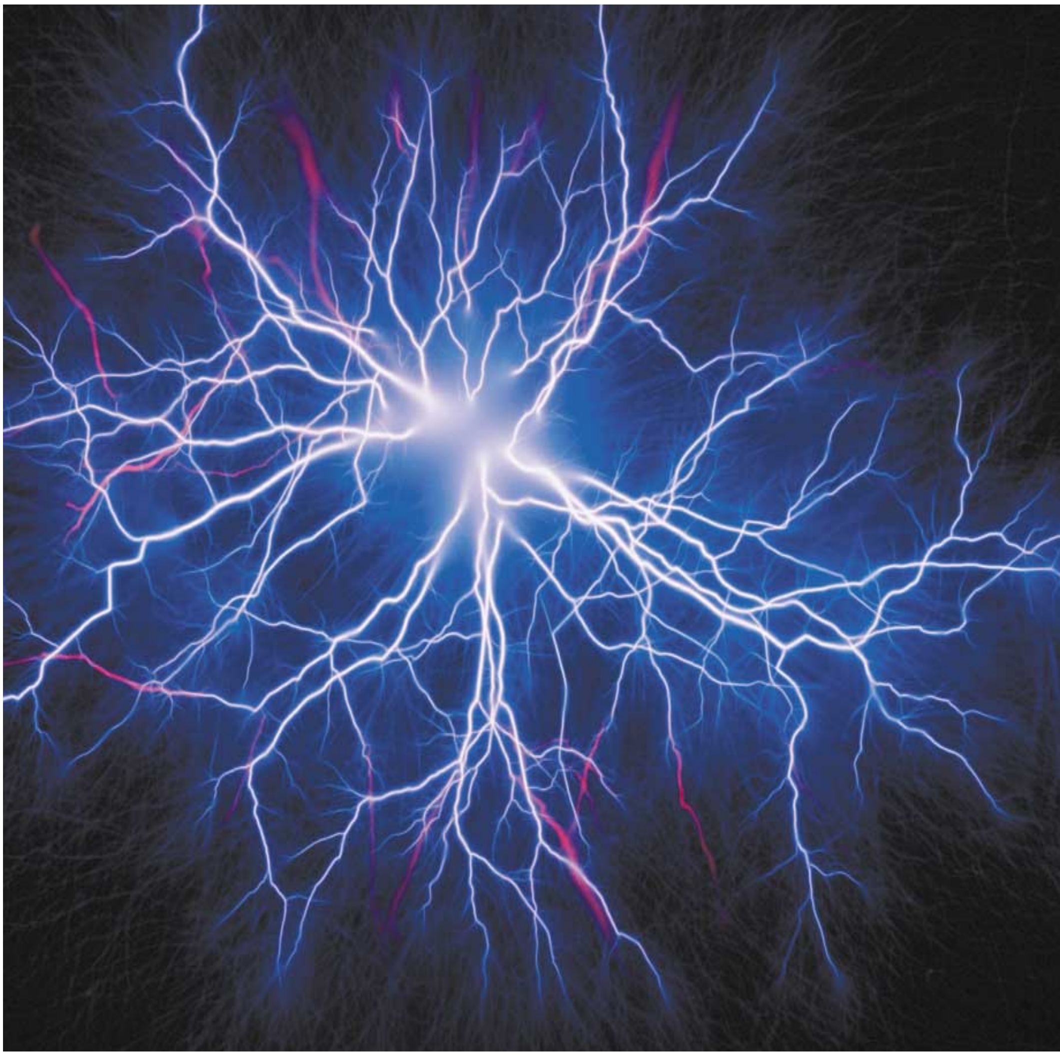
Global Equity Research

An Introduction to Fuel Cells



Phil Doran
(Frankfurt)
+49-69- 1369 8438
phil.doran@ubsw.com

John Dean
(London)
+44-20-7568 3473
john.dean@ubsw.com

UBS Warburg

Contents

Global Fuel Cell Research
Phil Doran
+49-69-1369-8438
phil doran@ubsw.com

Global Fuel Cell Research
John Dean
+44-20-7568 3473
john.dean@ubsw.com

Canada
James David
+514-20-985-8164
james.david@ubsw.com

USA
Quentin Nufer
+212-821-2314
quentin.nufer@ubsw.com

page

Introduction

The Fuel Cell industry is young, but investor interest is growing rapidly.

One consequence of rapid communications is that the stock market becomes aware more quickly of industries before they themselves have had a chance to develop. That is certainly true of the Fuel Cell industry. The demand for information on the technology and the potential it offers is growing rapidly, despite the fact that, for those who invest in Europe, there is still no quoted sector in existence. In fact, the North American industry is not much further ahead of Europe in technological terms either, although it does have a modest quoted sector.

The remit for our first industry report is therefore simple to define. We are seeking to establish the following:

(1) What is fuel cell technology?

(2) What is fuel cell technology capable of doing?

(3) What are the main drivers to its potential markets?

This report is intended as an introduction – company-specific research will follow. This report - a primer on the industry - is intended as an introduction which can be used as a reference point in coming months. We hope it offers sufficient detail to properly prepare clients for the massive change we believe is about to take place, and to identify the investment opportunities we believe will result. UBS Warburg will be producing full valuation comparisons in due course.

We intend to broaden the scope of our research into complementary and competitive technologies

The excitement surrounding fuel cells is replicated in other sectors of the new energy industry and we cannot ignore that context. In the future we intend to explore those sometimes complementary, sometimes competitive technologies and to draw conclusions on how they fit together. Certainly, many of the drivers that we believe will benefit micro-turbines, for example, will also benefit fuel cells and there are other important synergies between solar and wind technologies, for example. There are also some important challenges to be faced by those industries affected by fuel calls and their reactions to the various opportunities and threats posed are likely to provide some interesting investment opportunities themselves.

Variable quality of information from companies necessitates diligence in research

To cater for the widest requirements of clients, we have produced the obligatory Summary section, which provides an overview on the industry and its drivers. The main body of the report develops those themes in considerably more detail – not least because the industry and its technology is complex and intensely competitive. Many companies ostensibly do not currently detail the problems they occasionally face as fully as we believe they will eventually. Until that point at least, we need to be diligent in our investigations.

There remain substantial issues to investigate – but the potential is considerable.

There are no guarantees that fuel cells will succeed – but we believe they will. There is no clear indication yet of who the winners will be – though that will become increasingly apparent over time. And the valuations of those companies that do exist are tentative to say the least, but (potentially) no less appropriate for that. There is a great deal still to explore. But for now, we hope you find this introduction beneficial.

Summary

In this section we provide an overview of the main issues surrounding the fuel cell industry and the opportunities it faces – as well as the threats it will need to overcome.

The main body of the report contains substantially more information and explanation in support of the assertions we make in this section. But it also explains a great deal that is not readily available – especially from some of the protagonists. We hope it will provide a useful reference for clients as the industry starts to develop, and as more fuel cell companies come forward with their own views on what is achievable.

The Technology

Different electrolytes can lend themselves to different markets.

Fuel cells are separated into five distinct types - dictated by the electrolyte. These have various operating characteristics and some types lend themselves to particular applications better than others. Identifying those types and characteristics is an important part of deciding which companies (which tend to specialise in particular types of fuel cells) are most likely to succeed in which markets.

Competing in Today's Non-homogeneous Markets

The market is not homogeneous – there are very different price entry points.

We are convinced that it is quite wrong to view the potential of fuel cells – or even of the various technologies that comprise it – as winner takes all. There will be room for many players, as there is in so many other markets. There are also substantially different price entry points for those various markets (from premium to commodity – again, in common with other industries). This is clearly why the premium markets are likely to provide companies with the earliest sales opportunities and the initial volumes that will improve manufacturing costs and hence viability in other commodity markets.

Any impact of environmental legislation must be put in context.

It is important to note that while the building momentum in environmental legislation is likely to benefit fuel cells, the success of the technology is not dependent upon that. The main attraction of fuel cells is that they are inherently efficient AND they provide a number of additional benefits – including their environmentally benign nature. Fuel cell companies themselves talk of competition based upon price, not environmental performance.

Inherent Strengths of Fuel Cells

Fuel Cells have compelling, inherent strengths.

Notwithstanding the differences across the various technologies and markets, the main advantages of fuel cells are:

(1) **Fuel Efficiency**. Combustion technologies are theoretically incapable of providing the level of fuel/electrical efficiency that fuel cells can.

(2) **Flexibility**. Fuel cells offer high efficiency over various loads and do not require running at or close to peak load to deliver the required economics.

(3) **Environmentally benign.** Although fuel cells 'consume' hydrocarbons like conventional combustion engines, the processes involved are very different. As

a consequence they do not produce nitrogen or sulphur oxides (NO_x and SO_x) nor do not produce particulates. Carbon dioxide is produced if hydrocarbon fuels are used, but the quantities are smaller due to higher efficiencies. This may not be an issue yet – but the pressure on technologies that produce these pollutants will increase rather than abate.

(4) **High power density.** Particularly when compared to battery technology. In addition, fuel cells do not require recharging or replacement - ‘fuel and go’.

Peripheral (Though Important) Issues

Technology issues are not exclusively concerned with the cells.

The first commercial fuel cells will need to interact with existing, well-established infrastructures. They will need to consume hydrocarbon fuels and provide output to machines that need intermediate AC voltages. They must be considered as part of a system which includes a fuel processor (reformer) and a power conditioner.

(1) **The fuel reformer.** Fuel cells work using hydrogen and the most convenient source of hydrogen are hydrocarbons supplied through the petrochemical infrastructure. Extracting hydrogen from hydrocarbons is not difficult, but miniaturising the plant for transport applications is not straightforward. Carrying hydrogen, reformed elsewhere on a vehicle is possible, but storage capacity is limited. Reformer size is not such a problem with stationary applications.

(2) **The power conditioning equipment** Many seem to have assumed that power conditioning/control equipment would be readily available from established electronic equipment suppliers. In fact, this has not been the case. Many such businesses have not yet turned their attention to this market opportunity and it has been left in the hands of a small number of specialists in the field to address a rapidly growing market.

The Overall Picture

Price is an issue that we believe will be overcome. This is still first generation technology.

Although the capital cost of fuel cell systems is still well above what it needs to be, it is implicit in our belief in the technology that we expect manufactured cost of systems to fall to a level that makes them competitive in their chosen markets. It is effectively first-generation technology competing with (much more) mature solutions.

