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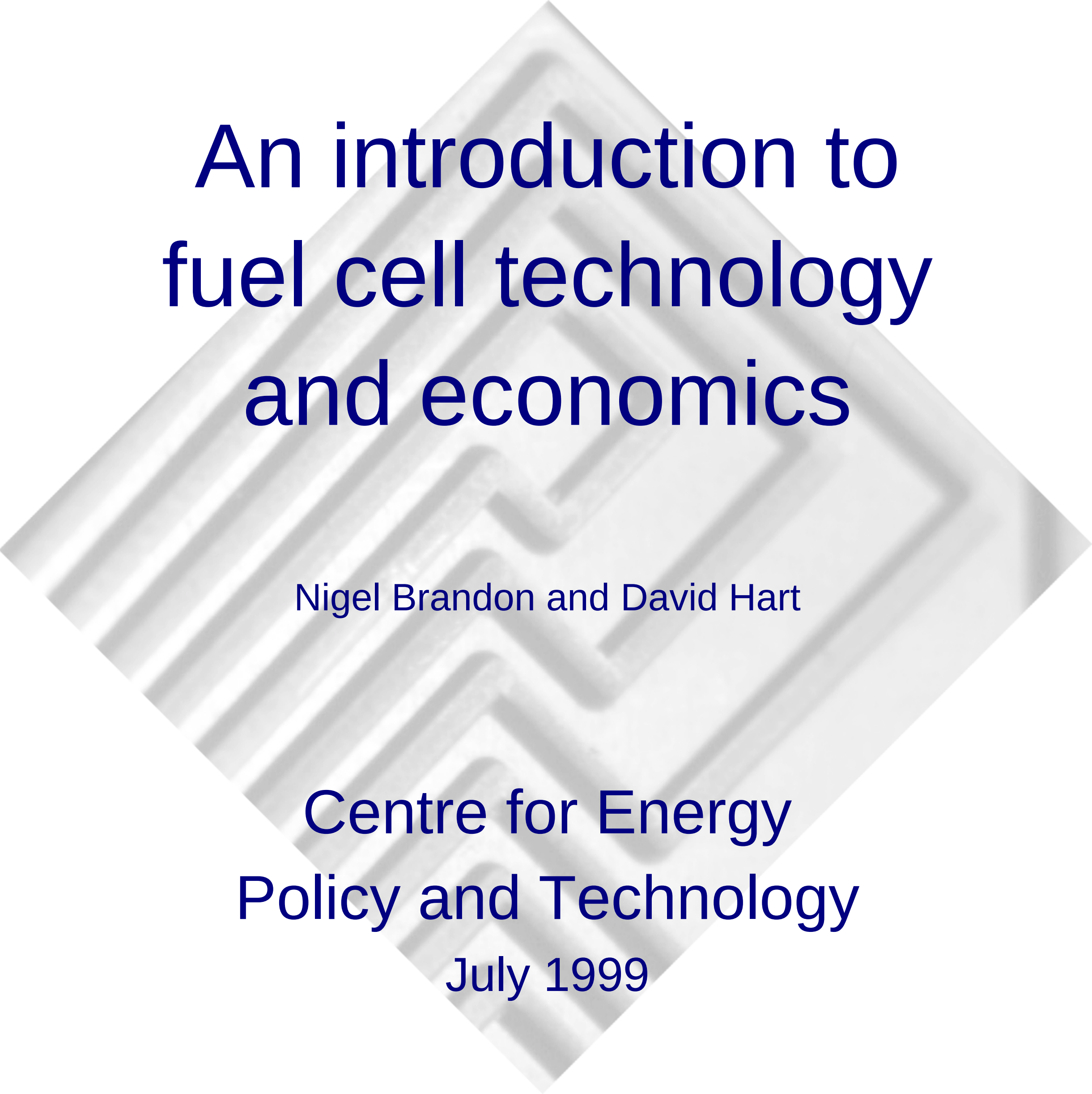

An introduction to fuel cell technology and economics

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Imperial College Centre for Energy Policy and Technology
Purpose, Background and Contact Details

Purpose

The Centre was formed to study technologies and policies on energy and environment. It will be unique in the UK and internationally and brings three long-standing strengths of Imperial College to bear on modern energy and environmental problems:

- The science and technology of all aspects of energy production and use and pollution abatement.
- The analysis of the environmental impact of energy-related pollution on ecosystems and human health.
- The economic, legal and institutional aspects of energy and environmental policies.

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The growth of the energy industry in the 20th century rested on far-reaching innovations and huge investments, with the creation of new disciplines in mining, petroleum, chemical, civil, electrical and mechanical engineering. All this required equally far-reaching investments in university education and research, and the requirements of the 21st century will be no less demanding.

Energy is in transition and change as never before – energy industries are going through rapid liberalisation, globalisation & technological development. The world market grows by an amount equal to the entire UK market *every year,* yet 2 billion people are still without modern energy. At the same time, local, regional and global pollution will need to be reduced substantially. Technological advance could bring about large reductions in pollution per unit of energy produced and consumed. But this won't happen by itself, nor will it be sufficient alone – supportive policy frameworks and more efficient resource management practises must also be developed.

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This series has been initiated to allow the timely dissemination of information, ideas and research developments within the wider community. Papers will be produced as and when appropriate, on all aspects of Energy Policy and Technology.

