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Performance evaluation of direct methanol fuel cells for portable applications

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ABSTRACT

This study examines the feasibility of powering a range of portable devices with a direct methanol fuel cell (DMFC). The analysis includes a comparison between a Li-ion battery and DMFC to supply the power for a laptop, camcorder and a cell phone. A parametric study of the systems for an operational period of 4 years is performed. Under the assumptions made for both the Li-ion battery and DMFC system, the battery cost is lower than the DMFC during the first year of operation. However, by the end of 4 years of operational time, the DMFC system would cost less. The weight and cost comparisons show that the fuel cell system occupies less space than the battery to store a higher amount of energy. The weight of both systems is almost identical. Finally, the CO_2 emissions can be decreased by a higher exergetic efficiency of the DMFC, which leads to improved sustainability.

1. Introduction

Fuel cells are ideal candidates for distributed power generation. They can provide a low emission and highly efficient source for co-generating heat and electricity [1]. Global concerns over energy sustainability and environmental impact of fossil fuels have motivated efforts to improve fuel cell technology. However, the main barriers that impede their widespread commercialization are the high cost of fuel cell systems and their relatively low reliability and durability. Enhancing the safety and performance of fuel cells, providing compact, light and secure fuel storage, and improving the efficiency, lifetime and stability of fuel cells, are the main requirements that need to be met before their widespread commercialization.

Fuel cells used for portable applications are one of the most recent and promising areas that have attracted a global interest. Primary (disposable) and secondary (rechargeable) batteries are well established as a power supply for portable devices. But since the power demand has been increasing faster than battery capabilities, for example in electronic portable devices (added functionality, larger display, more graphics, etc.), fuel cells have become a promising alternate for niche applications. In addition, they can offer a higher power density and longer lifespan compared to batteries for portable applications. Reliability is another important factor where the benefits of fuel cells outweigh those of batteries.

In this paper, a comprehensive comparison between a Li-ion battery and a DMFC is performed. The feasibility of replacing the Li-ion battery with DMFC for portable applications such as a laptop, camcorder and a cell phone is investigated. A performance assessment is also conducted through exergy efficiency. Its relation to environmental impact (in terms of CO_2 emissions) and sustainable development (in terms of sustainability index) is studied for comparison purposes. Moreover, a cost analysis to examine the market potential of direct methanol fuel cells is undertaken. Finally, a sensitivity study to investigate the effects of fuel cell operating conditions on the overall performance is conducted.

2. Fuel cells for portable applications

A fuel cell is a device that generates electricity from fuel (hydrogen or hydrogen-rich fuel) and oxygen via an electrochemical process. Although its invention dates back more than a century, fuel cells have only recently attracted the attention of manufacturers in the energy sector [2]. Fuel cell technology is rapidly advancing, with support from both private and public sectors. High efficiency and zero emissions from fuel cells are the main reasons. To mitigate threats from high oil prices and reduce greenhouse gas emissions from traditional sources of energy, fuel cells are considered to be the next generation of efficient and environmentally benign energy supply [3]. However, their slow pace of commercial-

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ization exists mainly because of their high initial costs and reduced lifetime.

Two types of fuel cells, which are generally used for portable applications, are proton exchange membrane fuel cells (PEMFC) and direct methanol fuel cells (DMFC). A low operating temperature and pressure, high energy and high power density are the main features of these devices. This section gives a brief description of each type of fuel cell. Further considerations will only be related to DMFC for the remaining analysis in this paper.

2.1. Hydrogen supplied PEM fuel cell

A PEM fuel cell is a low temperature, reliable and lightweight fuel cell that operates on pure hydrogen. Recent advancements of PEM fuel cells include improved membrane electrode assemblies, more advanced cell design and better thermal management [4]. As a result, enhanced power densities can be achieved. The electrochemical reactions occurring in a PEM fuel cell supplied by pure hydrogen are shown as follows:

- Reaction at the anode: $2H_2 \rightarrow 4H^+ + 4e^-$.
- Reaction at the cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$.
- Overall reaction of the fuel cell: $2H_2 + O_2 \rightarrow 2H_2O$.

A PEMFC is suitable for portable applications where size and energy density are important. The units can be manufactured in small sizes, while keeping the performance unaltered. PEM fuel cells can be used in a variety of applications, covering power outputs from microwatts to hundreds of kilowatts [5]. The main advantages of this type of fuel cell are fast startup capability, since it works at low operating temperatures, high power density and compact design. However, the main disadvantage of this type of fuel cell is its high cost, since it currently requires an expensive platinum catalyst to enhance the electrochemical reaction [6]. Moreover, difficulties with refilling hydrogen tanks compared to methanol refilling, make the DMFC a more suitable candidate for portable applications.

2.2. Methanol supplied fuel cell

The direct methanol fuel cell (DMFC) operates by direct electrochemical reaction of an aqueous solution of methanol without the use of a fuel reformer. Therefore, the complexity of methanol to hydrogen conversion is eliminated [7].

Power produced with a DMFC stems from a fuel supplied in the form of vapour, liquid or as a solution. The solution approach is most favorable because of its improved thermal management, and more efficient separation of CO_2 and methanol at the anode exhaust [8]. It is a relatively easy device to manufacture and refill when needed, and using methanol as a readily available, cheap fuel of high energy density makes the DMFC attractive as a power supply for portable applications, from the sub-watt range up to several hundred watts [6].

