Fuel cell technologies powering portable electronic devices

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The functionality of handheld and portable electronics has advanced to a level where existing battery technology is being stretched beyond its limits to meet the runtimes demanded by consumers. As a potential solution, direct methanol fuel cell technology is approaching commercial viability, but there are still concerns regarding energy density, cost and reliability, especially at power levels of less than 50 W. Direct *hydrogen* fuel cells can address many of these issues, and as such offer a viable alternative fuel cell solution to the power needs of portable electronic devices.

Consumers today are becoming increasingly dissatisfied with the runtime available from even advanced lithium-ion rechargeable batteries in both mobile phone and laptop applications. It is rarely publicized that lithium-ion batteries can permanently lose 35% of their energy capacity over 12 months if exposed to 40°C when charged to 100% capacity just on storage – the usual state a lithium battery is exposed to in an operating laptop (**Table 1**).[1]

The insatiable hunger for increased power and runtimes from handheld and portable electronic devices continues to be a problem that requires a solution, or more likely a set of solutions. Having said this, battery technology is still advancing in terms of energy density, and will continue to play the most significant role in powering electronic devices for the near future.

Indeed, Panasonic recently announced that it has developed a battery with an almost two-fold increase in energy density, 740 Wh/liter, relative to convention lithium-ion batteries.[2] While this is a truly impressive achievement, is it sufficient for all applications and consumer needs?

Beyond batteries

As technology developers search for alternatives to battery technology, the opportunity that springs most readily to mind is the direct methanol fuel cell (DMFC). There are almost 20 companies,[3] small and large, engaged in commercializing this technology, and which appear fully committed to demonstrating the potential of this technology to challenge batteries as the future leader in power supply for handheld and portable electronic devices.

Yet today, beyond some niche military applications, the technology seems to be stuck in the lab or in demonstration programs. The key remaining challenges most often cited are in the areas of cost associated with system complexity and relatively high catalyst loadings, fuel utilization due to methanol permeation across the membrane, and the fact that CO_2 is liberated as a by-product.[4]

While recognizing that these issues require further resolution, significant advances have been made by companies including MTI MicroFuel Cells, Toshiba, Hitachi, LG Chem and Neah Power Systems which are undoubtedly bringing the technology closer to commercialization. A 2006 report from Frost & Sullivan predicts that sales of consumer portable fuel cells will reach more than 38 million units by 2009, with commercial product introductions projected to begin in the 2007–2008 timeframe.[5]

Storage temperature	40% charge	100% charge
0°C (32°F)	**2%** loss after 1 year	**6%** loss after 1 year
25°C (77°F)	**4%** loss after 1 year	**20%** loss after 1 year
40°C (104°F)	**15%** loss after 1 year	**35%** loss after 1 year
60°C (140°F)	**25%** loss after 1 year	**40%** loss after **3 months**

Source: BatteryUniversity.com

Table 1. Permanent capacity loss for lithium-ion batteries relative to storage conditions.

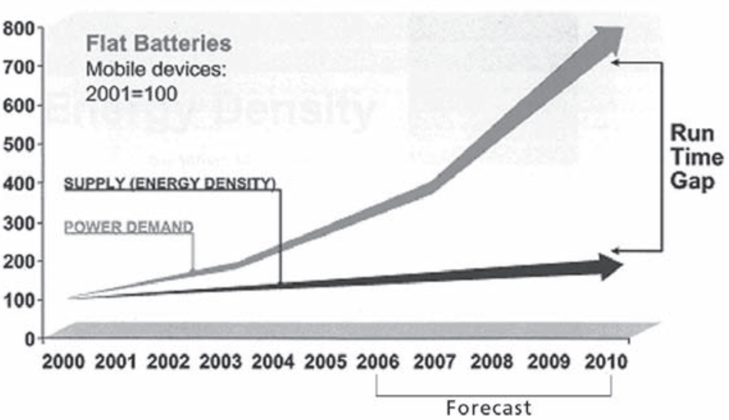

Figure 1. The runtime gap between device power demand and battery supply capability. [Source: PolyFuel Inc]

Market opportunity

In 2006 alone, the three largest Chinese producers of lithium-ion batteries manufactured more than 600 million units.[6] So this is a enormous industry, with the existing and future requirement for devices that will provide consumers with increased energy density and significantly sustained runtimes. This market driver provides significant pull for companies that can produce technologies which address this demand from device manufacturers and consumers.

The ever-growing gap in power demand versus supply is most clearly described in **Figure 1**, which was published by the DMFC membrane company PolyFuel. It is this combination of market demand and the technology advances in micro fuel cells, as battery replacements, that has led industry-leading market and research firms like Frost & Sullivan to predict that by 2012 there will be more than 80 million fuel cell-based power devices sold into various consumer-based portable electronic applications.