The cover image shows the fuel channel labyrinth for a solid polymer fuel cell bipolar plate, courtesy of DaimlerChrysler AG.

An Introduction to Fuel Cell Technology and Economics

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Summary

A fuel cell is a device for directly converting the chemical energy of a fuel into electrical energy in a constant temperature process. In many ways the fuel cell is analogous to a battery, but a battery which is constantly being recharged with fresh reactants. As well as offering a high theoretical efficiency, especially at low temperatures, fuel cells emit low or zero levels of pollutants. They can run on a wide range of fuels, ranging from gaseous fuels such as hydrogen and natural gas to liquid fuels such as methanol and gasoline.

Fuel cells could potentially be used to replace conventional power equipment in many cases. The main applications are likely to be in stationary power generation, transportation, and battery replacement. At present there are several different fuel cell types at various stages of development around the world, and for each fuel cell type there are several designs being pursued by differing industrial players. This can make it difficult for those new to the field to identify the issues associated with fuel cell development. This paper seeks to act as a first introduction to fuel cell technology, and to discuss in an objective manner the pros and cons of different fuel cell types, and their suitability for differing applications. Further, the paper looks to introduce both the technical and economic issues facing the introduction of this technology.

Fuel cells are already commercially available, albeit at high cost, for applications such as portable power sources and small-scale power generation. It is expected that commercial devices for battery replacement will be commercially available around 2001. Transport based low temperature fuel cell systems are already coming down in price but require real automotive mass-production to become cost-competitive in the standard passenger car market. The manufacturers are evenly divided between 2003 and 2004 for the first commercial car release. Some estimates suggest that around $5bn has already been spent by the major automotive companies over the past five years in fuel cell technology development. In contrast, the larger-scale stationary fuel cell systems are inevitably the furthest from commercialisation. Not only does more investment have to be put into the development and systems integration, but long-term tests are required and, like automotive fuel cell production, large manufacturing facilities. It is likely to be 2005-2010 before these systems are available on the market.

What is a fuel cell?

A fuel cell is a device for directly converting the chemical energy of a fuel into electrical energy in a constant temperature process. The fuel cell is analogous to a battery which is constantly being recharged with fresh reactants. Like a battery, each fuel cell comprises an electrolyte – an ionic conductor – and two electrodes (the positive anode and negative cathode) which are essentially electronic conductors.

The nature of the ion transfer varies between the different types of cell, but the principle shown in Figure 1 for a Solid Polymer Fuel Cell (SPFC) is representative. Hydrogen is fed to the anode of the cell where it splits into its constituents of a proton and electron; the former passes through the electrolyte and the latter is forced around an external circuit where it drives a load. The proton and electron combine with oxygen from the air at the cathode, producing pure water and a small amount of heat.

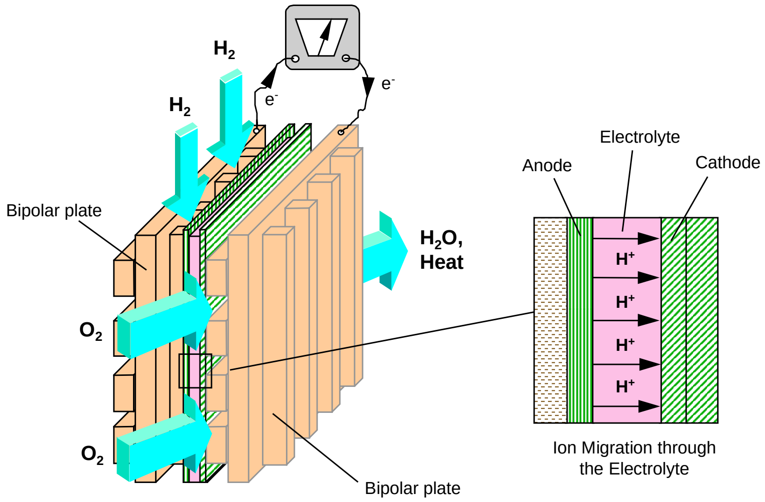

Figure 1: Operation of a Solid Polymer Fuel Cell(SPFC)

Under load a single cell produces about 0.7 Volts, so in order to achieve a useful output power individual cells are connected together in a ‘stack’. This is achieved using an interconnect or bipolar plate, which joins the anode of one cell to the cathode of the next cell. The interconnect also separates and often distributes the fuel and oxidant. An example of an SPFC stack is shown in Figure 2. In this case, the interconnect is termed the flow field plate, and the combination of electrolyte and electrodes as the membrane electrode assembly. Other fuel cell types use different terminology for these components, but their function remains the same.