Fig. 1 shows the basic characteristics of a DMFC, including the anode and cathode half-cell reactions. Carbon dioxide (CO_2) and water are produced according to the overall reaction:

- $2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O$

DMFCs are viewed as a viable candidate for portable applications due to their high energy density and long lifetime [9]. Therefore, extended electrical discharge, compared to existing electrochemical power sources, is expected. However, CO_2 emissions, relatively low efficiency and high fuel crossover offset the advantages that a DMFC offers. At present, there are extensive efforts on commercialization of DMFC technology for portable applications.

There are two types of DMFC: active and passive type. The difference between the two types lies in the way they introduce methanol and air into the DMFC. The air and fuel are injected into the DMFC by controlled stoichiometry in the active type. Fuel and CO_2 must be separated at the anode, and the balance of plant must control the fuel dilution in an active type DMFC, which adds to the complexity of the system, especially for portable applications [10,11]. However, in the passive DMFC, air is introduced into the cell by self-breathing and the fuel is injected into the cell with less control over its quantity. Therefore, although a passive DMFC generally performs worse than the active type, it possesses a much simpler structure. Hence, passive DMFC could be used for devices with low power requirements such as MP3 players, while the active cell performs well for higher power devices such as laptops and digital cameras [6].

3. Batteries for portable applications

3.1. Nickel–cadmium (Ni–Cd)

Nickel–cadmium rechargeable batteries are popular devices used for many portable applications. The electrodes are made of nickel oxide hydroxide and metallic cadmium, which promote the chemical reaction occurring in the cell. This type of battery possesses a fairly good re-charging efficiency, low internal resistance and small variation in external voltage during discharge. However, Ni–Cd batteries have a relatively low energy density and high self-discharge. Moreover, because of the metallic contaminants of Ni–Cd batteries, this type of battery is not considered to be an environmentally friendly solution, so it still requires substantial improvements [12].

3.2. Nickel–metal hydride (Ni–MH)

A rechargeable Nickel–metal hydride battery uses a hydrogen-absorbing alloy for its negative electrode and minimizes its environmental impact by eliminating any need for toxic cadmium. Although there are many similarities between the Ni–MH and Ni–Cd batteries, there are significant differences in the operating conditions and outputs of each battery. Ni–MH batteries are often used in digital cameras, mobile computing and wireless communications, and perform well in high current applications (e.g. batteries for hybrid vehicles [13]). But Ni–MH batteries have many limitations such as performance degradation at high temperatures, limited discharge current, high maintenance and high self-discharge. However, the main advantages of this type of battery over a Ni–Cd battery are the higher energy density and lower susceptibility to “memory” effects.

3.3. Lithium-ion (Li-ion)

A lithium-ion battery, the most novel and promising energy supply for portable applications, works on the basis of transferring

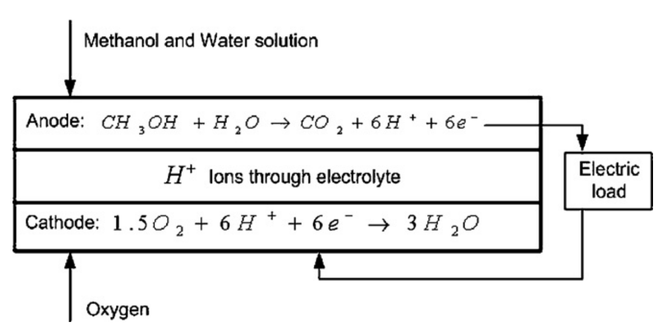

Fig. 1. Operating principle of DMFC.

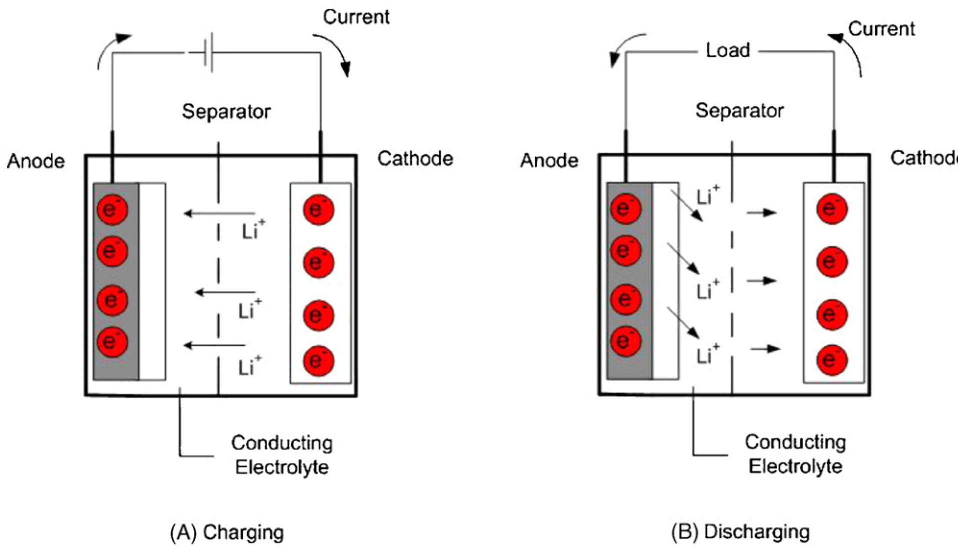

Fig. 2. Operating principle of a rechargeable Li-ion battery.