Enabling Potential and Changing Price Structures

Some powerful drivers that will encourage the use of Fuel Cells.

We believe that fuel cell technology will allow substantial markets to be attacked. But the real potential of fuel cells is only truly appreciated when we consider the changes that are taking place in, for example:

(1) Our increasing demands for reliable, high quality, cheap power.

(2) The drive to reduce/eradicate health risks from local emissions.

(3) The accelerating pressure to reduce GHG emissions

All these factors will spur the fuel cells market. Why? Because price structures and business models will change and fuel cells technology offers a balanced resolution to the issues to be addressed.

Rejecting Damage, Discounting Costs

The experience of California's ARB demonstrates the political capital in pollution issues.

The California Air Resources Board has demonstrated that there is political mileage in pursuing clean air legislation after the enormous local support it has achieved for the maintenance of its mandate. Politicians will recognise this in increasing numbers. Recent press coverage of global warming and climate change issues has been substantial and the concurrent escalation of interest in the fuel cell sector - from all quarters, including corporates, banks and lobbyists – has produced a unique atmosphere where both the problems, and the potential solution, are directly and repeatedly associated.

How do Investors Play the Sector?

By Looking at the Wider Sector Ramifications...

Fuel Cells are an enabling technology – some business models will change.

For those able to invest in the North American markets, the quoted sector there already provides a modest number of proxies. In the rest of the world, there is no quoted sector – yet. But there are companies who will be affected by the same issues that will drive the success of fuel cells. And some companies are going to change their business models because of the opportunities that are offered by fuel cells. For example:

(1) Some utilities are already planning to own and supply fuel cells for domestic markets. They will enable a gas utility to capture both gas and electricity supply to a household on long forward contracts.

(2) Energy companies are already positioning themselves as suppliers of different fuels – not just oil.

(3) Automotive manufacturers are energetic in their development of new, clean technologies.

(4) Component and materials companies have started to evaluate where they could fit in to the supply chain with technologies they already have and could readily develop.

By Anticipating New Energy Market Drivers

There are other technologies in the New Energy market – some may prove early winners.

Fuel cells offer unique advantages in the Power Generation sector – but they are not the only technology available in many of their target markets. There is a real prospect that micro-turbines, for example will make substantial inroads into some distributed power markets ahead of fuel cells (even though we believe fuel cells have the potential to displace them) with their immediate capital cost advantage. But the drivers that apply to that industry are much the same as those for fuel cells.

We will concentrate on the various fuel cells being commercially developed in this report, their potential markets and the conventional technologies they will seek to displace.

The market could be worth $50bn to $100bn by 2010 – but that will likely only be the beginning.

Our first impressions indicate that fuel cell system sales could reach US$50 to US$100bn by 2010E. Even at this level of sales, the fuel cell industry would still be very much in its infancy. This report is designed as an introduction to the technology and we therefore restrict ourselves to asserting rather than justifying our initial market expectations in a detailed way.

Suffice it to say, that the genuinely portable markets, could be worth US$10- 20bn, the stationary markets, including UPS and remote applications, could reach a total system value of US$25 to US$50bn, while the traction markets could be worth US$15 to US$30bn by 2010E.

At this stage, the priority is not about accuracy of numbers, it is about determining the viability of a potentially very disruptive technology; the scale of the opportunity it presents; and the ways in which it will impact the investment world.

Throughout the note we have shaded areas of text which we believe, whilst important, are not necessary reading to gain an understanding of the major issues.

Historical Background

The genesis of fuel cells

In 1839 Sir William Grove, Welsh Judge and physicist, demonstrated at the Royal Academy in London, that electricity could be derived from the electrochemical process of combining hydrogen with oxygen in a device that has become known as a fuel cell. Since Grove's demonstration, fuel cells have held the promise of efficient and clean energy production but their development remained largely an academic pursuit until the early 1960s. Various advances were reported but nothing that attracted industrial interest. By the late 1950s, the state-of-the-art fuel cell consisted of a 5kW low temperature alkaline fuel cell (AFC), capable of powering a welding machine, developed by the Cambridge engineer, Francis T. Bacon. But fuel cell research and development, particularly of the low operating temperature variety, was about to receive an unprecedented injection of human and financial resources as the US attempted to wrestle the initiative from the Soviet Union in the unfolding space race.

The successful launch of Sputnik on 4 October 1957 stunned the West and from that date until the mid-1960s the Soviet space programme scored significantly more successes than the US effort. On 25 May 1961 John F. Kennedy defined the course of the US space programme by proposing to Congress that America would undertake a manned lunar landing within the decade. At that time, the sum total of U.S. manned-space flight experience was Alan B. Shepard's 15 minutes of sub-orbital flight, executed three weeks prior to the President's announcement.

Development of fuel cells spurred on by the space race

There was no rocket vehicle capable of supporting such a mission, nor did the technology exist for providing the on-board power required by the crew. With a trip to the moon likely to take up to two weeks, NASA was not going to do this using batteries. The weight of batteries necessary to power the modules made them prohibitive. What attracted NASA to fuel cell research was the promise of compact size, high efficiency, zero emissions and the utilisation of the exhaust water. Thus the space race provided the first significant injection of resources into fuel cell development with NASA funding a total of some 200 research projects.

PEMFC and AFC development in the 1950-60s

The Gemini programme pursued the second type of low temperature fuel cell, the Proton Exchange Membrane fuel cell (PEMFC). This type was invented by the General Electric Company (GE) in the mid-1950s. The Apollo program concentrated on the AFC based on Bacon's work and subsequently developed by Pratt and Whitney (United Technologies). The alkaline system won the day in the Soviet Union and the United States, proving to be both reliable and durable in the closed space-ship environment. United Technologies' AFC systems have provided electricity and drinking water to every manned mission since Apollo up to and including today's Shuttle flights. It was not cost that sunk the PEMFC system, both AFC and PEMFC systems were ludicrously expensive, it was reliability. While alkaline systems had been demonstrated by the late 1950s, PEM development was still very much in the lab.

PAFC (Phosphoric Acid Fuel Cell) development in the 1970s

The early setbacks experienced with PEMs, and the subsequent drastic reduction in the number of researchers investigating the technology, led to the further development of the medium temperature electrolyte, the phosphoric acid fuel cell (PAFC). This technology was most vigorously pursued by United Technologies in the 1970s for terrestrial applications. While PAFCs are now used principally in stationary applications it was originally thought that they would be ideal for automotive use. In this application range PAFCs have long since been overtaken by the rediscovery of PEMFCs. Geoffrey Ballard and his partners in Canada revived development of the PEMFC in the early 1980s. Ballard quickly repeated and surpassed the performance of the General Electric cells and the company has subsequently become the world leader in all manner of PEMFC applications. PEM technology is now widely considered as the best-suited electrolyte for a wide variety of land-based mobile applications and is even being considered once again for space flight.

High-temperature Fuel Cells under commercial development for more than 30 years

There are two other types of hydrogen fuel cell being commercially developed namely Molten Carbonate (MCFC) and Solid Oxide (SOFC) fuel cells. Both operate at relatively high temperatures and though not developed within the Space Programme, they have long and respectable commercial development histories.

FCs can address energy requirements from milli-watts to multiple mega-watts

Given the fact that the hydrogen fuel cell family can address a huge range of power needs, from milli-watt to multiple mega-watt requirements, many companies around the world are attempting to commercialise the technology. Some are well-known multi-national concerns while others are small, virtually unheard of entities. All are striving to exploit the bewildering array of opportunities the technology potentially offers. In the next section we will give a brief overview of the principle at work in a functioning fuel cell.

Fuel Cells: How Do They Work?

Fuel cells convert chemical energy into electricity and useful heat

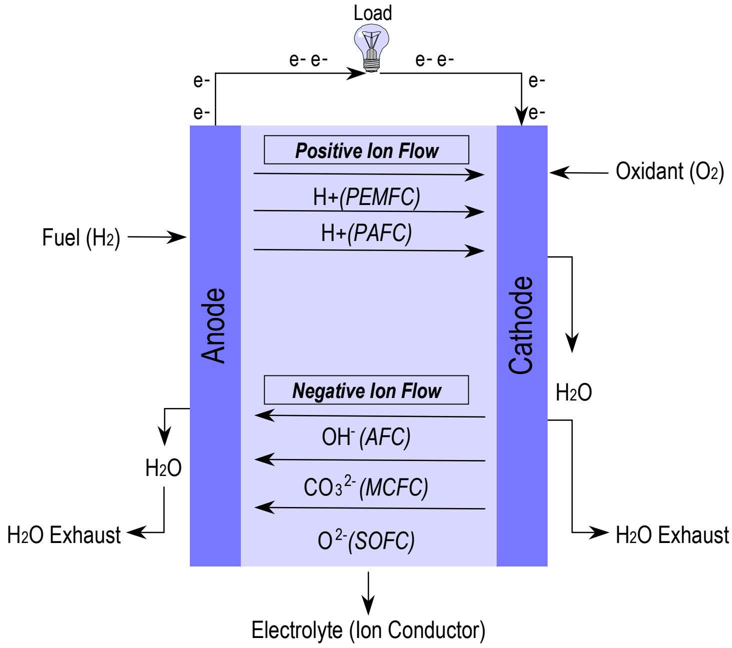
By combining hydrogen (H_2) and oxygen (O_2) into water (H_2O) fuel cells convert chemical energy into electricity and heat. Fuel cells are thus energy conversion devices just as are the batteries in portable phones; the internal combustion engines in automobiles and the gas turbine plant employed to generate electricity. They are similar to batteries in that both make use of electrodes, electrolytes and positive and negative terminals and both produce direct current electricity. Both convert energy electrochemically. But batteries store their fuel supply internally, often in toxic media, and must be disposed of or recharged when the fuel is exhausted. By contrast, fuel cells draw on an external fuel supply, like combustion engines, and likewise, in theory, will run as long as the fuel is supplied. But unlike heat engines fuel cells operate at relatively low temperatures, produce no pollutants, even when operated on hydrocarbon fuels, and significantly lower quantities of the greenhouse gas, carbon dioxide (CO_2).

In this section, we give an overview of individual fuel cells and the different electrolytes they employ. We illustrate how cells are combined into 'stacks' to achieve appropriate levels of power and outline how a fuel cell stack fits into a complete system to deliver electrical power.

