{-1} and 160 Wh L^{-1}, respectively, considering the weight and volume of the fuel cell system. In other words, with the assumption that the fuel solution of the DMFC system accounts for half of the total system weight and one-third of the total system volume, the specific energy and energy density based on the total system are 0.08 Wh g^{-1} and 54 Wh L^{-1}, respectively. These calculated values neglect the crossover fuel loss and the reduction of cell efficiency according to the operation time.

To confirm these estimated, system-based, DMFC values, a comparison with the specification of "BEGANI" [31,32], listed in Table 1, produces values of 0.094 Wh g^{-1} and 52.39 Wh L^{-1}, respectively. Because this product was developed not for only laptops but also for a wide range of portable applications, its specific energy and energy density may vary slightly from the estimated values in the present paper.

Using the estimated values in the present paper, the volume and weight of the total DMFC system required to have the same capacity as one Li-ion battery, 51.84 Wh, are calculated to be 648 g and 960 ml, respectively. Therefore, considering the status of DMFC technologies, their specific energy and energy density based on the total system are even less than those of the Li-ion battery system, primarily due to the large weight and volume caused by due to the low concentration of the 2 M MeOH solution. Therefore, research is necessary to increase the fuel solution concentration and decrease the system volume.

5.2. CO_2 and water generated in the DMFC system

The DMFC system theoretically generates CO_2 gas at the anode compartment at a rate of 0.279 L Wh^{-1} (at standard state), equating to 44.6 L of CO_2 gas generated per day for a 20 W laptop computer operated for 8 h a day.

In addition, the DMFC also generates water (together with unreacted air) at the cathode compartment during the operation. A total of 0.670 g of water is generated at a power output of 1 Wh, which corresponds to 107 g of water generated per day using the 20 W laptop computer for 8 h. However, according to the reaction in DMFC, one-third of the generated water can be recycled for use in the anode reaction to maintain the MeOH fuel solution concentration at 2 M. However, the remaining two-thirds of the total water generated, 71.3 g, must be drained out every working day.

Fig. 5 shows the CO_2 and water accumulated over 1 year, equating to 16.7 kL (at standard state) and 26.8 kg, respectively.

Therefore, the DMFC's CO_2 and water generation necessitate CO_2 ventilation and drainage of the accumulated water, which may be obstacles in the future commercialization of DMFCs as the power supply for laptop computers, compared with the Li-ion battery.

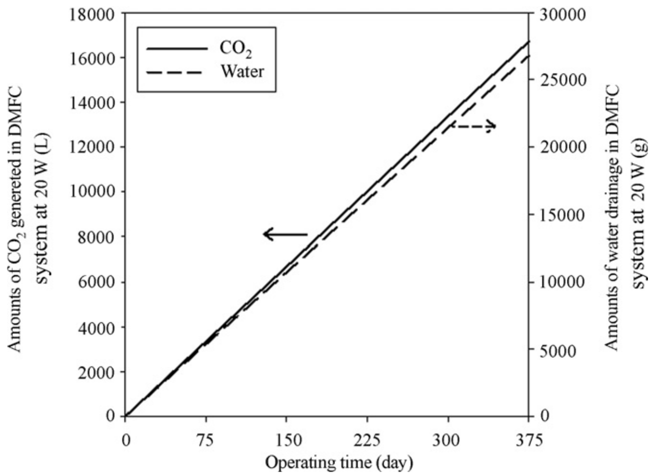

Fig. 5. Amount of CO_2 and water generated in the DMFC system operated as the power supply for a 20 W laptop over a 3000 h operational year.

6. Conclusions

Applying DMFCs and Li-ion batteries to the power supply of laptop computers in the Korean environment, and assuming some generally accepted conditions, the present paper analyzes and discusses their relative competitiveness in terms of total cost. The average power output and operational lifetime of the laptop computers were designated as 20 W and 3000 h, respectively.

Considering the status of their respective technologies, the manufacturing costs of the DMFC and Li-ion battery systems were calculated to be \$16.65 W^{-1} and \$0.77 Wh^{-1}, and the energy consumption costs were estimated to be \$0.00051 Wh^{-1} and \$0.00032 Wh^{-1}, respectively. The DMFC fuel cost was calculated based on the lowest MeOH retail price of \$0.5 kg^{-1} and the order of magnitude of the MeOH crossover of −7. Despite the MeOH having a lower price than electricity in Korea, the higher DMFC fuel cost was primarily ascribed to the additional fuel loss due to the MeOH crossover. In fact, if the order of magnitude of the crossover were reduced to under −9, the fuel cost could be neglected in the present paper. Therefore, the best conditions for the DMFCs to be able to compete with the Li-ion batteries in terms of fuel cost were the order of magnitude of the crossover level of −9 at the MeOH price of \$0.5 kg^{-1}. Under these conditions, if the DMFC system manufacturing cost could be reduced to \$6.30 W^{-1}, i.e., about one-third of the current cost initially assumed in the present paper, the DMFC system would gain at least the same level of competitiveness as the Li-ion battery system for powering a 20 W laptop over an operational life of 3000 h in Korea.

While the theoretical specific energy and energy density based on the pure fuel were even larger than those of Li-ion batteries, DMFCs were even less competitive than Li-ion batteries in terms of specific energy and energy density based on the total system weight and volume. In DMFCs, these were calculated to be 0.08 Wh g^{-1} and 54 Wh L^{-1}, respectively, which were even less than those of the Li-ion battery system at 0.15 Wh g^{-1} and 250 Wh L^{-1}, respectively. This result was primarily ascribed to the DMFC's large weight and volume due to the low concentration of the 2 M MeOH solution. Therefore, research should be directed at increasing the fuel solution concentration and decreasing the system volume in order to increase the specific energy and energy density based on the system.

A further hurdle in the commercialization of DMFCs is the CO_2 and water generation during operation. Under the given conditions, the annual accumulated CO_2 and water were calculated to be 16.7 kL (at standard state) and 26.8 kg, respectively.

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