a lithium-ion between the anode and cathode of the battery. The movement of ions occurs from the anode towards the cathode during discharge, and from the cathode to the anode for charging. Fig. 2 shows the operating principles of a lithium-ion rechargeable battery [14]. A Li-ion rechargeable battery is widely used as the power source for common mobile devices, such as mobile phones and notebook PCs. It is quickly replacing Ni–MH batteries. Their use in electric vehicles is the latest and most novel application [14]. Ongoing research on Li-ion batteries has reduced the weight and size of the power supply dramatically, and this trend is still progressing. Li-ion batteries offer an ultimate eco-friendly energy supply, without using restricted pollutants such as cadmium, lead, and mercury. This type of battery could be used repeatedly, thus reducing waste. An important advantage of the Li-ion battery over other types of batteries, such as Ni–Cd, is that they do not exhibit any "memory" effect. Therefore, repeated insufficient charging and discharging of the battery does not affect the battery capacity. Hence, partial charging is possible for this type of battery [15]. Table 1 summarizes the characteristics of rechargeable batteries for portable applications discussed above.

4. Comparison between DMFC and Li-ion battery for portable applications

A fuel cell power supply can make electronic devices much lighter, due to a higher energy content per unit mass than conventional batteries [16]. The size of the power supply is another important issue that must be considered. Fig. 3 shows the variation in size of a battery and three different DMFCs with different power outputs, versus the amount of energy stored within each system (The DMFC plotted in Fig. 3 is assumed to have a power density of 80 mW cm^{-2} and average cell thickness of 0.3 cm. The sealing, manifolding and peripherals are assumed to occupy three quarters of the total volume of the DMFC system.). In order to store low amounts of total energy, a battery can be made smaller than a fuel cell. But to store high energy levels, fuel cells will be smaller and more advantageous. This result emerges predominantly as a trade-off between fuel storage and balance of plant specifications for fuel cells.

Apart from refilling the fuel, a fuel cell is virtually maintenance free, whereas the battery needs to be replaced periodically. The

Table 1
Characteristics of rechargeable batteries for portable applications.

Battery type	Nickel–cadmium (Ni–Cd)	Nickel–metal hydride (Ni–MH)	Lithium-ion (Li-ion)
Gravimetric energy density (Wh kg^{-1})	40–60	30–80	90
Volumetric energy density (Wh l^{-1})	180	140	210
Nominal cell voltage [V]	1.25	1.25	3.6
Equivalent series resistance (ESR) [Ω][a]	Extremely low	Extremely low	High
Self-discharge at 20 °C [% month^{-1}][b]	20–30	15–20	5–10
Typical slow charge time [h]	12–36	4–10	Does not tolerate slow charge time after fully charged (charging by constant voltage only)
Typical fast charge time [h]	1	0.25–1	1.5
Cost comparison	Least expensive	More expensive than Ni–Ca but less than Li-ion	Most expensive
Most common/severe degradation mechanisms (reliability)	High current overcharge, cell polarity reversal (during discharging)	High current overcharge, cell polarity reversal (during discharging)	Accidentally shortening the battery
Age-related failure modes	Crystalline growth shorting out the cell	N/A	N/A
Operating temperature [°C]	Charging: 0–50 Discharging: 10–40 Optimum operating temperature: 25	Charging: 0–50 Discharging: 10–40 Optimum operating temperature: 25	Charging: 0–45 Discharging: −20–60 Optimum operating temperature: 25

Source: [14,15].
[a] The maximum current that a battery can deliver is directly dependant on the ESR.
[b] Highly dependent on temperature. Self-discharge increases as the battery temperature increases.

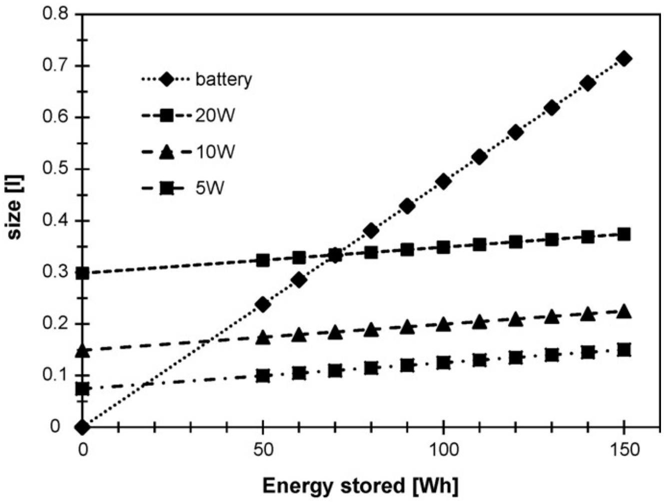

Fig. 3. Practical battery and fuel cell power system volume.

main disadvantage of a battery system is that the voltage of the battery degrades with a decrease in charge, while the fuel cell system can maintain a constant voltage, as long as it is supplied with fuel. Battery performance is also severely affected by operating at low temperatures, while this is not the case for a fuel cell system.

4.1. Safety and environmental impact

Lithium-ion batteries are highly volatile and permanently damaged, if discharged below a minimum voltage. Therefore, to prevent battery over-heating, over-voltage and polarity reversal, batteries are usually protected electronically inside the "battery module". The battery module includes several mandatory safety devices such as a shut-down separator, vent and a thermal interrupt [17]. Although cobalt in Li-ion batteries could be problematic for the environment after disposal of the battery, with recent advances in recycling of Li-ion batteries, this is no longer a major issue (e.g. [18,19]).