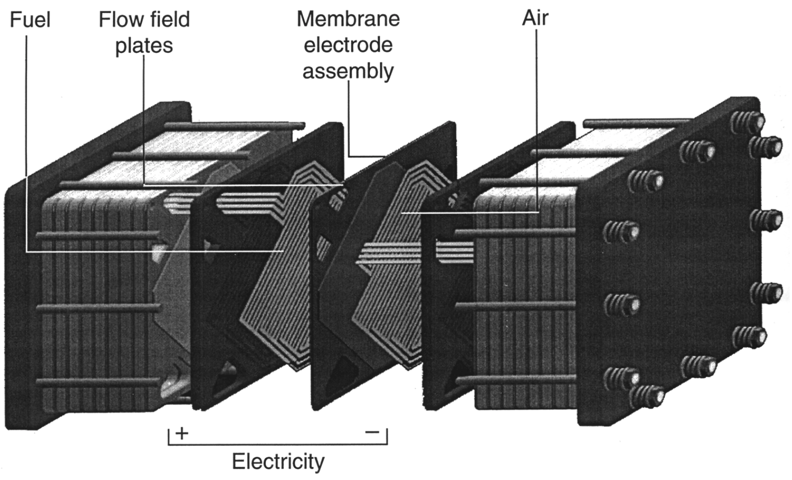

Figure 2: Example of a Solid Polymer Fuel Cell (SPFC) stack

The fuel cell differs from conventional heat engine technology (such as the internal combustion engine or the gas turbine), in that it does not rely on raising the temperature of a working fluid such as air in a combustion process. The maximum efficiency of a heat engine is subject to the Carnot efficiency limitation, which defines the maximum efficiency that any heat engine can have if its temperature extremes are known:

$$\text{Carnot efficiency} = \frac{T_H - T_L}{T_H}$$

where T_H is the absolute high temperature and T_L is the absolute low temperature.

In contrast, the theoretical efficiency of a fuel cell is related to the ratio of two thermodynamic properties, namely the chemical energy or Gibbs Free Energy (ΔG^0) and the total heat energy or Enthalpy (ΔH^0) of the fuel:

$$\text{Fuel cell efficiency} = \Delta G^0/\Delta H^0$$

Figure 3 provides an illustration of the theoretical efficiency possible from a fuel cell running on hydrogen as a function of temperature, and compares this to the Carnot efficiency at the same temperature, assuming a low temperature of 25°C. Efficiencies are quoted as lower heating value, or LHV. As the Gibbs Free Energy falls with increasing temperature, while the Enthalpy remains largely unchanged, the theoretical efficiency of the fuel cell falls with increasing temperature. Indeed, at high temperatures, the theoretical efficiency of a heat engine is higher than that of a hydrogen driven fuel cell. However, because of the need for motion in a heat engine, either rotary or linear, there are significant materials issues associated with operating them at high temperatures, from the perspective of both durability and cost. Fuel cells do not have moving parts operating at high temperatures and thus are less susceptible to this problem.

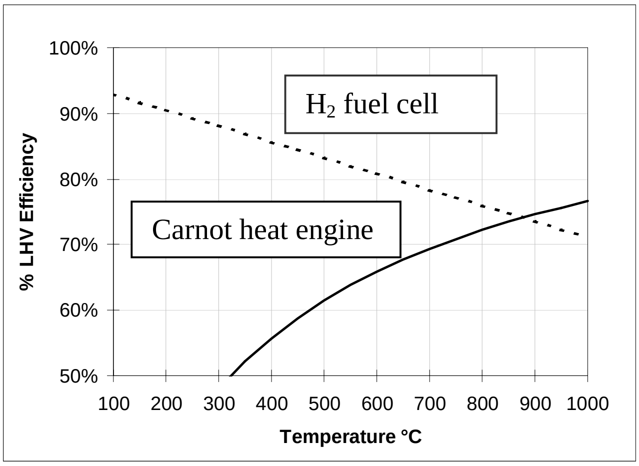

Figure 3: Relative theoretical efficiency change with temperature of a fuel cell and heat engine

In addition, other factors play a role in determining the actual efficiency of an operating fuel cell. For example, losses associated with the kinetics of the fuel cell reactions fall with increasing temperature, and it is often possible to use a wider range of fuels at higher temperatures. Equally, if a fuel cell is to be combined with a heat engine, for example in a fuel cell/gas turbine combined cycle, then high fuel cell operating temperatures are required to maximise system efficiency. All these factors mean that there is considerable interest in both low temperature and high temperature fuel cells, depending upon the application.

As well as offering a high theoretical efficiency, especially at low temperatures, all fuel cells emit low levels of pollutants such as oxides of sulphur (SO_x) and nitrogen (NO_x). SO_x emissions are low because low sulphur fuels such as methanol or desulphurised natural gas are required. NO_x emissions are negligible because even the high temperature fuel cells operate at temperatures well below those needed to form NO_x by the thermal combination of nitrogen and oxygen. However, the formation of NO_x at high temperatures is a problem for those trying to push up the efficiency of heat engines by increasing their maximum operating temperature. Further advantages are cited for fuel cells:

1. They are quiet, and involve few moving parts, other than some fans or a compressor to blow air into the device, and hence do not require much maintenance
2. They are modular, such that several can be coupled together to increase the capacity of a system, but can be mass-manufactured to reduce cost
3. They exhibit an increase in efficiency at low loads, unlike a heat engine which normally only exhibits maximum efficiency around the design point for the device. This is illustrated in Figure 4 for the case of a solid polymer fuel cell system (including ancillaries) versus two heat engines, an advanced diesel and a direct-injection gasoline engine.