Five types of hydrogen fuel cells are being commercially developed

There are five types of fuel cell being commercially developed each with its own electrolyte, or membrane. Proton exchange membrane (PEMFC) and phosphoric acid fuel cells (PAFC) both use acid-based electrolytes. Alkaline fuel cells (AFC) and molten carbonate fuel cells (MCFC) employ liquid alkaline-based electrolytes while Solid Oxide Fuel Cells use a zirconia-based ceramic. An idealised schematic, detailing gas flows, electron flow and the direction of ion conduction for the various types of fuel cells is shown below:

Chart 1: Composite Fuel Cell Diagram



Source: Adapted from schematic in DoE's Fuel Cell Handbook, 1998.

Hydrogen (H_2) and oxygen (O_2) gases are combined into water (H_2O) to generate electricity

Regardless of the specific nature of the type of fuel cell employed, the process of combining hydrogen and oxygen gasses into water results in the generation of electricity.

A single fuel cell, the width of which is measured in millimetres, essentially consists of an ion conducting material (electrolyte), two electrodes (a negatively charged anode, and a positively charged cathode) and two gas-channelling plates (not detailed), which have grooves etched into their surfaces to carry the H_2 and O_2 gases into the cell. As well as feeding gases into the cell the plates also remove the product (H_2O) water out of the cell as well as functioning as current collectors, transporting the electrons to the load.

The gases are continuously fed into the cells, hydrogen to the anode and oxygen (or air) to the cathode, at which point the electrochemical reactions that produce electrical current get under way. The electric current, or electron flow, is from the anode to the cathode, via the load or external circuit, regardless of the electrolyte. The direction of the ion flow on the other hand, is dependent on whether the ion is positively or negatively charged. This in turn is determined by the choice of electrolyte. In general the acid based-electrolytes conduct positively charged ions, or protons from anode to cathode, while the alkaline-based electrolytes conduct various negatively charged ions from cathode to anode. As can be seen above, the direction of the ion flow fixes the site of water formation and ejection.

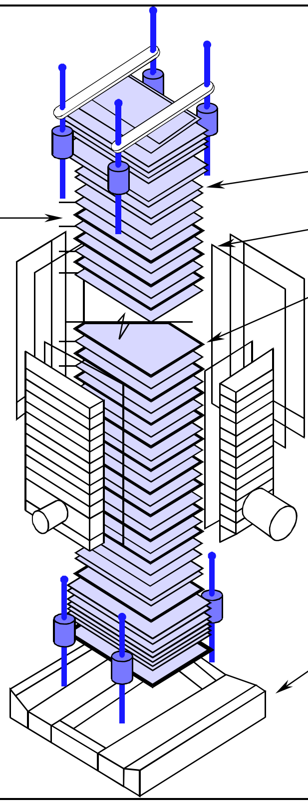
Chemistry limits the voltage of an individual fuel cell to a theoretical maximum of about 1.23 volts. Cells typically operate at 0.7 of a volt (V). A good fuel cell will deliver about 0.5 amps (I), per square centimetre of cell surface area. The power of the cell, or the number of watts (W) it can produce, is equal to the voltage multiplied by the current according to the formula:

$$W = V*I$$

The power output of a cell is proportional to the active surface area. To generate significant power output cells need to be connected together in stacks.

The following diagram shows the construction of a 100-kilowatt (kW) molten carbonate stack:

Chart 2: Construction of 100-kilowatt (kW) Molten Carbonate Stack



Source: FuelCell Energy

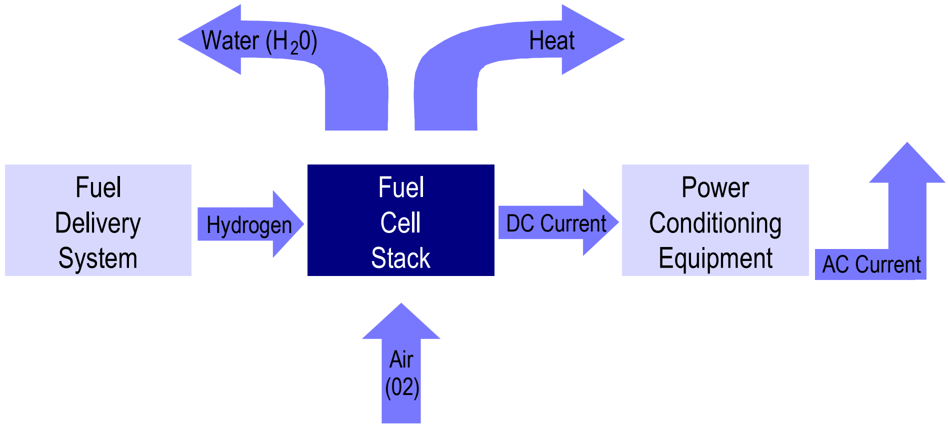
Stacking cells increases power

The stacking procedure is much the same for any of the cell types and can be arranged vertically or horizontally and are held together by end plates. All stacks require a manifold to feed each individual cell uniformly with air and fuel. (The inclusion of an internal reforming unit shown above is unique to the higher temperature cells - the individual electrolytes are discussed in more detail below) The salient point here is that increasing power is achieved via the 'stacking' of individual cells, in exactly the same way that power is increased in batteries.

Stacked cells are but one part of a bigger system

A fuel cell is one component in a system. A complete a fuel cell power plant includes a stack, a fuel processing subsystem and a power conditioner. The fuel system can range from a simple flow control unit, in the event that hydrogen is the fuel, to a complex fuel processor when a hydrocarbon fuel such as gas or methanol is used. The power conditioner converts the electrical output from the stack into the type and quality of power required. These systems range from simple voltage control units, when powering direct current equipment, to complex devices capable of converting direct current into alternating current used by most electrical equipment. The following schematic describes a complete fuel cell system:

Chart 3: Complete Fuel Cell System



Source: UBS Warburg

Fuel cell systems are suitable for a number of applications

The power plant above could as easily power a vehicle as a commercial building or a portable electronic device. Exactly what the system powers is largely a question of the type of electrolyte employed system design and source of fuel.

As previously noted, fuel cells 'consume' oxygen (O_2) and hydrogen (H_2). While the O_2 can be separated from the surrounding air, the provision of H_2 presents significant problems. Hydrogen may constitute the most abundant element in the universe but to all intents and purposes it does not exist on earth in its elemental form, (H_2), and so has to be extracted from a feedstock. Hydrogen can be taken from several sources. Apart from cracking H_2 from water, it can also be extracted from any carbonaceous fuel including petrol, diesel, natural gas, methanol and ethanol. In most near- to medium-term fuel cell applications the necessary hydrogen will be extracted from a hydrocarbon feedstock.

Hydrogen Infrastructure – An Automotive Issue

Potential infrastructure problems, mainly an automotive issue

Before discussing the individual electrolytes it is worth noting that the issue of infrastructure poses significantly different hurdles, depending on the intended application. Genuinely portable applications in all probability will employ the Direct Methanol Fuel Cell (DMFC), a variant on the proton exchange membrane (see pages 19 and 20 below). Such cells do not use any form of fuel processing equipment as they extract the hydrogen directly from a water/methanol mix within the fuel cell itself. The fuel is stored in small cartridges like the ink-cartridges used to refill fountain pens. It is unlikely that the retail distribution of such cartridges would pose any infrastructure problems.

Low power devices such as air compressors, recreational power for camping and low power remote applications will use propane for which a significant infrastructure already exists. Fuel cells used in all manner of stationary applications from homes to industrial plant, will use natural gas and its existing infrastructure.

Defined Cycle Fleets – An Exception

But not for all vehicles

The real infrastructure problems are in private transport and haulage markets, given the current prospect that a new fuel such as methanol or hydrogen has to be used. Defined cycle vehicles such as local delivery trucks, city buses and captured fleet vehicles, such as those operating within airports, can refill at their central depot and therefore will not depend upon major infrastructure investment to be viable. The test buses used in the Vancouver and Chicago trials, for example, ran on hydrogen electrolysed at their respective depots. The 30 buses DaimlerChrysler is putting in nine European and one Australian city will also use hydrogen electrolysed at their depots as do the various hydrogen vehicles currently operating at Munich Airport.

Hydrogen infrastructure-related issues

But outside of these markets there are three issues to address before a hydrogen-refilling infrastructure becomes widely available, through nationwide service stations. These issues are:

(1) The technical problems associated with the storage and transportation of hydrogen

(2) The astronomical capital cost of installing a hydrogen infrastructure

(3) The problem of producing hydrogen in a cost competitive way

In part to address these issues, and in conjunction with the development of fuel cells, fossil fuel reforming methods are being developed which will enable the employment of fuel cells ahead of the installation of a hydrogen infrastructure.

Whilst we do not doubt that the world will move towards becoming a self sufficient hydrogen economy, this is likely to come in two stages:

Stage one: introduction of conversion devices for fossil fuels

The first stage of transition will begin with the introduction of cleaner, more efficient conversion devices, like fuel cells, which, with the aid of catalytic fuel reforming technology, will initially exploit hydrocarbon fuels. Thus while we await the resolution of the substantial issues dogging the deployment of the hydrogen economy, we can start the transition with a more efficient exploitation of fossil fuels.

Stage two: direct extraction of hydrogen from water

The second stage, involving the direct extraction of hydrogen from water, will only come when the storage and transportation problems as well as the capital and operating cost problems have been surmounted. Such an economy would be free of pollutants along the entire energy chain, but for the present, remains a long-term objective. In the meantime reforming technologies to enable fuel cells to make full use of the existing refuelling infrastructure are being developed and deployed.

Fuel cells are energy efficient and environmentally friendly

The reason fuel cells can be regarded as clean, even when using fossil fuels lies in their superior efficiency, which gives more power per unit of fuel, but also in the way they extract the energy from the fuel. On the one hand the significantly higher fuel efficiency of fuel cells over combustion engines, combined with the fact that the hydrogen is extracted catalytically in the reformer, reduces carbon dioxide emissions by up to 50% per unit of fossil fuel used. On the other hand, the use of electrochemical processes at relatively low temperatures avoids the creation of local pollutants such as oxides of nitrogen (NO_x) and sulphur (SO_x) and particulate matter (PM). We will return to the issue of the environment in much more detail later.

First we briefly outline some of the reasons fuel cells look set to make an impact on their chosen markets.

Why Now?

Reasons for rising confidence in fuel cell technology

There are many reasons why fuel cell technology is thought to be on the verge of non-subsidised commercialisation. Below we list the main reasons for this rising confidence:

(1) Many of the necessary advances in materials science have been made.