Methanol is a colorless alcohol that is polar and flammable. Methanol has a high auto-ignition temperature and it is a dangerous poison, enhanced by its ability to mix with water. However, methanol has less environmental impact than conventional liquid fuels [20]. Recent improvements in storage and transportation of methanol make it one of the safest fuels for portable applications. The US Department of Energy has recently permitted the transportation of methanol on airplanes, which further strengthens the global interest in using methanol as a future alternative fuel [21].

The product of the electrochemical reaction occurring in the DMFC is water and carbon dioxide. The amount of carbon dioxide produced is much less than the CO_2 emitted by the direct combustion of fossil fuels. Therefore, fuel cells with higher efficiencies than conventional engines emit less carbon dioxide. The product of the electrochemical reaction of the fuel cell is thus more environmentally benign.

Table 3
Assumptions made for the DMFC system.

DMFC power density [mW cm^{-2}]	80
Methanol concentration fed to the stack [molar]	2
Operational temperature [°C]	50–60
Fuel cell manufacturing cost* [$ W^{-1}]	5
Average percentage of rated energy capacity for 4 years operation [%]	90

* *Source*: [23].

5. Case studies of a laptop computer, camcorder and cell phone

5.1. Laptop computer

A laptop computer typically has a power output of around 10–15 W for standby operation, and up to 30 W at maximum power output. An average power output of 20 W will be assumed in this study. This study does not consider explicitly the variation in load, and how that affects the efficiency of a DMFC and batteries, respectively.

5.1.1. Power supplied by DMFC

A 20 W DMFC operating for 5 h per day provides 146,000 Wh energy for a 4-year operational time target. Table 2 shows the methanol fuel specification. Furthermore, Table 3 shows the assumptions made for the DMFC in the laptop.

The reversible cell voltage of a DMFC from the half-cell reactions can be calculated by

$$E = \frac{-\Delta \bar{g}_f}{zF} = \frac{698.2 \times 10^3}{6 \times 96485} = 1.21\,\text{V}$$

where 'z' is the number of electrons transferred for each molecule of fuel reacted in the fuel cell and $-\Delta \bar{g}_f$ is the change in Gibbs free energy.

However, at the best electrical efficiency of DMFC to achieve power densities up to 80 mW cm^{-2}, a cell voltage of 0.5 V at 41% efficiency can be obtained [8]. Therefore, the specific gravimetric and volumetric energy density of the fuel reduces to 2.51 Wh g^{-1} and 1983 Wh l^{-1}, respectively, as given in Table 2. Considering a 90% average rated energy capacity for 4 years of operational time, a total of 64.6 kg pure MeOH is required. The crossover of fuel, which is the main reason of low efficiency of a DMFC, is not included in this figure. Therefore, Table 4 is constructed to investigate the variation of fuel crossover on the overall performance and cost of a DMFC.

Under the assumption that the weight of fuel accounts for one half of the total fuel cell system weight [22], at a 100 Wh energy output, the fuel cell would weigh 1.37 kg. However, this figure would further increase because of the fuel crossover and reduction of cell efficiency.

In order to calculate the volume of the fuel: Volume$_{(DMFC)}$ = (electrical power output of fuel cell/fuel cell power density) + (energy stored/effective energy content of fuel) [24]. Hence, assuming a single fuel cell thickness of 0.3 cm and power density of 80 mW cm^{-2}, the volume of a DMFC would be 0.3 l.

The byproducts of the DMFC are water and carbon dioxide. The DMFC system generates 0.67 g of water at an energy output of 1 Wh. However, one-third of the total water produced could be recycled back to the anode compartment for the electrochemical half-cell

Table 2
Methanol fuel specifications.

Pure MeOH specific energy [Wh g^{-1}] at 1.21 V	Pure MeOH energy density [Wh l^{-1}] at 1.21 V	Pure MeOH specific energy [Wh g^{-1}] at 0.5 V	Pure MeOH energy density [Wh l^{-1}] at 0.5 V	Fuel cost [$ kg^{-1}]
6.08	4803	2.51	1983	0.5

Source: [22].

Table 4
Variation of fuel crossover on the overall performance and cost of DMFC.

Fuel crossover [mol cm^{-2} s^{-1}]	Total fuel needed for 4 years [g]	Cost of fuel neglecting water [$]	Total fuel cell cost for 4 years of operation[a] [$]
4.0E-6	905,590.37	452.79	578.79
4.0E-7	148,726.37	74.36	200.36
4.0E-8	73,039.97	36.52	162.52

[a] Peripheral cost of $26 for a DMFC to power a laptop computer is assumed in the calculations.

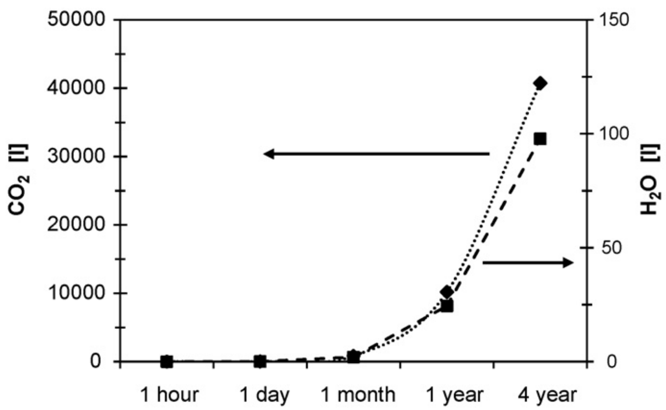

Fig. 4. Water and carbon dioxide emission during 4 years operational time of the laptop.

reaction. CO_2 is also produced at a theoretical rate of 0.279 l Wh^{-1}. Fig. 4 shows the total amount of water and CO_2 emission for 4 years of operation. As shown in Fig. 4, both water and CO_2 are produced at very low quantities during the first month of fuel cell operation. However, a total of 97.8 kg of H_2O and 40,434 l of CO_2 are produced by the end of the operating period.

