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Fuel cells: a survey of current developments

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Abstract

Since the first practical uses of fuel cells were developed, it has become clear that they could find use in many products over a wide power range of milliwatts to tens of megawatts. Throughout the 1990s, and later, there has been significant work carried out on adapting the various different fuel cell technologies for use in targetted consumer and industrial applications. This paper discusses these developments and gives details on the specific market segments for providing power to vehicles, portable devices and large- and small-scale stationary power generation.

Keywords: Commercialization; Market share; Infrastructure; Fuel cell

1. Introduction

Fuel cells are seen by many commentators as a solution to a whole range of environmental challenges, such as global warming and harmful levels of local pollutants, for instance those from cars in the urban environment. Fuel cells may also be able to provide economic benefits due to their high efficiency. All of these driving forces for the introduction of this technology are regularly cited [1–3].

In reality, however, perhaps the most important reason for such widespread development of this technology is its flexibility. Fuel cells have found use in transport from bicycles to spacecraft and can be used to power devices as small as a mobile phone or to provide electricity to a factory. Until the end of 2002, around 4000 fuel cell systems had been built and demonstrated, across all of these applications [4]. This number continues to increase at a significant rate.

As a result of this flexibility, however, there is no such thing as an ideal fuel cell. Different uses require different attributes. Some applications will be able to use the waste heat, some require fast start-up, many are concerned with the overall environmental impact whilst others need the niche benefits that certain types of fuel cell can bring. This variety in the requirements for a fuel cell has led to a number of different approaches being taken. Companies are looking at all types of fuel cells, even some for seemingly unlikely applications, such as solid oxide technology (SOFC) for milliwatt-scale devices.

2. Which technologies?

It is interesting to note that, over the past 20 years, the focus in terms of research and development on fuel cells has shifted dramatically. In the wake of the oil price spikes in the 1970s, the main focus was on large-scale power generation and investment was primarily directed towards molten carbonate fuel cell (MCFC) and phosphoric acid fuel cell (PAFC) technologies, respectively. In the 1990s, transport, in particular light duty vehicles, gained more attention, leading to greater concentration of effort into proton exchange membrane technology (PEMFC). This change in market share can be seen in Fig. 1, which shows the number of prototype or early commercial units placed in the field. Data available elsewhere, reveals similar trends in terms of expenditure [5].

Since 2000, there has been increasing interest in small-to-medium scale generation of power, benefitting SOFC and PEMFC. Since that date, direct methanol fuel cell (DMFC) development (usually for portable or mobile products) has accelerated, with the number of companies and other organizations involved increasing rapidly. Fuel cells therefore, stand at an interesting stage: alkaline (AFC), DMFC, MCFC, PAFC, PEMFC and SOFC systems all have their advocates. Over the longer term, however, it is unlikely that the six different technologies will all compete in the various

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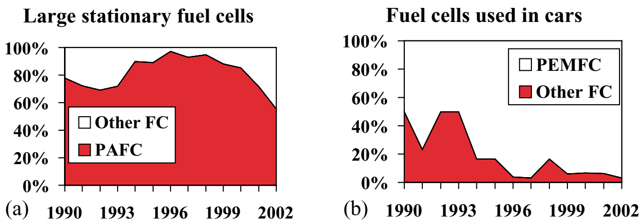

Fig. 1. (a) Competition in market share between PAFC and other fuel cells in large stationary units and (b) competition between PEMFC and other fuel cell types in cars. Both are shown as a percentage of new systems produced annually.

applications. What, therefore, will determine the success of any particular technology? Most likely, it will lie with requirements of the end-user, and this is best demonstrated by examining the individual segments where fuel cells can be used.

3. Transport applications

For any market, developers should be conscious of the distinction between a technology push and a market pull. With a long history and potential environmental benefits, it is all too easy to overestimate the end-user's desire to buy a particular product or technology.

One way, for example, of achieving acceptance is through regulation. For instance, the automotive market is highly regulated, particularly in terms of its environmental impact. In fact, almost all gasoline engine improvements have been made because of forcing legislation, such as the European emissions regulations [6], which has required technical alterations to be made. Driving forces for further improvement in automotive technology continue to exist. Local emissions of pollutants, global warming and national energy security are perhaps the three most important [7]. Fuel cells can provide solutions to all of these issues and currently appear to be an attractive proposition, perhaps alongside other innovations such as hybrid electric vehicles.