(2) Performance is rapidly approaching comparability with the thermal engines and batteries that fuel cell systems seek to displace.

(3) Billions of research and development dollars have been invested by industry and government.

(4) Cost reductions have been achieved that run into orders of magnitude.

(5) The rise of environmental legislation is changing the price structure in favour of clean technologies.

(6) Critical industries such as the auto, oil and energy sectors are embracing fuel cell systems

(7) Many (North American) companies are coming to market, some for a second time, to finance the construction of manufacturing plant

And if the fuel cell industry proves to be commercially viable, once it has arrived its very nature will afford those companies with genuine technological edge a significant degree of protection.

Barriers to Entry

Fuel cells possess significant barriers to entry

It is important to recognise that this is a technology characterised by at least three significant barriers to entry. The initial investment risk will not be exaggerated by the massive entry of 'me-too' companies as commercialisation takes off.

The barriers are:

(1) Demonstration time of the fuel cells cannot be short-circuited:

a) Cars must run for 5,000 to 10,000 hours,

b) Stationary applications demand a minimum life time of 40,000hrs

(2) The nature of the knowledge invested technology lends itself to patent protection.

(3) The knowledge required to design and build fuel cell systems also lends itself to being easily compartmentalised and hence it is relatively easy to maintain trade secrets.

Before highlighting the individual fuel cell electrolytes, in the next section we focus on more general features shared by the family of hydrogen-air fuel cells.

Electrolyte Comparisons

Fuel cells are now widely regarded as one of the most promising energy conversion technologies for the not-too-distant future. Some of main advantages enjoyed by all fuel cell systems, regardless of electrolyte include:

Common features of fuel cells include:

(1) Efficiency

(2) Scalability

(3) Modularity

These features facilitate huge versatility in their use

Owing to the fact that fuel cells convert fuel electrochemically, they are inherently more efficient than conventional combustion technologies. In addition, the efficiency of the fuel cell stack is determined by the performance of the individual cells, leaving small fuel cell power plants as efficient as large ones. Thus scaling the stacks up or down leaves efficiency unaffected. Further, fuel cell systems lend themselves to modularity. For example, a 1-megawatt unit could be made up of say four stacks of 250kW. One clear advantage of such modularity allows for stacks to be shut down when not required or when routine maintenance checks are being conducted without the need to close the entire system down. An additional important feature shared by all fuel cell technologies is the fact that efficiency remains high across a wide range of load.

Distinguishing Features

One method used to distinguish between fuel cells is by the electrolyte, which can be arranged according to the operating temperature as shown in the following table:

Table 1: Comparative Fuel Cell Types by Electrolyte

Electrolyte	Polymer (PEM)	Alkaline (AFC)	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Operating Temp.	50 – 100°C	50 – 100°C	~200°C	~600°C	500 – 1000°C
Heat Applications	Space + Water	Space + Water	Space + Water	Combined Cycle, CHP	Combined cycle, CHP
Fuel sources	H_2, Reformate, Methanol*	H_2	H_2, Reformate	H_2, CO, Natural gas	H_2, CO, Natural gas
Electrical Efficiency	40-50% ~20%*	70%	40 –50%	50 – 60%	45 – 55%
Ionic conductor	H+	OH-	H+	$CO_3^{=}$	$O^{=}$
Electrolyte Phase	Solid	Liquid	Liquid	Liquid	Solid
Catalyst	Platinum	Noble and Non-noble	Platinum	Non-noble	Non-noble
CO	Poison	Poison	Poison	Fuel	Fuel
CO_2		Poison			

Source: UBS Warburg * Refers to Direct Methanol Fuel Cells, a variant of PEM technology. See page 19 below

Operating temperature is important to application

In the lower and medium temperature electrolytes such as AFC, PEM and PAFC, the waste heat from stationary fuel cell systems can be used for space and water heating, increasing the overall energy conversion efficiency of the plant. In the higher temperature systems the quality of the exhaust heat is such that it can be used in operations requiring high quality heat. These include process manufacturing, hotels and hospitals. Alternatively the exhaust heat from these systems can be used in combination with a turbine in a bottoming cycle to raise the overall electrical efficiency of the system to above 80%.

And has implications for the quality of the hydrogen fuel fed into the cell

While fuel cells run on hydrogen[1] it is important to be clear that the cells are indifferent as to the source or carrier of the hydrogen. In the medium term, the hydrogen will be supplied to the majority of fuel cells from a hydrocarbon source such as natural gas in stationary applications, petrol and/or methanol in automotive use and diesel in military operations. In extremely low power military and civilian communications devices the most likely fuel candidate in the absence of satisfactory hydrogen storage containers is methanol in the low temperature Direct Methanol Fuel Cells, a variant of the standard PEM cell. Having stated that fuel cells run on hydrogen the quality of the required hydrogen varies significantly depending on the electrolyte and operating temperature. In general the lower temperature cells require extremely high quality hydrogen, which increases system complexity and hence cost. On the other hand the high temperature MCFC and SOFC cells can consume less than pure hydrogen streams, though not with sulphur in the gas.

Fuel efficiency remains high across a wide range of load, unlike in ICEs

It is worth noting that 'efficiency', as shown above, refers to fuel efficiency, ie how much energy the fuel cell extracts from the fuel. The important point is that the high efficiency rates of fuel cells hold over a wide range of the load. By contrast the efficiency of combustion engines falls as soon as the engine is no longer working at peak load. To be sure, when comparisons are made between fuel cells and heat engines the efficiency numbers quoted for the thermal engines are normally peak, and therefore, depending on the application, can be extremely misleading. This theme is explored in more detail in section on conventional technologies.

Solid electrolytes can be configured in any orientation

Another important consideration is whether a fuel cell employs a liquid or a solid electrolyte. Two obvious advantages solid electrolytes enjoy over liquid cells is that; a) in principle they can be constructed in any orientation and b) it is inherently simpler to manage a solid electrolyte compared with a liquid. However, given the vast array of electrical applications it is unlikely that these considerations would prove fatal limitation for the liquid electrolytes.

No single fuel cell is capable of satisfying all electricity requirements

The differing operating temperatures across the electrolytes are of great significance both for how the different fuel cell systems can best be employed and the materials used to construct them. The chemistry and the nature of the electrolyte also go a long way to explain why some fuel cells are better at some applications and not at others. **But taken as a group, the five fuel cells within the hydrogen/oxygen family are, in principle, capable of satisfying all electricity requirements, from the milli-watts used in a mobile phone to the megawatts consumed in an industrial plant. No single electrolyte can satisfy the full range of our electrical power needs.**

Platinum may not be the obstacle often claimed

Much is made of the issue of precious metal catalysts in fuel cells. Only the acid-based electrolytes, PEM and PAFCs, use platinum and the amount used in today's pre-commercial demonstration units at 0.2mg is 140 times less than the 28mg used in early stacks. This corresponds to around US$10 per kilowatt and falling.

[1] The high temperature cells can also use carbon monoxide (CO) as a fuel, but this will not be explored further.

Fuel cell stacks within the same class can be designed very differently.

It should be pointed out that the same basic fuel cell stacks can be designed to run under vastly different operating conditions. For example pressure and hence operating temperature can vary widely, according to design. Thus the operating temperatures indicated above relate to stacks operating under standard, ie, non-pressurised conditions. Design of the operating regime is essentially an optimisation problem, with the type of application also playing an important role. Apart from mentioning the vast array of design possibilities we will not attempt to address the issue any further.

With this in mind we now outline some of the differences between the five hydrogen-oxygen fuel cells. We begin with the most widely publicised of the fuel cell family, the proton exchange membrane fuel cell.

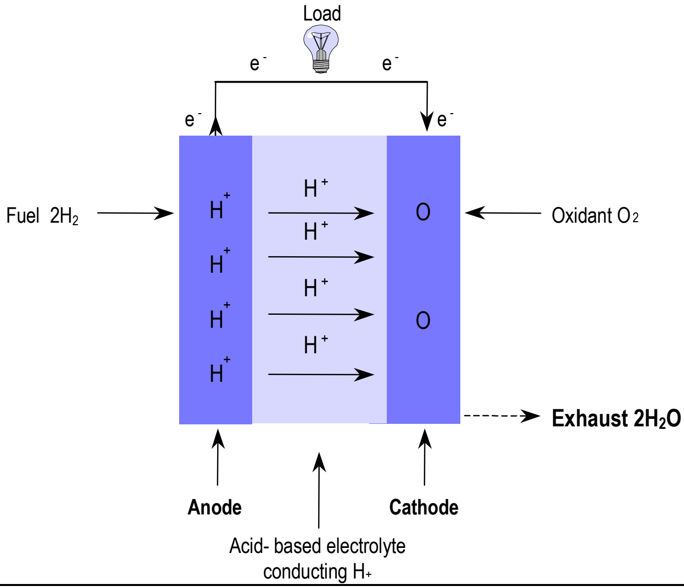
Proton Exchange Membrane Fuel Cells (PEMFC)

Description

In addition to the standard PEM system, two variants, namely Direct Methanol Fuel Cells and Regenerative Fuel Cells are discussed below. All operate according to the principles outlined in Chart 4.

At the heart of all PEMFC is a layered combination of electrolyte - an acid-based ion-conducting (H^+) plastic membrane - and two electrodes. Around 0.2mg of platinum per cm^2 is applied to either side of the membrane, providing a catalyst for both cell reactions. This unit, shown below, is known as a membrane electrode assembly or MEA. The MEA is encased in gas diffusion layers and bipolar plates (not shown). They are termed bipolar as one-side channels the H_2 fuel into the cell while the reverse side channels the O_2 oxidant into the adjacent cell.

Chart 4: PEM Fuel Cell Diagram



Source: UBS Warburg

The PEM schematic laid out above can be expressed algebraically as follows:

Table 2: PEM Fuel Cell Reaction Formula

Anode Reaction:	$2H_2$	→	$4H^+ + 4e^-$
Cathode Reaction:	$O_2 + 4H^+ + 4e$	→	$2H_2O$
Total Reaction:	$2H_2 + O_2$	→	$2H_2O$

Source: UBS Warburg

Hydrogen is fed to the anode, where it is split into protons and electrons. The electrons flow around the external circuit to the cathode as a result of the potential difference between the two electrodes. The protons are conducted through the membrane to the cathode. Oxygen molecules, supplied to the cathode, are broken into their constituent atoms, with each attracting two negatively charged electrons and two hydrogen protons, completing the circuit and producing the cell's only by-product, water.