5.1.2. Power supplied by a Li-ion battery

The battery studied here for comparison purposes is a 100 Wh rechargeable Li-ion battery, currently used for laptop computers [25]. Table 5 summarizes the assumptions made for the Li-ion battery in the laptop computer.

Three batteries would be required to produce the power for a laptop computer over 4 years of operation (i.e. 146,000 Wh), under the assumption that a single battery lasts for 500 charge–discharge cycles. If the AC adaptor to charge the battery is manufactured with a cost of $40 and the electricity used for charging is $0.20 per kWh (including the cost of electricity loss in the AC adaptor, battery and wires), the total cost of the power supply for the laptop Li-ion battery would be $249.20, which is comparable to the DMFC power supply with a fuel crossover on the order of 10^{-7} or less.

If instead of Li-ion batteries, the DMFC with a fuel crossover on the order of 10^{-7} or 10^{-8} mol cm^{-2} s^{-1} is utilized to provide the power for the laptop computer, an overall $40 or $80 cost could be saved over the 4 years of operation, respectively. At the current pace of worldwide improvements and research on DMFCs for portable applications, even lower costs are envisioned. In order to calculate the volume and weight of the battery, the energy stored in the battery is divided by the volumetric and gravimetric energy densities (as stated in Table 1). Therefore, the weight and size of the battery would be 1.11 kg and 0.47 l, respectively.

Table 5
Assumptions made for the Li-ion battery used for the laptop computer.

Battery operating voltage [V]	15
Battery current hour [mAh]	6600
Maximum number of charge–discharge cycles	500
Operation per cycle [h]	5
Manufacturing cost of battery [$ Wh^{-1}]	0.6

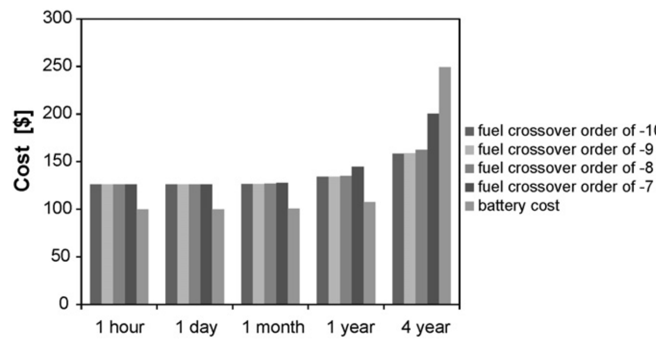

Fig. 5. Total cost of DMFC and Li-ion battery systems, as power supplies for a 20 W laptop, over 4 years of operation for a varying DMFC fuel crossover level.

5.1.3. Sensitivity study

A sensitivity study is performed in order to investigate the feasibility of a DMFC to power a laptop computer. Fig. 5 shows the total cost of DMFC and Li-ion battery systems to power a laptop computer, to work 5 h per day over 4 years of operation. The figure shows the DMFC with different fuel crossover levels for comparison purposes. During the first year of operation, the battery shows a lower cost compared to the DMFC. However, the battery needs to be replaced after 500 cycles of charging and discharging, and it results in higher battery cost after 4 years of operational time. This result is even valid when the MeOH crossover level occurs on the order of 10^{-7} mol cm^{-2} s^{-1}.

In order to investigate the variation of costs with the fuel cell specific power (i.e. power/area), Fig. 6 is presented. A higher fuel cell specific power reduces the cost of the DMFC because of more efficient electrochemical reactions. Hence, less MeOH is needed to produce the required power output, which reduces the cost. Fig. 6 is based on fuel crossover on the order of 10^{-7} mol cm^{-2} s^{-1}. Therefore, with a reduction in MeOH crossover, a significant reduction in cost of DMFC can be achieved.

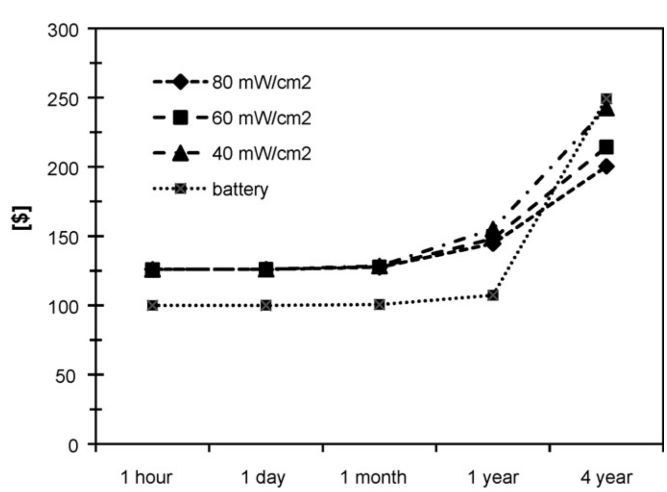

Fig. 6. Effect of varying DMFC specific power on the total cost (laptop case study).