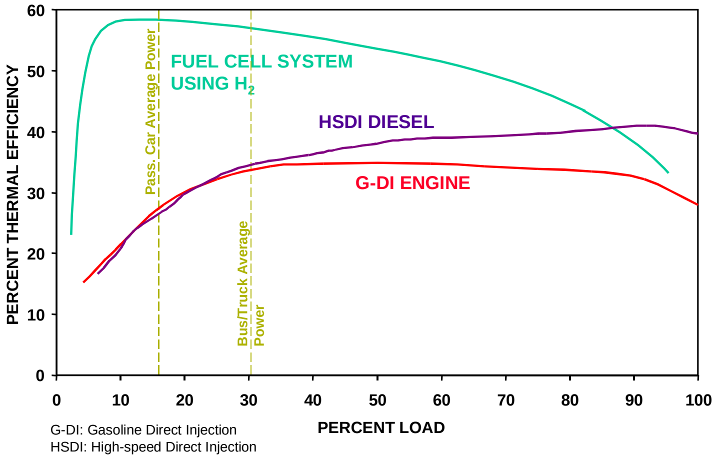

Figure 4: efficiency map of an SPFC system v internal combustion engines at all loads

What are the different types of fuel cell?

There are five main classes of fuel cell, each with differing characteristics, and differing advantages and disadvantages. The five types are summarised below in Table 1, with each taking the name of the electrolyte used in its fabrication.

Fuel cell type	**Alkaline**	**Solid Polymer**	**Phosphoric Acid**	**Molten Carbonate**	**Solid Oxide**
Acronym	AFC	SPFC	PAFC	MCFC	SOFC
Operating temp.	60-90°C	80-100°C	200°C	650°C	800-1000°C

Table 1: Fuel cell types

These five classes of fuel cell can essentially be further grouped into one of two classes, distinguished as either low temperature fuel cells (AFC, SPFC, PAFC), or high temperature fuel cells (MCFC, SOFC). The low temperature fuel cells can be distinguished by the following common characteristics:

- They generally incorporate precious metal electrocatalysts to improve performance.
- They exhibit fast dynamic response and short start-up times.
- They are available commercially (AFC, PAFC) or are near commercialisation (SPFC).
- They require a relatively pure supply of hydrogen as a fuel (e.g. SPFC catalysts are poisoned by carbon monoxide, AFCs damaged by carbon dioxide). This usually means that a fuel processor is required to convert primary fuels such as natural gas.

In contrast, the high temperature fuel cells can be classed as having the following general features:

- Fuel flexibility: they can be operated on a range of hydrocarbon fuels.
- Their increased operating temperature reduces the need for expensive electrocatalysts.
- They can generate useful ‘waste’ heat and are therefore well suited to co-generation applications.

- They exhibit long start-up times and are sensitive to thermal transients.
- They can require expensive and exotic construction materials to withstand the operating temperature, particularly in the balance of plant (piping, heat exchangers, etc.).
- Reliability and durability is a concern, again due to the operating temperature.
- They can be integrated with a gas turbine, offering high efficiency combined cycles.
- They are only at the demonstration stage.

The above summary is of course a simplification. There is work on-going to develop ‘intermediate’ temperature SOFCs for example, which operate at 500°C and could run directly on methanol as a fuel. Similarly, work also is being carried out to develop low temperature fuel cells which operate directly on methanol, rather than clean hydrogen. Nonetheless, it is reasonable to distinguish between the low temperature and high temperature variants as being best suited to transportation and stationary power applications respectively, applications which place differing requirements on the fuel cell stack and system.

What fuel do they run on?

All fuel cells can run on hydrogen as a fuel. This is combined with oxygen, normally fed into the fuel cell as air, to form water. The reaction is thus:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

However, high temperature fuel cells can also run directly on other fuels, especially hydrogen-rich gases such as methane, and some low-temperature systems are able to run on specific liquid fuels such as methanol. The application of the fuel cell system often determines on which fuel it will run, and whether that fuel first needs to be processed into a hydrogen-rich ‘reformate’, possibly also containing carbon dioxide, nitrogen or other non-detrimental products.

Fuels for stationary power generation

The common fuel for the few stationary systems that exist (mainly PAFC) is natural gas, which is reformed by a separate steam reformer before the resulting hydrogen is fed into the fuel cell stack. Demonstration SPFC systems also use this method.

High-temperature fuel cells are able to operate directly on some gas streams, though they may need to be cleaned up (sulphur and some other impurities must be removed) before this can happen. The advantage is that high-temperature cells are able to reform fuels such as methane directly on the anode of the fuel cell, because they have sufficient thermal energy and catalyst present to do so. However, the process can cause severe temperature gradients across the stack, and many designers prefer to use a separate catalyst bed within the system to split the hydrogen and carbon. These processes are called Direct and Indirect Internal Reforming, respectively.

Fuel cells will also run on hydrogen-rich reformate from other fuel sources, and there are a few successful demonstration PAFC systems using gas from landfill sites or sewage plants.

Fuels for transportation

The fuelling problem in transport is more complex than in stationary systems, because there are far more severe size, weight, cost and performance constraints. Vehicles could be fuelled using pure hydrogen, compressed and stored in a tank. Indeed, this is how most demonstration buses are supplied, making them true zero emission vehicles. However, there is rarely provision for hydrogen fuelling, so if fuel cells are to be used in cars in the medium term there may have to be another solution.