Disadvantages/Challenges

(1) The low temperature acid-based electrolyte requires platinum as the electrocatalyst to accelerate the process of H_2 and O_2 gas disassociation.

(2) Because of the platinum electrocatalyst, the H_2 fuel stream should contain less than 10 parts per million (ppm) of carbon monoxide (CO), and preferably none. Performance is substantially degraded in the presence of higher CO concentrations as this molecule is strongly attracted to the platinum. The bonding of CO to the platinum results in the effective permanent deactivation or poisoning of the catalytic property of the platinum.

Advantages

(1) The low temperature allows for quick start-up.

(2) PEMFCs adjust well to variable power demands making them particularly useful in automotive applications.

(3) The fact that the membrane is solid allows the cell to be configured in any orientation.

Applications

Given the low operating temperatures and the fact that the electrolyte is solid PEMFCs would appear to be the most versatile of the hydrogen-air fuel cells. They are most widely known for their potential in automotive markets given the media's preoccupation with this set of applications. But PEMFCs are well suited for a vast array of uses from low-power applications such as power tools, a wide range of construction equipment including air compressors, concrete mixers and lifting gear, recreational power requirements for mobile homes, boating and camping, to medium power applications supplying heat and electricity to single and multiple family homes to high power applications supplying commercial buildings, schools and hospitals.

Sample Companies and Developers

Ballard, DCH Technologies, Plug Power, H-Power, Energy Partners, Energy Ventures, Alstom, Siemens, Proton Motor and H-Tec.

Other Proton Exchange Membrane Fuel Cells

Direct Methanol Fuel Cells (DMFC)

Description of DMFC (Direct Methanol Fuel Cells)

The DMFC does not rank as a distinct electrolyte, as its solid polymer electrolyte is a variant of the proton exchange membrane. It distinguishes itself by the fact that it directly feeds a water/methanol (CH3OH) mix into the anode and not hydrogen. The catalyst within the anode extracts the hydrogen from the water/methanol solution. While the electron and ion flows are exactly the same as for the hydrogen-oxygen PEM cell, as detailed above, the chemistry is totally different as can be seen from the algebraic description of the reactions as follows:

Table 3: DM Fuel Cell Reaction Formula

Anode Reaction:	$CH_3OH + H_2O$	→	$CO_2 + 6H^+ + 6e^-$
Cathode Reaction:	$3/2O_2 + 6H^+ + 6e^-$	→	$3H_2O$
Total Reaction:	$CH_3OH + 3/2O_2$	→	$CO_2 + 2H_2O$

Source: UBS Warburg

A methanol water solution is fed into the anode where it is broken-down into carbon dioxide, protons and electrons. The CO_2 is exhausted at the anode and the electrons flow via the external circuit to the cathode while the protons migrate through the membrane. At the cathode water is formed, which is subsequently exhausted. In low power applications the volumes of CO_2 and water would be so small as to not be a+-pparent to the user.

Disadvantages/Challenges

(1) The single most important outstanding problem with the DMFC is known as the crossover problem. This refers to the fact that the methanol fuel crosses over from the anode to the cathode through the membrane, drastically reducing the performance of the cell.

(2) Significantly more platinum is required at the anode to catalyse the water-methanol mix.

(3) While the technology looks promising in the medium term for consumer electronics applications it would appear to require considerably more time before it can be used in high power applications like automobiles.

Advantages

(1) A liquid fuel fed directly into the anode would obviate the need for complex reforming equipment.

(2) Power-to-weight ratio compared to batteries is theoretically in the order of 10 times better.

(3) In automotive applications the cost of amending the existing infrastructure would be significantly less than replacing it with a hydrogen network.

(4) DEMFC vehicles would attract 0.6 of a full zero emission credit under the Zero Emission Vehicle mandate enacted by the California Air Resources and due to come into force mid-2003. (see Environment section below)

Applications

The low operating temperature and solid electrolyte combined with the ability to use a liquid methanol fuel in the cell, makes DMFCs ideally suited for small and mid-sized applications. DMFCs will initially attempt to displace the batteries used in low-power consumer and military electronics. Later markets could include the automotive sector, where DMFCs would go a long way to solve the infrastructure problems

Sample Companies and Developers

Ballard, Manhattan Scientifics, Motorola, Medis El, Los Alamos National Labs, Fraunhofer Institute

Regenerative Fuel Cells (RFC)

Description

Regenerative fuel cells, which also belong to the PEM group, form a closed loop energy system. These systems use hydrogen and oxygen in a PEM fuel cell to generate electricity, but capture and store the water exhaust. This water is recirculated back to the electrolyser and converted back into hydrogen and oxygen which is stored for later use. An external power source supplies electricity to the electrodes in a so-called reversible fuel cell forcing the disassociation of the water. The external power can be supplied from the grid, a windmill or solar cells. NASA for example is developing a flying wing which, at 30,000 metres, flies by day using solar power. By night the propellers make use of electricity from a standard PEM fuel cell running on oxygen and hydrogen electrolysed by surplus solar power during the day.

Disadvantages/Challenges

(1) The major disadvantages in these systems are the total system cost and to be truly independent they are dependent on developments within wind and solar technologies.

Advantages

(1) Apart from the advantages shared with PEMFCs in general, Regenerative systems' single most significant advantage is the fact that it can operate independent of a recognised fuel/energy infrastructure.

Applications

Regenerative fuel cells will certainly be considered for uninteruptable supply applications as well as energy storage for remote power requirements and solar rechargeable aircraft like the Helios flying wing being developed by NASA. Larger systems could be used in peak shaving

Sample Companies and Developers

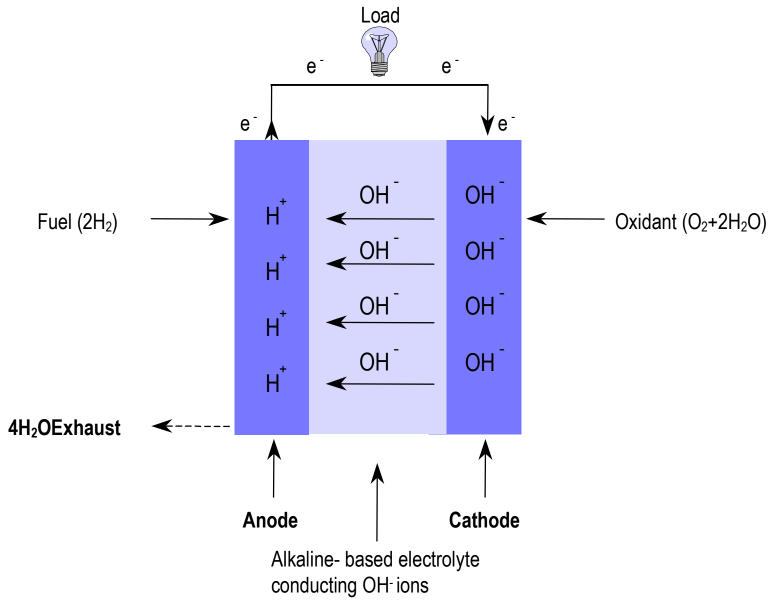
ElectroChem Inc, Proton Energy Systems Inc, NASA, Lawrence Livermore National Laboratories.

Alkaline Fuel Cells (AFC)

Description

AFCs employ a liquid potassium hydroxide (KOH) solution as the electrolyte, which conducts hydroxyl ions (OH^-). The electrocatalysts can be noble or non-noble metals. In contrast to the acid electrolytes, AFCs conduct negatively charged ions from the cathode to anode.

Chart 5: Alkaline Fuel Cell Diagram



Source: UBS Warburg

The ACFC schematic laid out above can be expressed algebraically as follows:

Table 4: Alkaline Fuel Cell Reaction Formula

Anode Reaction:	$2H_2 + 4OH^-$	→	$4H_2O + 4e^-$
Cathode Reaction:	$O_2 + 2H_2O + 4e^-$	→	$4OH^-$
Total Reaction:	$2H_2 + O_2 + 2H_2O$	→	$4H_2O$

Source: UBS Warburg

At the anode the hydrogen molecules (H_2) are broken into single hydrogen atoms and stripped of their electrons (e^-), leaving hydrogen ions (H^+) at the anode, which cannot cross the KOH electrolyte. At the cathode oxygen and hydrogen molecules are split into their respective atoms which, with the electrons arriving from the load reconfigure to form negatively charged hydroxyls (OH^-). To close the circuit the hydroxyls must be conducted through the electrolyte to the anode, where they are attracted to the positively charged hydrogen ions to form water.

Disadvantages/Challenges

- While all fuel cells function best on pure oxygen and pure hydrogen AFC performance is particularly sensitive to contaminants in the gas streams. Carbon dioxide (CO_2) removal from both fuel and air streams is necessary as this molecule will react with the KOH electrolyte to form a carbonate, thereby reducing the conductivity of the OH^- ions' across the electrolyte.

Applications

(1) One of the main advantages enjoyed by alkaline fuel cells is the fact that the chemical reaction taking place at the cathode is much faster than in other electrolytes and thus leads to high electrical efficiencies. To be sure, AFCs are capable of generating power efficiencies of up to 70%

(2) AFCs offer the promise of being cheap to manufacture:

   a) A wide range of catalysts can be used including both noble and non-noble metals.

   b) The potassium hydroxide solution (KOH) used as the electrolyte is inexpensive and

   c) The gas channelling plates can be manufactured from plastic.

(3) AFCs start-up time is extremely quick owing to the low operating temperature.

Applications

The application of AFCs in space represents the greatest success to date of any fuel cell system. They are ideally suited to closed environments containing their own supply of hydrogen and oxygen such as submarines and space ships. They have also been demonstrated in a variety of automotive applications, including airport vehicles, taxis and municipal vans as well as in marine applications. AFC's are also being developed for stationary use and, given their efficiency are being considered for use in desalination. Given the range of AFC demonstrations, the requirement of clean H2 and O2 gas streams may not be the insurmountable objects that some commentators have maintained. The deployment of AFCs within regenerative systems would overcome the CO_2 from the fuel stream.