Table 6
Total costs of the DMFC power supply for different fuel crossover levels.

Fuel crossover [mol cm^{-2} s^{-1}]	Total fuel needed for 4 years [g]	Cost of fuel neglecting water [$]	Total fuel cell cost for 4 years operation[a] [$]
4×10^{-5}	847,423.04	423.71	453.71
4×10^{-6}	90,559.04	45.27	75.27
4×10^{-7}	14,872.6	7.43	37.43
4×10^{-8}	7,303.9	3.65	33.65

[a] Peripheral cost of $5 for DMFC to power the camcorder is assumed in the calculations.

Table 7
Assumptions made for the Li-ion battery and camcorder.

Battery operating voltage [V]	7.2
Battery current hour [mAh]	1389
Maximum number of charge–discharge cycles	650
Operation per cycle [h]	2
Cost of the charger [$]	20

5.2. Camcorder

The camcorder in the analysis has an average power consumption of 5 W and it is used for 2 h per day, during 4 years of operational time. Therefore, the DMFC and battery must provide 14,600 Wh of electrical energy. The DMFC used to power the camcorder has a power consumption of 5 W, while the remaining specifications are similar to the fuel cell used for the laptop (refer to Table 3). Total costs of the DMFC power supply with different fuel crossover levels are summarized in Table 6.

Performing a similar volume and weight calculation as the laptop case reveals:

- Size of the battery = 0.048 l;
- Weight of the battery = 0.11 kg;
- Size of the DMFC = 0.0797 l;
- Weight of the DMFC = 0.137 kg.

The battery and charger specification assumed for this application is summarized in Table 7. Using the data given in Tables 7 and 5, the total cost for the battery over 4 years of operation is $41.

Fig. 7 shows the total water and CO_2 emissions of the DMFC over the 4 years of operational time. After 4 years of operation, a total of 9.8 kg of water and 4073.4 l of carbon dioxide are produced. A sensitivity study similar to the DMFC for the laptop computer is performed for the camcorder. Figs. 8 and 9 illustrate the effect of fuel crossover and specific power on the operational cost of DMFC, over the 4 years of operation, respectively. The results follow the same trend as the results of the laptop case.

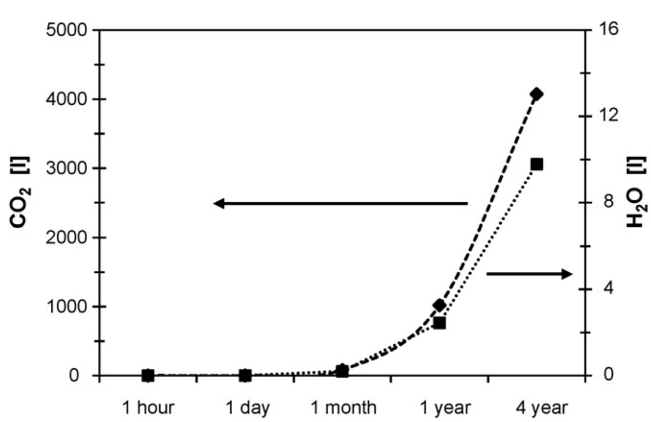

Fig. 7. Water and CO_2 production of DMFC power supply over the 4 years of operational time of the camcorder.

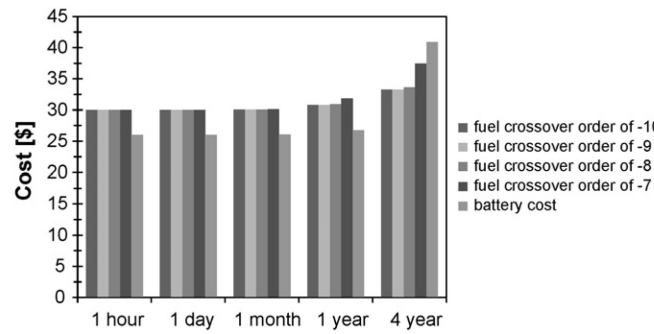

Fig. 8. Total cost of DMFC and Li-ion battery systems as power supplies for a 5 W camcorder over 4 years of operation for varying DMFC fuel crossover levels.

5.3. Cell phone

A typical cell phone has a maximum power consumption of 1 W and the battery or DMFC needs to provide 4 Wh of energy to power the cell phone for 4 h of operation per day. The power consumption of the cell phone is much lower when it is idle. Hence the 4 Wh energy is considered an average energy required for the cell phone for 1 day of operation. The DMFC used for this application has the same characteristics as stated earlier for the camcorder and laptop. The total costs of the DMFC power supply with different fuel crossover levels are summarized in Table 8.

Performing the same procedure as the camcorder and the fuel cell:

- Size of the battery = 0.019 l;
- Weight of the battery = 0.044 kg;
- Size of the DMFC = 0.017 l;
- Weight of the DMFC = 0.05 kg.

The battery and the charger specification for this application are summarized in Table 9.