Like stationary systems, transport fuel cells (usually SPFC) can operate on reformate. This is less efficient than using pure hydrogen but may be a pragmatic approach to the fuelling issue.

Methanol has been suggested by a number of manufacturers as a good compromise fuel. Although it also requires a supply infrastructure to be developed, it is a liquid and can be handled in a similar way to gasoline. It is also comparatively easy to process into hydrogen, using steam reforming, a lower-temperature technique known as partial oxidation, or a combination of the two known as autothermal reforming. Gasoline can also be processed using partial oxidation, though the resulting reformate stream contains less hydrogen than from methanol, and reduces the performance of the fuel cell somewhat more. System outlines are shown in Figure 5. Reformer-based systems always have longer response times and are less efficient and more polluting than direct hydrogen systems.

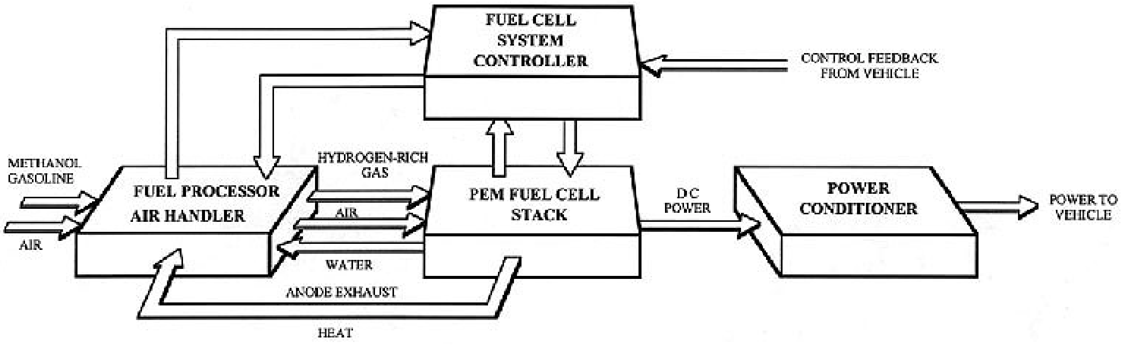

Figure 5: Possible vehicle fuel cell system in schematic

The fuelling question is still a large one as the expectations for fuel cell vehicles have been raised very high. 2003-4 is the date that has been officially suggested by a number of the world’s largest manufacturers for the first commercial fuel cell cars. If methanol turns out to be the fuel of choice then not only will methanol reformers with sufficiently high performance and low cost have to be integrated into all fuel cell cars, but the problem of supplying methanol to the consumer will also have to be solved.

If hydrogen is to be used for vehicles then storage systems need to be improved, though it is possible to use compressed hydrogen in cylinders designed for compressed natural gas and other methods are under evaluation. More important are the standards and regulatory decisions that have to be made to allow hydrogen vehicles on the road, and it must be shown that hydrogen is no more dangerous than other road fuels, though it does have different characteristics.

In some cases, fuels other than hydrogen can be used within the fuel cell without processing. Significant effort, for example, is being applied to the development of a direct methanol fuel cell which can use methanol as a fuel directly without any pre-processing. Whilst this decreases system complexity, it makes the fuel cell more difficult to design and could result in lower efficiency. Direct methanol fuel cells are thought to be at least five years further from commercialisation than conventional SPFC systems.

Applications

There are many areas in which fuel cells could potentially be used to replace conventional power equipment. Stationary power generation and transport have already been mentioned, but fuel cells could also be used in place of batteries in many cases.

Stationary power generation

Even within stationary applications there are a number of distinct divisions, though the most important ones have to do with temperature and the amount of waste heat that can be used. Low temperature fuel cells such as SPFC and PAFC are useful for very small-scale applications, though a series of PAFCs were connected together in Japan in the early 1990s to prove their modularity and produce an 11MW power plant. In general, plant sizes of 250kW (enough for a leisure centre or small office block) down to perhaps 5kW (a single house) have been suggested.

High temperature systems can be used in more demanding applications where larger systems are required and/or additional heat is useful. While heat of 80°C or more can be used for space heating, hot water and possibly absorption chillers to allow for cooling, industrial steam raising or gas turbine bottoming cycles require temperatures of at least 500°C. This not only allows for the potential of generating extra electrical power, thus improving the overall system electrical efficiency to nearly 70%, but also the possibility of using cogenerated heat (or cold) and thereby increasing total energy efficiency to 90%. Either of these options brings down the cost per unit of energy even if the capital cost of the system is high, though stationary systems will be expected to have a lifetime of 40,000 hours (five years continuous running).

Transport

Transport applications tend to demand rapid start-up and instant dynamic response from fuel cell systems, so a high temperature fuel cell is unlikely to be competitive in this instance. The prime candidate for these vehicle propulsion systems is the SPFC, which exhibits both of the above characteristics while also having very high power density. This is important as it must occupy a similar amount of space to an internal combustion engine.

AFC systems have traditionally been used in space applications by NASA – in the Gemini, Apollo and Space Shuttle programmes – but are also being investigated for certain transport applications, mainly in vehicles with limited duty cycles such as fork lifts and possibly taxis.