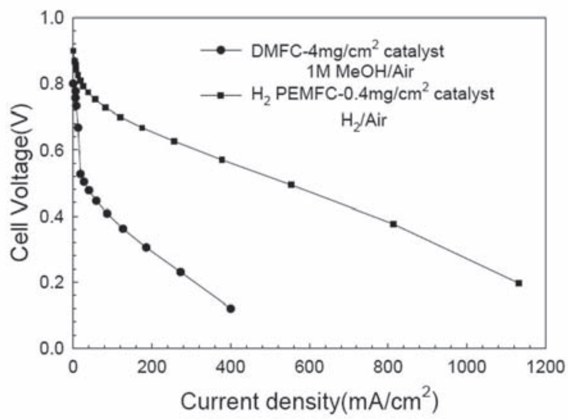

Figure 2. Performance comparison of a direct hydrogen fuel cell (DHFC, upper curve) and a direct methanol fuel cell (DMFC, lower curve) with Nafion 117 at 60°C and 1 atm. [Source: J.M. Fenton, Fuel Cell Engineering, University of Connecticut, 2002]

Figure 3. MTI MicroFuel Cells has implemented its Mobion® DMFC technology in devices such as this handheld RFID reader, shown here with a methanol cartridge being loaded into the fuel cell unit. [Photo courtesy of MTI Micro]

The overall market opportunity is captured most succinctly in a quote by Lee Gomes published in the *Wall Street Journal* back on January 12, 2004: 'Lithium-ion batteries, the last major breakthrough in battery technology, were introduced more than 10 years ago, and simply cannot keep up with the demand for more energy, creating the power gap. Clearly, the opportunity is sizable for any technology that can extend the operating time and power for the next generation of mobile devices.'

Direct methanol micro fuel cells

DMFCs were borne out of the need to develop technology that could be powered by a readily available liquid fuel, without the requirement for a 'chemical plant' that would first convert the liquid fuel into hydrogen, which in turn would provide the energy source for the fuel cell. While DMFCs address the barrier related to the use of gaseous, low energy density fuels like hydrogen, they introduce another key challenge which is critical to the application of fuel cell technology for microelectronic devices: power density.

It is a simple, but damning, reality of thermodynamics that the electrochemical oxidation of methanol is orders of magnitude slower than that of hydrogen. This fact leads to the production of a lower power output per unit active area of fuel cell components, the key cost element of which is the precious metal catalyst. In general, DMFCs use in excess of 1.5 mg/cm^2 of precious metal catalysts in devices that have commercial potential, while micro fuel cells capable of operating on direct hydrogen have demonstrated catalyst loadings of less than 0.5 mg/cm^2.

A somewhat dated, but still relevant comparison of performance between a DMFC and a direct hydrogen fuel cell is shown in **Figure 2**. In this example, the DMFC has a 10-fold higher catalyst loading than the direct hydrogen fuel cell; yet even with this large excess of catalyst, the power output from the DMFC device is much lower.

Beyond this issue, there are still other factors which could impact the rate of commercialization. In particular, these are the toxicity of methanol and the leakage of fuel from the device through membrane crossover, and the complexity of the balance-of-plant and sensor micro-system components.

To help address these concerns, MTI MicroFuel Cells has developed its Mobion® technology, which is claimed to overcome many of the technical barriers standing in the way of DMFC commercialization for handheld and portable electronic devices. According to MTI Micro, the core of Mobion technology rests in a unique approach to managing the product water produced by the fuel cell.[7] A key overall system advantage of this technology would be the reduction in balance-of-plant components and a simplification of the operating and controls subsystems. The company has unveiled prototypes of handheld devices such as RFID readers (**Figure 3**).

An alternative approach to address the concerns of DMFCs for small, portable electronic power applications has been developed by Neah Power Systems through the use of silicon-based materials. This obviates the need for, and many of the issues associated with, polymeric membranes.[8] Neah claims that its solution to DMFC issues will enable a higher power in a small form-factor, while driving down costs.

Finally, California-based UltraCell has sidestepped many of the issues of conventional DMFCs by developing a highly efficient micro reformer.[9] UltraCell claims it has smaller and lighter products than conventional DMFCs, with longer runtimes at overall lower costs. The company is commercializing its reformed methanol fuel cell technology in the UltraCell XX25 lightweight power solution for military and intelligence operations (**Figure 4**).

Beyond the numerous small private and public companies that are developing DMFC technology, there are many large Japanese and Korean global electronic device and battery manufacturers – such as Sony and Samsung – committed to securing the commercial

Figure 4. UltraCell is commercializing its Reformed Methanol Fuel Cell technology in the UltraCell XX25, a lightweight power solution for military and intelligence operations.

Figure 5. Angstrom Power has implemented its direct hydrogen fuel cell technology in products such as the A2 micro hydrogen™ fuel cell flashlight. Running on hydrogen stored in the handle and air from the environment, the 1 W LED flashlight delivers a continuous runtime of more than 24 h on a single charge of hydrogen.

success of DMFCs as a viable alternative to battery technology. Given this level of effort, commitment, scientific and engineering talent, it is likely to be more a matter of 'when', rather than 'if', we see DMFCs powering portable electronic devices.