In technical terms, PEMFCs dominate in transport. In part, this dominance is simply because of the large number of companies engaged in PEMFC development for this sector but, on a more fundamental level, such fuel cells have the high energy density required to meet the space constraints in a light-duty vehicle [8]. A low operating temperature should also lead to quick start-up and shut-down. The tolerance of PEMFC to the presence of carbon dioxide is also attractive (in comparison with AFCS, which can also exhibit high power densities and fast start-up [9]). Nevertheless, the technology still has several technical difficulties such as sensitivity to poisoning by other chemicals, water management and start-up from temperatures below freezing. One possible side-effect of this concentrated automotive research into PEMFC is that costs may be reduced more quickly than for the other types of fuel cell, which may allow the technology to take a share of other markets, simply on a capital cost basis.

The PEMFC is also the chosen system for providing primary, motive power for buses involved in the clean urban transport for Europe (CUTE) project, which runs from 2003 to 2006. The only real competition in the transport market comes in the form of SOFC units which could be employed for auxiliary power (heating, air-conditioning etc.). BMW is one company that has already examined this technology in prototype vehicles.

4. Portable products

The market drivers for fuel cells in the portable sector are very different to those for transportation. Here, environmental issues are not the key driver and the main advantages of fuel cells are, instead, potential long run-times and high energy density and storage, which allow portable electronic devices to function for longer periods than those with batteries.

One very specific advantage that fuel cells hold compared with batteries is the decoupling of energy stored from peak power delivered. In a battery, these are closely related to each other and to size. For a fuel cell, the size of the cell determines the power while the total energy available depends on the fuel stored [10]. A fuel cell system is therefore rather more flexible as the energy storage can be increased with relatively little increase in the weight of the overall system weight.

In terms of fuel cell type, portable applications promise to be one of the battlegrounds between the different technologies. Both PEMFCs and DMFCs are being investigated, as shown in Fig. 2. Direct methanol's distinct advantage is the comparative ease of refuelling, using methanol cartridges. It will, though, be interesting to see how easily such a form of refuelling could be introduced on a wide geographical scale. A variety of electrical products could benefit from the use of fuel cells, but laptop computers appear likely to be one of the first consumer markets, outside military applications which are able to bear higher costs.

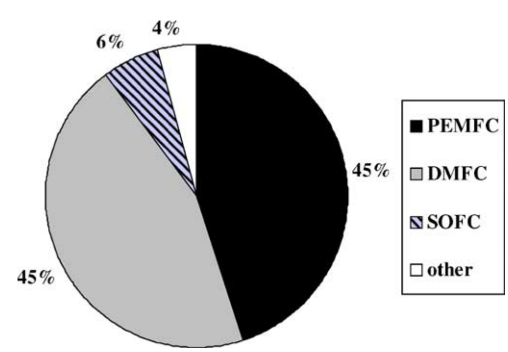

Fig. 2. Proportion of developers involved in each technology for portable applications.

5. Large-scale power generation

Many of the fuel cells commercially sold have been used for multi-kilowatt power generation, such as the 200 kW PC25 units produced by UTC fuel cells. To date, phosphoric acid fuel cell technology has taken the lion's share of the market, but MCFC, PEMFC and SOFC units have all also been demonstrated. It seems that these three last mentioned technologies are more likely to meet the criteria for mass market acceptance, particularly cost, than phosphoric acid. The PAFC has already lost ground in this market (Fig. 1(a)) and the growth of interest in other types of fuel cell appears to be a direct result of the lack of progress towards commercially sustainable prices. The PEMFC may therefore be able to take some market share because of the automotive industry's focus on cost reduction. Indeed, it is expected that automotive-size stacks will be adapted for large-scale power generation [11].

At higher power, perhaps above 250 kW, MCFCs and SOFCs are more likely to be adopted, due to their higher overall efficiencies. Companies such as FuelCell Energy are already planning to produce units that generate more than 1 MW of electricity. None of these technologies, however, has yet demonstrated the required long periods of durability, and this, as much as high efficiency, may determine the successful technology.