Of course, transport is not confined to the car and aerospace markets – locomotives, ships, scooters, and a whole host of other applications offer potential for a variety of fuel cell systems. For ships and trains, where the application is almost akin to having a stationary power plant running constantly, start-up and system dynamics are less important than noise, emissions, fuel consumption and vibration. Serious investigations are under way as to the benefits of installing SOFCs, for example, on ships to replace the marine diesel engine – traditionally a source of heavy pollution, very high noise levels and damaging vibration. However, in these cases the preferred fuel would be heavy fuel oil, one of the most difficult to process for a fuel cell application.

SPFC systems have also been commissioned for a number of the World’s navies – Ballard and Siemens have each been active in their respective countries putting SPFCs into submarines.

Battery ‘replacement’

An area in which it is possible that fuel cells may break through to commercialisation in the very near future is in the replacement of conventional batteries. Battery power for laptop computers, mobile phones and many other devices is expensive and often inconvenient if recharging is required every few hours. A small fuel cell with an equally small fuel source could potentially operate for longer than a battery, but with refuelling only taking a few minutes instead of many hours. Batteries cost much more for the amount of power they can supply than almost any other application, and this gives the fuel cell a good chance of entering the market, although it is still expensive. The ideal fuel cell for these applications is the SPFC, which not only has the high power density required for miniaturisation, but also has the most easily handled electrolyte of the low-temperature fuel cells.

However, there is also potential for micro-sized single SOFCs to be introduced into vehicles, for example, to power local electronic circuits. These are currently dependent on batteries but a small SOFC could possibly run on the vehicle exhaust gases.

Table 2 summarises the likely suitability of different fuel cell types for a range of potential applications. It includes an estimate of the probable size range in which the fuel cell modules would be fabricated. A larger system would be built up by assembling a number of these modules together. Also shown is the temperature of the waste heat emitted from each fuel cell type. Both factors are important when assessing a particular fuel cell type for a particular application.

			Suitable applications				
Fuel cell type	*Module size range (kW)*	*Waste heat output (°C)*	*Domestic power*	*Small-scale power*	*Large-scale cogeneration*	*Transport*	*Battery replacement*
AFC	<1-200	<60	✔	✔	✘	✔	✘
SPFC	<1-500	<80	✔	✔	✘	✔	✔
PAFC	5-500	<200	✘	✔	✘	-	✘
MCFC	250-5000	~600	✘	✔	✔	✘	✘
SOFC	5-5000	~850	✔	✔	✔	✘	-

Table 2: Applications for different fuel cell types

Specific fuel cells for specific markets

Alkaline Fuel Cells (AFCs)

The alkaline fuel cell, as mentioned, has a long history in space programmes, primarily as it was the first to be sufficiently developed. It is still used in the space shuttle in a very expensive guise, producing power for the on-board systems by combining the pure hydrogen and oxygen stored in the rocket-fuelling system, and producing water for the astronauts to drink. It has recently undergone something of a renaissance because it can be made cheaply in comparison with other currently available fuel cells, though mass-manufacture of other cells may reduce this advantage.

Solid Polymer Fuel Cells (SPFCs)

SPFCs have high power density, rapid start-up and low temperature operation, and so are ideal for use in transport and battery replacement, amongst other things. The present cost of SPFC systems is high, and does not help its cause in the stationary power generation market. However, mass-manufacturing techniques will bring down those costs and may enable SPFCs to compete with conventional generators and other fuel cells within the next few years. Domestic power production is a useful example. Although SPFCs operate at about 80°C, this is sufficient for space heating and hot water requirements, and there are already domestic systems of around 5kW on test in 5-10 homes in North America and Europe. The opportunity to replace the domestic boiler with something that also generates electricity is promising, but the potential for replacing diesel stand-by generators that are often dirty, noisy, expensive and unreliable is also engendering great interest. As many countries move towards liberalisation of their energy systems the opportunities for decentralised generation are growing.

There are also demonstrator plants of 250kW being produced and operated. These run on natural gas using a reformer, for the main part, and offer very low emissions but high efficiency as their benefit. They are currently expensive, as is any technology in the test phase, but the synergies that may be derived from automotive mass-manufacture of many SPFC components could bring the price down well below that of competing alternatives.

Phosphoric Acid Fuel Cells (PAFCs)

Although PAFC systems have been successfully integrated into buses, they are not ideal for transport applications. They have been very successful in fuel cell terms over the past five years as stationary cogeneration plants, with over 170 of the ONSI 200kW PC25 installed and operating worldwide. Typical applications lie in hospitals, where the waste heat can be used in laundry and other areas and where consistent and reliable power is required; in power provision for computer equipment, where the absence of power surges and spikes from the fuel cell enables systems to be kept running; and in army facilities and leisure centres that have a suitable heat and power requirement. The PAFC is by far the most commercial of the fuel cells to date, but it may well be superseded in the longer term by SPFC plants that can potentially be produced more cheaply, and by high-temperature plants that have high-grade (>500°C) heat output.