Sample Companies and Developers

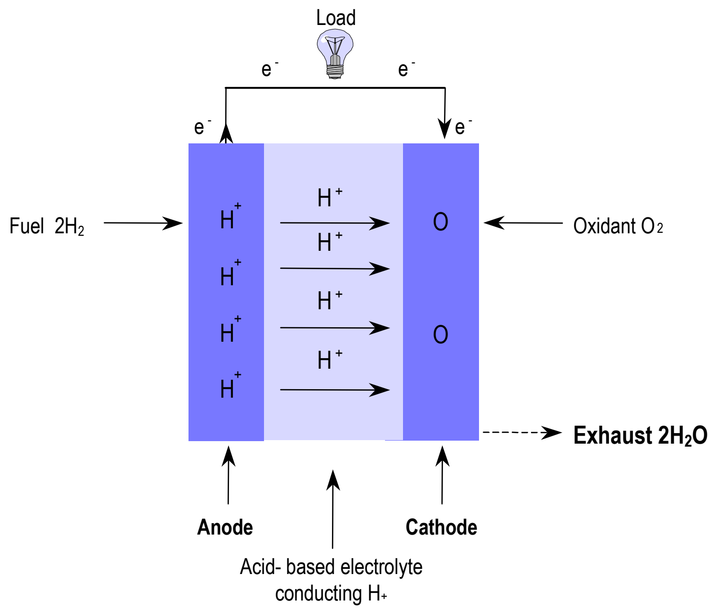
United Technologies, Zetek Plc, Astris-Energi, Siemens.

Phosphoric Acid Fuel Cells (PAFC)

Description

As can be seen below the mechanism of the PAFC is exactly the same for the as PEMFC, with both conducting protons through an acid based electrolyte employing platinum electrocatalysts. While the PEM uses a solid membrane operating in the 50° to 100°C range PAFC cells use a concentrated liquid phosphoric acid (**H_3PO_4**) immobilised in a teflon, silicon carbide matrix with an operating temperature of around 200°C.

Chart 6: PA Fuel Cell Diagram



Source: UBS Warburg

The PAFC reactions are as follows:

Table 5: PA Fuel Cell Reaction Formula

Anode Reaction:	$2H_2$	→	$4H^+ + 4e^-$
Cathode Reaction:	$O_2 + 4H^+ + 4e^-$	→	$2H_2O$
Total Reaction:	$2H_2 + O_2$	→	$2H_2O$

Source: UBS Warburg

The electrochemistry of the PAFC is exactly the same as for the PEMFC and is detailed above on page 18.

Disadvantages/Challenges

(1) As with the PEMFC, the use of platinum and its associated problem with CO bonding with the catalysts presents problems, though not as severe as in the PEMFC owing to the higher operating temperature within the PAFC.

(2) Additional disadvantages with PAFC stacks include low current and low power owing to poor ionic conduction, a large footprint and correspondingly high weight.

(3) The most important challenge for PAFCs is cost. Despite being 'commercially' available for most of the last decade the price has gone up, not down. This technology appears to be inherently expensive.

Advantages

(1) Over the years these systems have proven to be extremely durable with a very stable electrolyte. The US military reports that its 15 model 'C' units have recorded more than 247,000 hours service, generating some 247,044 MWhrs of electricity. The 14 older 'B' models have a collective service of 284,039 hours generating 47,045MWhrs of power.

Applications

Whilst PAFC benefited from the demise of PEM in the late 1960s, the range of applications that PAFCs have found is much less than originally hoped for. To be sure they are almost exclusively used in medium to high stationary applications. Onsi's (United Technologies) 200kW PAFC technology has been around for the best part of a decade, with around 200 units having been sold. It is thus not surprising to note that they can be found in hospitals, hotels, schools, a swimming pool and office buildings amongst other locations. The single largest owner of these power plants is the US military.

Sample Companies and Developers

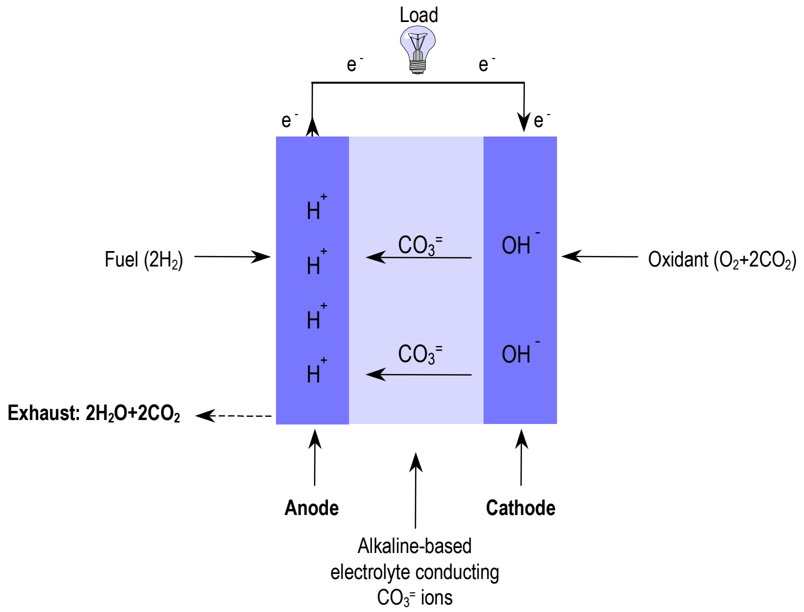
United Technologies, Toshiba, Fuji, LG-Caltex

Molten Carbonate Fuel Cells (MCFC)

Description

MCFCs also employ a liquid electrolyte, though this is a molten alkaline carbonate, operating at around 650°C and held within a lithium aluminate matrix. This relatively high operating temperature is absolutely necessary for the transportation of the carbonate ions ($CO_3^{=}$) across the electrolyte to take place.

Chart 7: MC Fuel Cell Diagram



Source: UBS Warburg

The MCFC schematic laid out above can be expressed algebraically as follows:

Table 6: MC Fuel Cell Reaction Formula

Anode Reaction:	$2H_2 + 2CO_3^{=}$	→	$2H_2O + 2CO_2 + 4e^-$
Cathode Reaction:	$O_2 + 2CO_2 + 4e^-$	→	$2CO_3^{=}$
Total Reaction:	$2H_2 + O_2 + 2CO_2$	→	$2H_2O + 2CO_2$

Source: UBS Warburg

As is usual the hydrogen fuel is fed into the anode where it is broken up into single atoms and stripped of its electrons for the electrical circuit. In contrast to the other systems, molten carbonate cells require carbon dioxide (CO_2) for the system to function. Together with oxygen (O_2), the CO_2 flows into the cathode where these molecules react with the electrons arriving from the anode to form the negatively charged carbonate ions ($CO_3^{=}$). These are subsequently conducted through the electrolyte to close the electrical circuit. On arrival at the anode the carbonate ions react with the positively charged protons (H^+) to produce water and carbon dioxide exhaust. While it is possible to supply the cathode with an independent supply of CO_2 it is usual that the CO_2 exhausted at the anode is recirculated to the cathode.

Disadvantages/Challenges

(1) The chemically aggressive environment of a molten lithium/potassium carbonate electrolyte places severe demands on the stability and life of the cell components.

Advantages

(1) The quality of the heat allows for the possibility of higher fuel-to-electricity efficiencies when used in CHP or combined cycle operations. The high operating temperature affords the ability of the stack to consume a wide variety of fuels, including natural gas and coal gas. High temperature also negates the need for noble metal catalysts. A further significant advantage of the high heat is the fact that it allows for the fuel stream to be internally reformed within the fuel cells, obviating the need for a separate piece of complicated kit thereby simplifying the overall system requirements.

Applications

Molten carbonate fuel cells, capable of multi-megawatt power output, are being developed for natural gas and coal based power plants for use in heavy industrial plant. Several megawatt plants, most notably FuelCell Energy's 2MW test plant in Santa Clara, California, have already been demonstrated. Commercial buildings, particularly those requiring high quality heat such as hospitals and hotels are also obvious applications for this technology. It has also been suggested that molten carbonate cell would be ideally suited to power trains.

Sample Companies and Developers

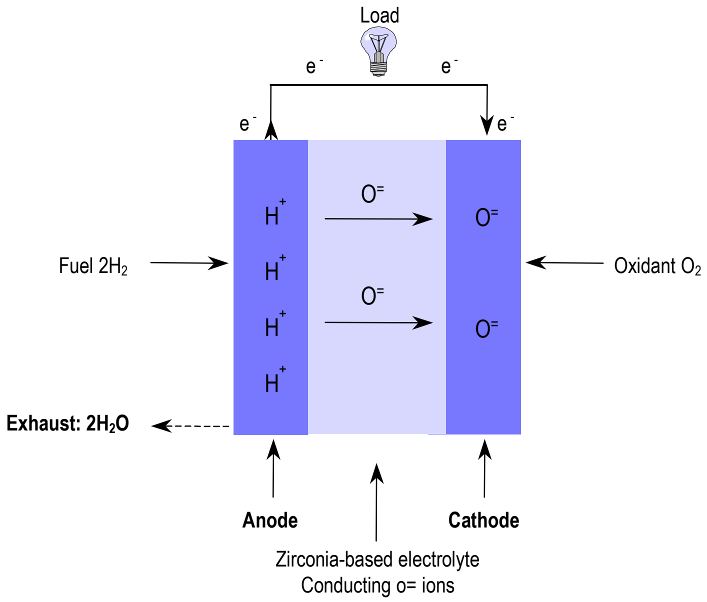
FuelCell Energy Inc., IFC, (United Technologies), Ansaldo, MTU, Hitachi, and Mitsubishi Electric Corporation.

Solid Oxide Fuel Cells (SOFC)

Description

SOFCs, like PEMFCs use a solid electrolyte, but operate at 650°C to 1,000°C compared to the 50°C to 100°C range for standard PEMs. The SOFC electrolyte is a nonporous metal oxide, which requires such high temperature to become ionically conductive.

Chart 8: SO Fuel Cell diagram



Source: UBS Warburg

The SOFC schematic as laid out above can be expressed algebraically as follows:

Table 7: SO Fuel Cell Reaction Formula

Anode Reaction:	$2H_2 + 2O^=$	→	$2H_2O + 4e^-$
Cathode Reaction:	$O_2 + 4e^-$	→	$2O^=$
Total Reaction:	$2H_2 + O_2$	→	$2H_2O$

Source: UBS Warburg

Hydrogen is supplied to the anode where it is disassociated and stripped of its electrons. Oxygen molecules (O_2) flow to the cathode and are broken into single atoms. These each attract two of the electrons arriving from the anode to form the negatively charged oxygen ions ($O^=$), which migrate through the electrolyte to close the electrical circuit. On arrival at the anode the oxygen ions combine with the positively charged protons (H^+) to produce the steam exhaust.