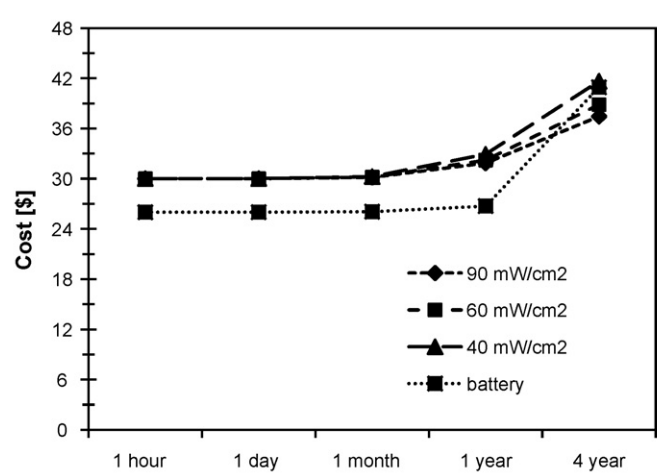

Fig. 9. Effect of varying DMFC specific power on the total cost (camcorder case study).

Table 8
Total cost of the DMFC power supply for different fuel crossover levels.

Fuel crossover [mol cm^{-2} s^{-1}]	Total fuel needed for 4 years [g]	Cost of fuel neglecting water [$]	Total fuel cell cost for 4 years operation[a] [$]
4E-5	338,969.21	169.48	181.48
4E-6	36,223.61	18.11	30.11
4E-7	5,949.05	2.97	14.97
4E-8	2,921.59	1.46	13.46

[a] Peripheral cost of $2 for DMFC to power the cell phone is assumed in the calculations.

Table 9
Cell phone battery and charger specifications.

Battery operating voltage [V]	3.7
Battery current hour [mAh]	1000
Maximum number of charge–discharge cycles	650
Operation per cycle [h]	4
Cost of the charger [$]	6

Based on the assumptions stated in Tables 5 and 9, the total cost of the Li-ion battery for 4 years of operational time is $14.40. Therefore, in order to compare the total operational cost of the battery with the fuel cell system, Figs. 10 and 11 are shown. The costs of the battery are slightly less than the DMFC during the first year of operation, but higher by the end of the 4 years of operational time. From Fig. 10, the DMFC with a fuel crossover level of 10^{-7} mol cm^{-2} s^{-1} or higher is not a competitive candidate for cell phone applications. Therefore, lowering the fuel crossover levels is essential for the commercialization of DMFC powered cell phones. Fig. 11 examines the impact of DMFC power density variation on the total costs. This graph follows the same trend as the laptop and camcorder case studies. There is a slight reduction of total cost of the DMFC by enhancing the power density from 40 mW cm^{-2} to 90 mW cm^{-2}. However, the cost reduction is most apparent when considering longer operating times. Therefore, the enhancement of DMFC performance is crucial before it can reach a commercialization stage. The total amount of water and carbon dioxide emitted from the cell phone during 4 years of operational time is shown in Fig. 12.

The weight and size of the DMFC is almost the same as the Li-ion battery system. This result satisfies the requirement of space and weight limitations for the power supply of portable devices. However, the cost analysis shows that DMFC is competitive to batteries for portable applications, with an improved specific power and reduced fuel crossover of about 10^{-8} mol cm^{-2} s^{-1} or less.

Fig. 13 is plotted to show the efficiency and cost variation of the DMFC with varying fuel crossover levels for a cell phone. Enhancing

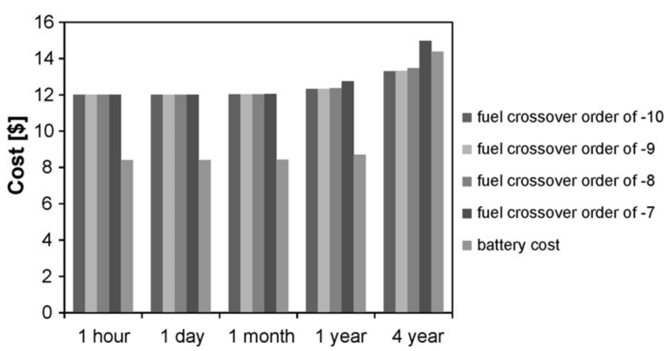

Fig. 10. Total cost of DMFC and Li-ion battery systems as power supplies for a 1 W cell phone over 4 years of operation for varying DMFC fuel crossover levels.

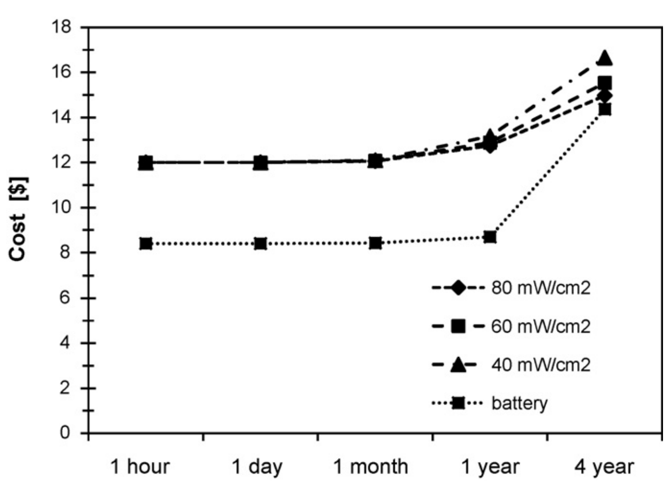

Fig. 11. Effect of varying DMFC specific power on the total cost (cell phone case study).