Solid Oxide Fuel Cells (SOFCs)

Solid oxide fuel cells operate at high temperatures, and therefore lend themselves to applications in which this high-temperature heat can be used. This heat can be used in two basic ways – for heating processes such as those in industry – or possibly in homes – or for integration with turbines for additional electricity production. Until recently the concept of adding a gas turbine cycle to the fuel cell system would have necessitated a system size of well over 1MW. However, recent advances in microturbines (usually derived from vehicle turbochargers or military equipment) have led to the concept of a combined power plant of 250kW with an electrical efficiency approaching 70%. Specific applications in which SOFCs may be used are in decentralised electricity generation of 250kW to 30MW; industrial cogeneration of 1-30MW; or domestic applications of close to 5kW. The latter option is being pursued by Sulzer Hexis, which has test fuel cells running in Germany and Switzerland with this in mind. As mentioned previously, high-temperature fuel cells are also flexible in their fuelling, which may make them a good future choice for locations without dedicated natural gas grids.

Molten Carbonate Fuel Cells (MCFCs)

The molten carbonate cells are likely to occupy the same market segment as the SOFCs. They run slightly cooler at 650°C, making their combination with a gas turbine less simple, but the operating temperature could be raised if necessary. Whether this would bring about materials problems is an important issue. The primary difference between the MCFC and the SOFC is the need for CO_2 recirculation in the MCFC system, meaning that it is difficult to design one below about 250kW. This removes the market in domestic scale power.

Main players

While most fuel cell types have only a few companies worldwide investing in their development, the field of SPFC companies stands at over 40 as of July 1999 and is growing rapidly. Table 3 below lists a few companies regarded as leaders in their fields, though it is by no means comprehensive.

Fuel cell type	*Company*	*Location*
Alkaline	International Fuel Cells	USA
	Zevco	Belgium/UK
Solid Polymer	Advanced Power Sources	UK
	Avista Labs	USA
	Ballard	Canada
	DeNora	Italy
	Energy Partners	USA
	Fuji Electric	Japan
	H Power	USA
	Mitsubishi Electric	Japan
	Plug Power	USA
	Siemens	Germany
	Toyota	Japan
Phosphoric Acid	ONSI	USA
	Toshiba	Japan
Molten Carbonate	Energy Research Corporation	USA
	MC-Power	USA
	Motoren und Turbinen Union	Germany
	Ishikawajima-Harima Heavy Industries	Japan
Solid Oxide	Allied Signal	USA
	Ceramic Fuel Cells	Australia
	Mitsubishi Heavy Industries	Japan
	Rolls-Royce	UK
	Siemens-Westinghouse	Germany/USA
	Sulzer Hexis	Switzerland

Table 3: The main players in fuel cells

In addition to the organisations listed here, many universities and research institutes worldwide are developing expertise across a range of aspects of fuel cell technology.

Economics

The costs associated with fuel cells are not yet clear – either from a capital or operating perspective. Current costs are well above conventional technologies in most areas, though this depends slightly on the type of fuel cell and the market area in which it may play a part.

It is clear that all fuel cell costs at present – and these are estimated at anything between 500 and 10,000 dollars per kilowatt (a mature technology such as a gas turbine costs about $400-600/kW) are high because they are representative of an emerging technology. Certainly for the low temperature fuel cells, there has been no suggestion of any technical 'showstopper' and once in mass production they could cost as little as $30/kW for transport, matching the internal combustion engine, and maybe $300/kW for stationary power. Table 4 gives an indication of current costs of the technologies and those predicted for mature systems by the companies involved.

	Technology					
Costs ($/kW)	*AFC*	*SPFC - stationary*	*SPFC - transport*	*PAFC*	*MCFC*	*SOFC*
Cost in 1999	2000	8000	550	3000	5000	10,000
Predicted cost	50-100	300	30	1000	600	600

Table 4: Fuel cell system costs - now and predicted

High temperature systems tend to be more expensive as they require significant investment in associated balance of plant, but should still be able to be manufactured for sale close to 600 dollars per kilowatt, not far from the current price for a gas turbine or gas engine.

Given the efficiency and the modular nature of fuel cell systems, this is a very low price. It suggests, for example, that a compact and emissions-free generating unit could be introduced at sizes and costs approaching that of a standard domestic gas boiler, with the capacity to provide both heat *and* power. Running costs for this unit would be slightly more than the boiler, though the overall cost to the consumer, according to several studies, should be less than buying the two services separately. Studies suggest that with a standard natural gas price of about 2p/kWh, electricity could be generated for perhaps 4p/kWh, undercutting domestic charges in the UK by about three pence. The situation is repeated in industrial examples where both gas and electricity are cheaper.

The economics of fuel cell systems are also very different in different market niches. The fuel cell has the potential to usurp many traditional technologies in a variety of markets, from very small batteries and sensors to multi-megawatt power plants. Each system has very different characteristics and will accept very different prices. For example, a laptop battery substitute that could run for 20 hours instead of two could command a high price, especially if it could be 'refuelled' in seconds from a canister rather than recharged over several hours. At the other end of the scale the potential for building modular power plants in which maintenance can be carried out on each module without shutting down the system is worth a significant amount of money to the owner.

Traditional economic calculations have suggested that the fuel cell system for large scale power generation needs to be less then $1,500/kW before it will be competitive, whilst the fuel cell system for automobiles and mass production must be competitive with the internal combustion engine at $50/kW or below. Some fuel cell systems will sell themselves at $10,000/kW, however, if they can be installed where there is currently no available technology capable of meeting requirements.