Disadvantages/Challenges

(1) The single biggest challenge to the SOFC is the difficulties presented by the operating temperature. Generally, if operated above 850°C significant material problems arise, in that expensive alloys must be used. Yet, if cell is operating below 850°C, where less exotic cell materials can be employed, ionic conduction becomes a problem and the cells' performance falls rapidly. Significant developmental work is being pursued with the aim of maintaining the SOFC's performance at operating temperatures below the 850°C level.

Advantages

(1) As with MCFC plant, the high operating temperature of SOFCs facilitates the internal reforming of a wide range hydrocarbon fuels, thereby simplifying system complexity. Equally, the high quality of the exhaust heat allows for efficiency to be greatly enhanced, via use in CHP systems or combined cycle electricity generation: The heat also promotes rapid chemical reactions without recourse to noble metal electrodes.

(2) The SOFC is a completely solid state device, which avoids the management problems inherent with liquid electrolytes. A further benefit of solid electrolytes is that, in principle, there is no restriction on the cell configuration thereby allowing for a high degree of flexibility in cell design.

(3) As with MCFC, high temperature also negates the need for noble metal catalysts. But SOFCs also have the advantage of having a solid electrolyte which means there are no corrosive fluids and allows for the construction of the stack in any orientation

Applications

SOFCs are being designed and demonstrated in various countries to supply a wide array of stationary needs, from the single digit kW base-load needs of single family homes to the multi-megawatt demands of industrial plant and central electricity generating stations.

Given the SOFC's ability to utilise carbonaceous fuels directly together with the benefits a solid electrolyte SOFCs are also being developed as APU systems for petrol and diesel powered vehicles.

Sample Companies and Developers

Siemens-Westinghouse, Acumentrics, Global Thermoelectric, Sulzer Hexis, SOFCO.

Market Drivers

The fuel cell industry is likely to be substantially affected by issues which fall into two distinct categories: Those which comprise inexorable market trends (the growth in the demand for energy, which we have taken into account); and those whose influence is not required for our forecast to be met (ie global warming/ CO_2).

In assessing the potential risk of investing in the fuel cell sector, it is important to look into the wider forces affecting the industry. These forces encompass a wide set of drivers, the most significant of which we highlight below:

(1) Environmental Drivers

a) Global Warming, The Kyoto Protocol and CO_2

b) The California Air Resources Board and Pollution

(2) The Demand for Stationary Electricity

a) Energy in the Developing Economies

b) Rising First-World Demand for Premium Electricity

Environmental Drivers

Environmental concerns are informing policy…

There are many forces at work operating under the umbrella of environmental concerns, including the news bulletins reporting on melting ice sheets, the dangers of a depleted ozone layer, freak storms, floods and more generally, global warming. In this section we discuss global warming and pollution.

Emissions differ in their impact

It is important to distinguish between the effects of gases that are thought to be responsible for global warming and those compounds that damage the local environment and health. Though the source of these emissions is often the combustion of fossil fuels, a distinction between their effects is important in order to understand what is driving policy and what alternative energies best suit that policy goal.

Global Warming

CO_2 insulates the globe

Global warming is caused by the emission of a variety of gases, including carbon dioxide and methane, which policy makers are seeking to reduce. CO_2 and its equivalents are compounds which disturb the earth's heat balance by forming an insulating layer high in the atmosphere and preventing heat radiating back out into space. The vast majority of these compounds are attributed to the burning of fossil fuels. CO_2 from the industrial and transport sectors for example is a consequence of liberating the energy in a fuel. The effect of global warming is independent of where the global warming agents are produced, hence the efforts to reach a global agreement on their control and reduction.

Local Pollution

Local pollutants damage health and the environment

There are a wide variety of local air pollutants responsible for damaging both health and the environment. Most debates concentrate on particulate matter (PM) and the oxides of nitrogen and sulphur, which create a variety of environmental and health hazards, including acid rain and respiratory ailments. The burning of fossil fuels creates them. While these pollutants can travel many hundreds of miles from their source their effects are not considered as global.

Local pollution control favours fuel cells

Any policy calling for the reduction or elimination of local pollutants would favour the quick introduction of fuel cells. Low temperature fuel cells produce no particulate matter or oxides of nitrogen or sulphur, even when using fossil fuels as their hydrogen source, while the emissions production from high temperature cells is barely detectable. The versatility of fuel cells means that they would reduce emissions resulting from the transportation and electricity generation sectors. As noted above CO_2 results from the liberation of energy stored in any fuel that contains carbon, regardless of the process employed. Fuel cells can reduce CO_2 emissions by virtue of the fact that their mode of operation is significantly more efficient that the process of extracting energy by combustion.

CO_2 control favours wind and solar conversion

Policies that place emphasis on the reduction or elimination of global warming compounds would appear to favour the deployment of wind and solar power. But it should be clear that such policies could only be considered successful if restricted to stationary electricity generation. Directly they can have no influence on the transportation sector.

Fuel cells and renewables are complements

But these technologies are more complementary than may appear. Wind and solar convert wind and solar energy into electricity. Fuel cells convert hydrogen into electricity that can be used in mobile and stationary applications. Wind and solar are unreliable and may not be available when required and as their share of the total energy mix rises the consequences of this become more apparent. According to the International Energy Agency as wind and solar power approach 12% of total electricity generated, policy makers need to start thinking about creating an energy buffer, as electricity itself cannot be stored. At 20% of the energy mix it is widely contended that a buffer is an absolute necessity. Hydrogen extracted from water would be an ideal buffer, as this can be stored and converted when needed in fuel cells. In such an arrangement intermittent power plant and fuel cells are complements and not competitors, and satisfy all environmental policy goals aimed at global warming and local pollutants across a very wide range of applications.

Local pollutant control driving US policy…

US legislators have focussed on curbing local pollutants for many years. Indeed the ruling on local emissions by the California Air Resources Board has had a significant direct impact on the global automotive industry, and a more indirect impact on the wider energy industry. In this report, we concentrate on local pollutant control as practised by the Californian Air Resource Board.

…Europeans focused on global warming…

In Europe, the environmental debate focuses much more sharply on global warming and therefore concentrates on CO_2. This is not to say that the Europeans are not concerned with local pollution issues, just that the current political emphasis is on global warming. Below we discuss the global warming debate within the context of the internationally agreed Kyoto Protocol.

… which is shifting costs in favour of cleaner technologies.

These environmental issues are driving policy, which in turn have been imposing costs on the way society produces and consumes all manner of goods and commodities for a long time already. Environmental policy considerations are continuing to shift the price structure in favour of cleaner methods of transportation and energy generation. This was keenly highlighted recently by the fact that Rolls Royce' energy division was forced to take a £120m provision following its industrial Trent engine failing to meet environmental standards

The Trend to Quantify Environmental Damage is Rising

A permanent shift in the price structure is not a subsidy.

It is important to distinguish between a subsidy, and a shift in the relative price structure. Subsidies effectively lower market values below factor cost while a shift in relative prices results from an increase in the cost of one product relative to a competing product. The fact that governments are imposing 'costs' on polluters is resulting in the confusion of subsidies with a shift in relative prices. And this has important implications for the understanding of the true power of cleaner technologies in general and fuel cells in particular given their enormous versatility.

Researchers are quantifying the effects of pollution, both in terms of mortality and morbidity, and GDP costs

Standard economics textbooks make the case that polluters have traditionally passed on the cost of polluting to the wider society in the form of lowering the general health of the population and/or degradation of the local environment. Traditionally these 'externalities' have been considered qualitatively rather than quantitatively. However, attempts at quantifying some of the costs of pollution are making their way into the media. Recently the medical journal, Lancet published research showing that 6% of deaths in France, Switzerland and Austria are due to pollution. Half this figure, or 20,000 deaths were directly attributed to traffic fumes. Importantly, the research attached a price tag of 1.7% of GDP to treating illnesses associated with traffic pollution alone. More dramatically, a 1996 study by the University of Miami Clean Energy Research Institute estimated that the consumption of fossil fuels resulted in economic damage of around US US$2.7 trillion, equivalent to 14% of world GDP.

Avoiding the financial costs of pollution has been possible owing to the fact that the market is not able to apportion an explicit price to pollution. It is a classic case of market failure. Such market failure can only be addressed via the political mechanism, where prices, however imperfectly, are imposed on the polluter. The rise of environmentalism has put pressure on governments to continue to "internalise" these so-called "externalities". In other words, make the polluter pay and there is little that changes behaviour more powerfully that a shift in relative prices.

Global Warming and the Kyoto Protocol

The Kyoto Protocol calls for industrialised countries to cut their collective carbon dioxide emissions by 5.2%.

The global warming debate centres on carbon dioxide (CO_2) emissions and whether human activity is altering the global climate. At the United Nations third annual Conference of the Parties (COP3) in 1997 in Kyoto, Japan, the so-called Kyoto Protocol came into existence. The accord calls for the industrialised nations to collectively reduce their emissions of CO_2 by 5.2% below the levels obtaining in 1990 and should be met between 2008 and 2012. The details of how the Protocol will work in practice are scheduled to be finalised at the UN's sixth Conference of the Parties (COP6), which takes place this year in the Hague between November 13^{th} and November 24^{th}.

Though the necessary ratification is far from certain.

The Kyoto Protocol, signed by more than 150 countries, calls for its provisions to be ratified by national governments by the end of 2002. So far 30 non-industrialised countries have ratified the Protocol. It should be pointed out that for the UN's emission reduction targets to become international law, the Protocol has to be ratified by industrialised countries responsible for 55% of the developed world's emissions in 1990.

The UN Intergovernmental Panel on Climate Change will release its third climate report early next year.

The most important research, as far as CO_2 policy is concerned, are the reports prepared for the 'Parties' by the Intergovernmental Panel on Climate Change (IPCC). Around 400 of the world's top climate scientists are involved in the production of the Panel's assessment reports. The IPCC has presented two assessments of the state of the global climate, its first in 1990 and its second in 1995. The third is scheduled to be published early next year.

In its 1990 report the Panel noted that the earth's atmosphere appeared to be warming but that more work would be required to determine its causes.

The tone of the 1995 report, though cautious, was more definite. One of the major conclusions was that:

'The balance of evidence suggests a discernible human influence on global climate'
(IPCC Second Assessment Report, 1995)

The Panel's latest report is the clearest to date on the effects of human activity on climate change.