In both large- and small-scale power generation, the selling point of a fuel cell is much more variable than, for example, in the portable or transportation sectors. Some processes or industries, for instance, have large amounts of waste biogas (e.g. wastewater-treatment plants) and these could easily be combined with fuel cells to produce power. Some users will value high reliability due to low numbers of moving parts.

In general, though, distributed generation (the siting of many smaller generators near the point of final energy use) rather than centralized electric power generation is the key selling point. This allows the supply of both heat and power together, which makes best use of fuel cell efficiency. It would also provide resilience to the grid as shown by the continued operation of a UTC fuel cell powered police station in New York's Central Park during the black-outs in North America in August 2003 [12].

6. Residential and small stationary power generation

Typically called residential fuel cells, units of between 1 and 10 kW are an intriguing commercial opportunity. Although the overall market is expected to be smaller than for automotive systems, the requirements for introducing a product successfully will be somewhat less demanding. Space constraints are less stringent and the fuel cell will not be expected to respond as quickly to fluctuations in electrical demand.

There is no single approach to the design of residential-size fuel cell systems, and there are important distinctions to be made between the different markets even over this relatively restricted power range. Japanese developers are looking at units of no more than 1 kW as the electrical grid is generally reliable and extends over the entire country. Almost all of these are based on PEMFC technology. In North America, fuel cell systems will be significantly larger as there is interest in generation in locations not attached to the grid. Here, and in Europe, SOFC units are also being investigated.

And, even within some geographical areas, there are different approaches from different developers. Since gas and electricity prices vary so much, some studies report that a fuel cell should be used to provide all of the electricity for the entire house (i.e. follow the electrical load) [13] while others insist it should only be used to provide a baseload with the extra supplied from the electrical grid [14]. The use of fuel cells in cogeneration also attracts attention with many of the European and Japanese developers even looking at fuel cells as a replacement for a boiler, with hot water the main product and electricity merely a useful by-product [15].

PEMFC and SOFC units gain the most attention (along with some interest in alkaline technology). Most companies are, however, working in the PEM field. The first semi-commercial products (as opposed to units placed in strictly controlled field trials) should start to appear in 2004/2005. Although these residential units will be similar in size to many back-up power generators, it will require significant development work, in conjunction with end-users and manufacturers of, for instance, uninterruptible power supplies, to ensure that fuel cell technology can meet the actual requirements of real-world purchasers (including a durability of greater than 5 years).

7. Fuel choice

In all of these separate markets, there are a number of issues that must be addressed before commercialization can be successful. Assuming that technical performance and cost targets can be met, the introduction of a new technology to compete with an incumbent product can be challenging. Two examples would be the launch of compact discs (CDs) or of mobile phones. The launch of CDs was helped by the hardware manufacturers and the music companies working together to a mutual advantage. CD players were sold as an augmentation to a record turntable and tape decks and, therefore, it was not a requirement to have a complete back catalogue of material available to encourage early adopters. Likewise, the introduction of mobile phones relies on the presence of a transmitting network. Typically, this has been built first in urban environments with the highest population density, which has ensured that the market can grow without complete coverage of a country or territory.

Fuel cells, of all types, face a similar problem. By definition each fuel cell will require a source of fuel. Sales of methanol to power laptop computers could be carried out from traditional retail outlets. Those shops might, however, require incentives to stock a product which would only sell in small volumes initially. Gas companies must be persuaded that natural gas of sufficient purity for use in fuel cells is a priority. And, most visibly of all, it is important that both the automotive industry and the oil industry see fuel cells as an opportunity, thus encouraging them to work together to develop an appropriate refuelling infrastructure.

In the transportation sector, methanol and gasoline appear to hold less promise than had previously been thought and on-board hydrogen storage will be used. Two questions do, however, remain: how is the hydrogen best stored and how should it be produced in the first place. Although a number of different storage methods have been examined, none can yet meet full customer requirements and it is not clear which may be successful. Hydrogen production is also not a settled question yet but programmes such as the European CUTE bus project will examine the practicalities, costs and environmental impact of different routes, and thus help to identify the most attractive options. Even then, however, there may be no single global solution to the most environmentally friendly or cost-efficient method of hydrogen manufacture, as this will depend on the availability of renewable sources of energy and the local hydrocarbon feedstocks (natural gas, oil etc.), amongst other factors.