Environment

One of the areas in which fuel cells should demonstrate significant advantages is in their potentially minimal environmental impact. Fuel cells, because of the way they work, have to have clean fuel inputs, and this is reflected in the very low levels of polluting outputs – usually zero. Fuel cell systems are already exempt from emissions permitting requirements in some US states, including New York, meaning that they can bypass one of the planning stages (in itself a useful bonus in reduced cost and time).

The high efficiency of the electrochemical process and fuel cell system is an added advantage, since less fuel is required to produce a given amount of power than would otherwise be needed. This means that less fuel is used and, increasingly importantly, that less CO_2 is released. Estimates suggest that a fuel cell power plant could produce 20-30% less CO_2 than traditional power plants, and that vehicles powered by fuel cells could provide similar benefits.

However, in the case of vehicles it is particularly important to examine the fuel on which they run, as this affects the efficiency of the fuel cell system. While fuel cell vehicles powered on gasoline reformer technology will have little or no benefit in reduced greenhouse gas emissions, methanol-powered cars may produce 25% less CO_2. Using hydrogen produced from natural gas could result in cuts of up to 40%, while hydrogen from biomass, potentially a closed-cycle process, could have net CO_2 emissions of zero.

In the ultimate ‘renewable/zero-emission’ scenario, fuel cells can be run on pure hydrogen produced from renewable energy, using electrolysis of water. This ensures that there are no polluting emissions at any stage of the fuelling process (though there will inevitably be some from the manufacture and construction of the plant). This scenario is applicable both to stationary power systems and to transport, and would enable countries to reduce their dependence on imported energy in various forms, in addition to being very clean. Hydrogen can, however, be produced from a whole variety of primary resources, including fossil fuels.

National Funding

The level of governmental fuel cell funding varies significantly from country to country, with North America, Japan and parts of Western Europe particularly active. There is also some support at the international level, primarily as EU funding opportunities but also with other organisations such as the International Energy Agency.

Table 5 below shows indicative levels of support from the USA, Japan and Germany: three of the largest programmes. Increasingly, these levels of investment are being overtaken by private companies as fuel cell technologies become more developed. Some estimates suggest that around $5bn has been spent by the major automotive companies over the past five years in fuel cell technology development.

Country	**Fuel cell funding (1997US$m)**	**Funding per capita (US$)**	**Funding as a proportion of GDP**
USA	c. 73	0.28	0.0012%
Japan	c. 65	0.52	0.0020%
Germany	c. 12	0.15	0.0007%

Table 5: Approximate public fuel cell funding in three key countries

Other countries with active programmes include Canada, Italy, Spain, the UK, the Scandinavian and Benelux countries, Korea and several others. Canada stands out as having had tremendous success with its programme. Although it has received comparatively little funding (several million Canadian dollars per annum), it has been highly targeted and is always leveraged by industrial funding. The prime success story is Ballard, a manufacturer of solid polymer fuel cells, which is currently the best known company in the industry through its tie-ups with

DaimlerChrysler, Ford and Alstom. The UK has both a DTI and EPSRC programme, though to date there is little commercial activity. Several companies not manufacturing complete fuel cells, such as Johnson Matthey, who are developing membrane technologies and fuel processing, are very much to the fore worldwide, however.

The state of the art

As has already been mentioned earlier in this paper, fuel cells are likely to be introduced into some applications much more rapidly than in others, either because of a simpler system or a higher intrinsic value:

1. Battery replacement for mobile phones/laptops: developments at Energy Related Devices, the Fraunhofer Institute, Motorola and Sanyo all point towards this area as one of great potential. The cost for battery systems is very high and so mass-production for cost reduction is less of an issue than some systems. It is expected that there will be some market availability in the period 2000-2001.
2. Portable power systems of several hundred watts for use in powering roadsigns or in replacement of small diesel generators are already becoming available. They tend to run on hydrogen and will be much more accessible once mass production begins. Again, 2000-2001 is the expected timeframe for initial commercial introduction.
3. Domestic-scale systems are already on test, both from an SPFC and SOFC perspective. According to some of the developers intensive testing over the next two years should result in commercialisation around 2001-2002 for SPFC with SOFC systems likely to be introduced in 2001-2004.
4. Transport based SPFC systems are already coming down in price but require real automotive mass-production of perhaps 250,000 units to become cost-competitive in the standard passenger car market. The manufacturers are evenly divided between 2003 and 2004 for the first commercial car release. However, bus engine production may start around 2002, and AFC vehicles will also have some part to play. One or two are already being tested with expectations that they could be introduced into some fleet vehicle markets between 2000 and 2002. The key targets for transport systems are reduced cost and adequate performance, perhaps using reformed hydrocarbon fuel.
5. Small power or cogeneration systems are already commercially available in the form of the PAFC. These are still costly and are expected to face competition in the short term from SPFC (2002-2005 commercial introduction) and then small-scale SOFC, perhaps in combination with a microturbine (2004-2010). All large stationary systems have to be tested for long-term operations of >40,000 hours, which will inevitably put their introduction further away than smaller systems. There are also MCFC systems at this small scale that are likely to debut over the next five years, though long-term demonstrations are still required.
6. The larger-scale 1-20MW systems will inevitably be the furthest from commercialisation. Not only does more investment have to be put into the development and systems integration, but large manufacturing facilities and long-term tests are required. It is likely to be 2005-2010 before these systems are available on the market.

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