Perhaps the more important question is whether DMFCs, given the inherent technical challenges of reaction kinetics, methanol crossover, CO_2 liberation and balance-of-plant requirements, have the capability to meet the energy density demands for power devices of less than 50 W?

Direct hydrogen fuel cells

There is, of course, an alternative fuel cell technology to DMFCs, which for some reason is not often discussed for application in microelectronic devices – namely, direct hydrogen fuel cells (DHFCs). As with other applications for DHFCs, the key issue that sparks scepticism relates to the challenges of hydrogen storage and the inherent low energy density of this fuel. Offsetting this concern to some extent are the numerous advances in metal hydride and chemical hydride storage technologies, as well as advances in DHFC stack technology, all of which have elevated the potential of DHFCs to compete with DMFCs as a battery replacement option.

At the spearhead of this development is Angstrom Power, a private company located in North Vancouver, Canada. Angstrom has already developed demonstration products with its micro DHFC technology, such as its A2 Flashlight (**Figure 5**), and has secured key strategic relationships with Motorola and Heliocentris to help bring its technology to market. Angstrom and others are also working closely with regulatory authorities to see hydrogen approved as a fuel for on-board use in aircraft, hopefully as early as 2009.[10]

On the chemical hydrogen storage side, New Jersey-based Millennium Cell is the clear leader with direct application of its hydrogen storage technology in 'hydrogen batteries'.[11] More recently, a private company in Australia, Oreion,[12] announced that it is actively evaluating DHFCs, among other fuel cell related technologies, developed by Australia's world renowned Commonwealth Scientific and Industrial Research Organisation (CSIRO).[13]

It appears that the longer DMFC technology takes to find true commercial application in micro power devices, the more interest is being generated in DHFCs as a truly competitive technology. Given the enormous market opportunity for high energy density portable power devices, with over a billion rechargeable batteries being sold annually, there will surely be a lot of room for both fuel cell technologies to capture significant value.

Future power sources for portable electronic devices

With the many hundreds of millions of dollars, pounds, euros and yen that have already been spent on DMFC technology and its near-commercial status, why should the investment community support the further development of DHFC technology for portable electronic applications? The fact is that the hydrogen technology does possess a number of advantages over DMFCs that secure its role as a viable fuel cell alternative in battery replacement applications.

With DHFCs already the chosen technology path for transportation and many other applications, it surely follows that future technology and key component development, hardware, controls and manufacturing processes and volumes can be more readily leveraged than will be the case for DMFCs. Furthermore, key DHFC components like membranes, catalysts and gas diffusion media must also benefit costwise through the leveraged scale-up of manufacture across all the applications.

Most fundamentally, because of the nearly two orders of magnitude higher kinetics of hydrogen oxidation over methanol oxidation, the energy conversion efficiency is higher and the use of precious metal catalysts is much lower,[14] leading to higher power density devices at lower cost. Finally, DHFCs are capable of near-complete fuel utilization with essentially passive operation, obviating the need for micro mechanics and sensors – which add cost, volume and complexity,

Feature	Batteries	Fuel cells
Discharge curve	Flat or sloping discharge curve	Flat discharge curve, which ensures constant power output
Energy density	• 350 Wh/l for commercial lithium-ion cells • 400 Wh/l for prototype cells	1400 to 1900 Wh/l likely for DMFCs
Chemical reactants	Storage of a fixed amount in the battery container	Provision of chemical reactants to the unit when it requires energy, enabling continuous operation
Cost	Less expensive materials	Expensive materials such as platinum for the catalyst
End-user usability	• Familiarity and safety • Safe disposal after use: can be a problem	• Instant refueling and no need for recharging • Potential safety issues with use of methanol or hydrogen as fuel
Product design	• Product-design flexibility: limited • Ultrathin and conformable batteries: on the horizon	Miniaturization goals: still goals

Table 2. Comparison of selected capabilities for batteries and fuel cells [Source: SRI Consulting Business Intelligence, May 2002]

which could in turn negatively impact durability and reliability. However, it would be naive to assume that the use of hydrogen as a fuel in DHFC devices for portable electronic applications has been fully solved, either on a technical or an emotive level for the consumer.

Micro fuel cells, whether based on DMFCs or DHFCs, are the best alternatives to compete with lithium battery technologies – which many believe are rapidly approaching the limit of their ability to provide the required power and runtime to the new generation of electronic devices (**Table 2**). The key advantage of fuel cells is that, unlike batteries, they can provide essentially continuous power as long as a fuel source is provided.

From an investment perspective, micro fuel cell technologies offer substantial operational advantages to existing technology at a competitive price. The remaining issues of fuel storage and supply are as much a regulatory issue as they are a technology issue. Ultimately, consumer demand will be the final determinant that ensures the success and acceptance of both DMFC and DHFC technologies as competitive alternatives to batteries.

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Research Trends

Fabrication of bilayered YSZ/SDC electrolyte film by EPD for anode-supported IT-SOFC

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