For portable applications of fuel cells, hydrogen and methanol are in direct competition. Hydrogen stored in cylinders or in metal hydride form seems more promising for larger portable systems, such as Ballard's 1 kW Nexa, whereas methanol is taking the lead for smaller devices. Although conceptually the creation of a methanol infrastructure is simple, there are still questions to be answered before it can be put into place.

Hydrogen is less likely to be the fuel of choice for larger stationary fuel cells. Here, natural gas or biogas are more attractive candidates. However, although an infrastructure for the supply of these might be in place, there are problems such as dealing with the sulfur-containing compounds that are used to give an odour to natural gas in case of leakage. There may yet be a market for such units running on hydrogen, particularly where this gas is already available, for instance at industrial sites such as chlor-alkali factories where hydrogen is a side-product. The proportion of large stationary fuel cells operating on each fuel (compared, with the total number of systems built) is given in Fig. 3. This distribution may change significantly over the coming years.

Overall though, the fuelling issue seems, at least temporarily, to be decided in each end-use. Longer term, there may be other alternatives and issues such as how best to supply hydrogen and which fuels are best for low life-cycle emissions of carbon dioxide will still have to be examined closely to determine the most appropriate fuels.

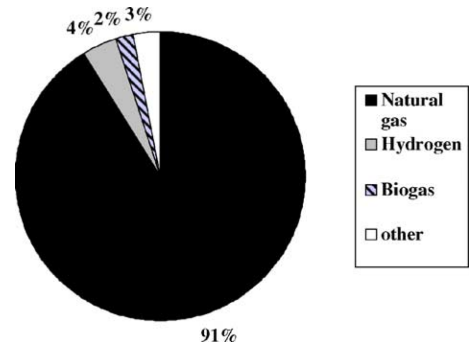

Fig. 3. Current proportions of large stationary systems (>10 kW electric power) operating on each fuel.

8. Overall industry requirements

As stated above, there is competition between the different types of fuel cell in many of the individual market segments. Which will be adopted should depend on meeting the requirements of the customer, whether that is the manufacturer of a product or its end-user. In part, these requirements will be for specific performance targets, such as power density and efficiency, which are difficult to forecast. Moreover, the customer will also require fuel cells to compete with the present incumbent technology an cost grounds. A fuelling infrastructure also has to be in place whether, for example, to supply methanol in cartridges for mobile phones or sulfur-free natural gas for residential power generation.

9. Future development

Over the last few years, the industry has moved from a pure research and development phase into a period of gearing up for production. Prices for products are not at their final level and performance is typically not all it might be. In this respect, a simple comparison with the mobile phone is informative. The first working prototype of a cell phone was demonstrated in the USA in 1973. When finally introduced in 1983, however, units still weighed 800 g each [16]. At this point, of course, the technology was really only suitable for early adopters: the clear benefits of having a portable telephone connection were outweighed for most people by the weight, cost, and other practicalities. In fact, the majority of the population could probably see no need for a mobile telephone. Now, however, both the cost and weight of a typical phone have decreased dramatically and sales are in the hundreds of millions of units annually. Fuel cells should be able to follow this product development curve.

Fuel cells are also being seen increasingly as an enabling technology for a number of environmentally-friendly energy sources. Large-scale power generation using MCFCs or SOFCs coupled with sequestration of carbon dioxide has attracted attention. Other projects look to renewable energy like wind or solar power to provide hydrogen through electrolysis. This hydrogen could then be stored and used as required in fuel cells and thus, allow renewable sources to provide power around the clock. This explicit linking of fuel cells to renewable energy will help to drive the market forwards.

Overall though, many areas related to fuel cells still require improvements to ensure that the technology is fit for daily use. Research and development is continuing at a high pace and improvements are being made. In many cases, first, or even second generation units are in field trials and the results of these are being used to continue to refine the technology. Although barriers remain, the industry is confident that it will be able to overcome these and move fuel cells firmly into the commercial marketplace.

The development of fuel cells has also gained momentum over the last few years, with an increase in interest from governments and a higher profile in terms of public interest. A supply chain is beginning to grow, with a number of companies working on large-scale manufacture of fuel cells and components. Some have even opened factories dedicated solely to fuel cells. But, perhaps the most impressive feature of the industry is the number of organizations involved. Whether they view fuel cells as an opportunity for future growth or as a threat to their current business, many people have found the case for fuel cells to be sufficiently compelling to start investing.

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