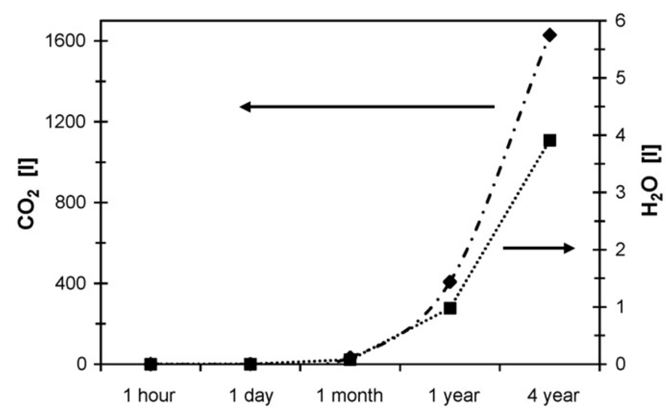

Fig. 12. Water and CO_2 production of DMFC power supply over the 4 years of operational time for the cell phone.

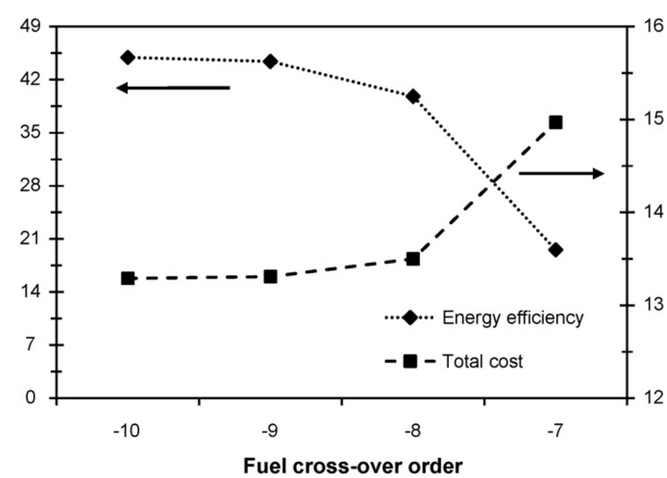

Fig. 13. Efficiency and cost variations of DMFC with varying fuel crossover levels for a cell phone.

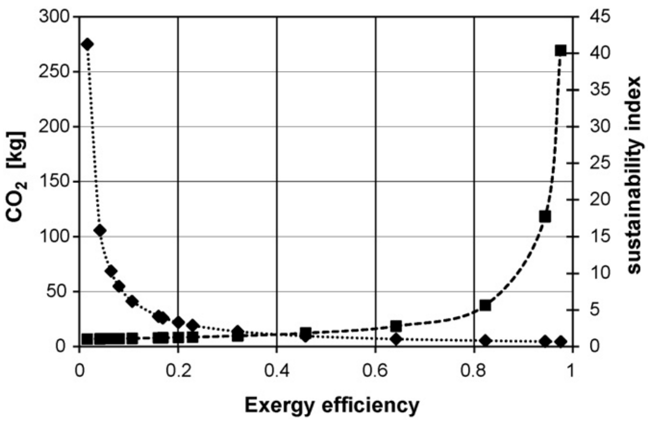

Fig. 14. Variation of environmental impact in terms of CO_2 emissions and the sustainability index with respect to exergy efficiency.

the DMFC performance by decreasing the fuel crossover magnitude increases the fuel cell efficiency, while decreasing the overall cost of the system.

Exergy is a measure of the energy availability. From a thermodynamic point of view, exergy is defined as the maximum amount of work that can be produced by a system or flow of matter or energy, as it approaches equilibrium with a reference environment [26–28]. Exergy efficiency is defined as the ratio of DMFC power output to total chemical exergy input of MeOH. Fig. 14 shows the carbon dioxide emissions and sustainability index of the cycle as a function of the process exergy efficiency, where the sustainability index (SI) can be defined as follows [29]:

$$SI = \frac{1}{1 - \eta_{exe}}$$

Increasing the exergetic efficiency of the fuel cell reduces the CO_2 emissions from the DMFC and improves the sustainability of the system. Enhanced sustainability results in lower environmental impact. Assuming that the emitted CO_2 leaves the DMFC at atmospheric pressure and temperature, 50, 5 and 2 kg of CO_2 are emitted during the 4 years of operation of the laptop, camcorder and cell phone, respectively. With an average carbon offset cost of $20 per tonne of CO_2, the laptop carbon offset costs about a dollar, while it is only a few cents in the case of the camcorder and cell phone, during the 4 years of operational period. Comparing the amount of CO_2 produced for each recharge of the battery system, to the CO_2 produced during the operation of the DMFC, the DMFC is a more promising and environmentally friendly option. The very low cost of carbon offsets for the DMFC system further strengthens this observation.

6. Conclusions

In this paper, a feasibility study of a DMFC to power a laptop, camcorder and cell phone, respectively, has been performed. A rechargeable Li-ion battery is compared with DMFC to power the portable applications. In addition, a parametric study to investigate the variation of MeOH crossover and specific power on overall performance and costs was undertaken. The results show that the volume and weight of the DMFC and battery systems are similar. However, the cost analysis demonstrates the advantages of the DMFC system over the battery. During the first year of operation, the battery system has a lower cost than the fuel cell system. However, for the total of 4 years of operational time, more than one battery would be needed, which increases the cost of the battery system dramatically. Further improvements in the fuel cell's specific power and lower fuel crossover increase the DMFC efficiency, and consequently reduce the costs. Finally, increasing the exergetic efficiency of the DMFC lowers the CO_2 emissions from the DMFC, further promoting its overall sustainability.

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