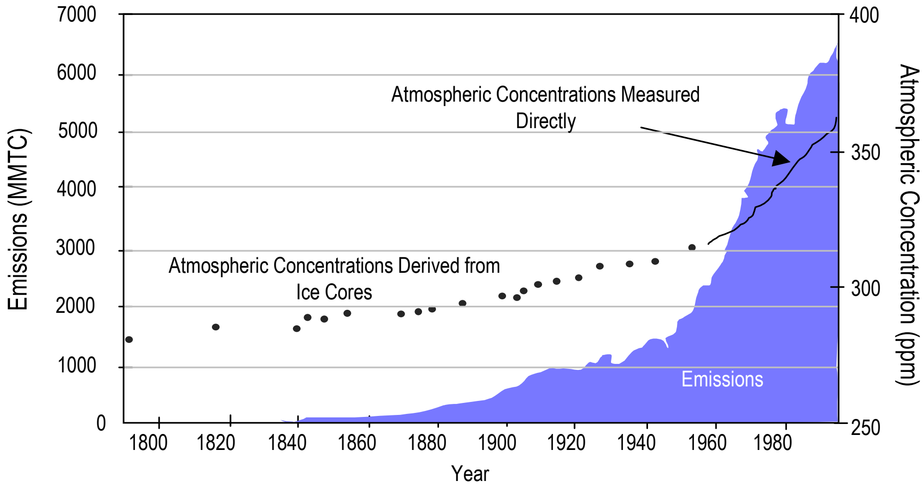
A draft summary of the 1,000-page Third Assessment Report has been sent to governments for their final review and simultaneously leaked to the media, just ahead of the COP6 meeting. The draft, which indicates a further hardening in tone, states that 'there is stronger evidence' on the human influence on global climate and that it is likely that the release of greenhouse gases, principally from the burning of hydrocarbons, 'have contributed substantially to the observed warming over the last 50 years'.

Carbon Dioxide and Global Warming

Industrialisation correlates with rising concentrations of atmospheric CO_2…

The general line of reasoning runs that the build-up of CO_2 in the atmosphere is inextricably linked to the burning of fossil fuels and is causing the earth's average global temperature to rise faster than any time in the last 10,000 years. The debate, while far from clear, is fuelled by empirical evidence plotting the rise of CO_2 since the Industrial Revolution. The following chart prepared by the Carbon Dioxide Information Analysis Centre plots global CO_2 emissions from 1790 to the present. (The US-based Centre provides climate datasets to researchers, policymakers and academics).

Chart 9: Global Emissions and Atmospheric Concentration of CO_2 Since 1790



Source: Carbon Dioxide Information Analysis Centre 1999

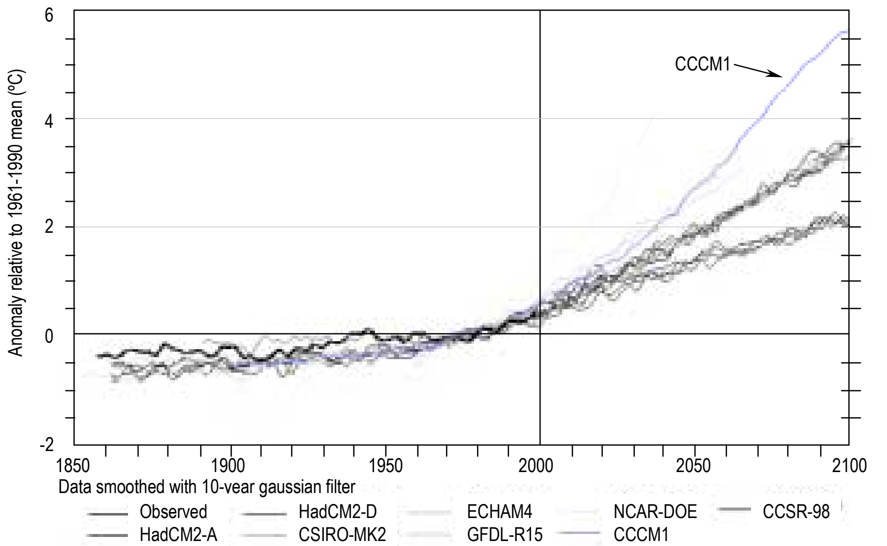
The left-hand scale plots annual CO_2 emissions in million metric tonnes. The right-hand scale traces the concentration of CO_2 in the atmosphere, measured in parts per million (ppm). As can be seen, the concentration of CO_2 in the atmosphere has risen from a pre-industrial level of around 280ppm to more than 360 today. It is claimed that the total the amount of carbon it took the earth to absorb in one million years is now being released every year.

Rising concentrations of atmospheric CO_2 correlates with rising temperatures.

The IPCC's 1995 estimates of the global mean temperature rise since the middle of the last century was put at somewhere between 0.3°C and 0.6°C. The Panel's latest estimates for the same period are now suggesting a rise of between 0.4°C and 0.8°C, confirming reports of an acceleration in the rate of temperature increase in the recent past.

The following chart is a collection of global temperature forecasts made by UK. German, US and Japanese research agencies and put together by Mark New, of the University of East Anglia for the United Nations Intergovernmental Panel on Climate Change:

Chart 10: GGa-Global Temperature



Model Sources: **HADCM** = Hadley Centre, UK: **CSIRO** = Australian government scientific research agency: **ECHAM** = Max-Planck-Institut für Meteorologie, Germany: **GFDL** = Climate Diagnostics Centre US: **NACAR** = The National Center for Atmospheric Research, US: CCCM = National Institute for Environmental Studies, Japan: CCSR = Center for Climate Research Studies, Japan. Created for the IPCC-DDC by Mark New.

Leading research agencies have been forecasting temperatures to rise 2°C to 5°C by 2100

Chart 10 measures mean global temperature changes relative to the mean temperature between 1961 – 1990 and is re-based to zero. Thus, at the lower end of the forecast range the Hadley Centre's M2-D model predicts a rise in global temperature of 2°C by the end of this century. At the other end of the range the Japanese National institute for Environmental Studies' model predicts a rise of almost 5°C. Given these forecasts relate to an average global number actual variations at the local level would naturally be more extreme.

The IPCC's Latest Forecasts Put It Top of The Charts

And now the IPCC is forecasting a potential temperature rise of up to 6°C by 2100.

Turning back to the IPCC, in its 1995 Second Assessment Report the Panel forecast a rise in mean global temperature of between 1°C and 3.5°C by the end of 2100 on the basis of "Business as Usual". The Panel has now dramatically raised that forecast to an increase of between 1.5°C and 6°C. **To put this forecast into context, today's average temperature is 5°C above that prevailing at the end of the last Ice Age**. At that time the average sea level was some 90 to 120 metres lower than today, low enough to walk from Dover to France. Around 90 million cubic kilometres or 22m cubic miles of ice was locked in ice sheets against today's figure of about 30m cubic kilometres or 7m cubic miles. Such rapid changes in temperature as forecast to occur over the next hundred years, go hand in hand with the expectations of chaotic weather patterns, encompassing storms, flooding and severe droughts.

There are still sceptics, but it's the policymakers count.

While the leaked IPCC report reconfirms the mainstream view on global climate change, there are still many scientists who argue that the evidence is not yet conclusive. Nevertheless, the substantive issue is the debate's impact on policy. Meanwhile, the head of the IPCC team responsible for the upward revision of the forecast maintains that the greatest uncertainty is how fast technology to reduce emissions can be developed.

CO_2 Trading Edging Towards Reality

Momentum behind CO_2 issues is building

Many companies around the world, including BP, Shell, IBM and Johnson and Johnson have initiated internal carbon trading or reduction schemes. Many banks are investigating carbon trading systems, while stock exchanges, including Deutsche Börse AG are investing in and developing carbon trading infrastructure. Some banks, including the World Bank and a JV between Dexia and the EBRD have set up carbon trading funds. The UK National Carbon Trading scheme is planned to be launched next April while the Danish Ministry of Energy said it will launch domestic CO_2 certificates trading in 2001. Finally, the EU intends to unveil its CO_2 trading market in 2005, which the Norwegians have asked to be allowed to join.

Ratification of the Protocol is far from guaranteed, but the issue will not go away.

Kyoto may well get a rough ride, indeed it may not be ratified, but the issue of CO_2 will not vanish as a result. To be sure, the momentum behind CO_2 reduction schemes, particularly in Europe, would suggest that CO_2 production will increasingly carry financial costs. Moves in Europe in particular, are being driven by the fact that European governments have stated that carbon schemes will come into force with or without the ratification of the Kyoto Protocol.

Before moving on to discuss pollution control as practised by the California Air Resources Board we note three provisions to be finalised at COP6 in the Hague, which could have a profound impact on the alternative energy industry.

The Protocol's Three Price Shifting Provisions

But if ratified, the Protocol could significantly boost investments in Alternative Energy...

Of relevance for alternative energy technologies are the following three provisions within the Protocol, which could significantly shift the price structure of energy provision in favour of cleaner conversion devices:

(1) Clean Development Mechanism (CDM)

(2) Joint Implementation (JI)

(3) Carbon Trading

Through its technology transfer mechanisms,

As noted the details of how these systems will work in practice is set to be finalised out at the pending COP6 meeting. In essence the CDMs and JIs are technology transfer mechanisms. CDM refers to clean project investments by industrial nations in developing economies while JI refers to cross border "clean' investments within the industrial countries. The idea behind these horribly named provisions is that certified carbon credits will be given to those entities that provide clean technologies in the countries other than their own. The CDM though is effectively a technology transfer mechanism.

And trading provisions.

These carbon credits generated through CDMs and JIs can be traded on financial markets between companies. For example, under the force of a ratified Kyoto Protocol, a company may be ordered to reduce its domestic CO_2 emissions by say 1,000 tonnes by 2010. The company could invest in new technology that would help it meet these goals and avoid whatever penalties may be in place. On the other hand it may decide that it would be cheaper to invest in a clean third world project

With CO_2 having a value, price structures would shift

and satisfy its domestic requirements via the certified CO_2 credits it would receive from the project. Alternatively, it may simply decide to buy the necessary credits from a registered carbon trader. The deciding factor will be the price of the CO_2, one ton of which has been estimated by governments and research institutes to be valued anywhere between several tens of US dollars to several hundred US dollars depending on the precise details of the Protocol. Given the quantities of CO_2 reductions called for under the Kyoto agreement, the ultimate value of the carbon credits market could extend into hundreds of billions of dollars, irrevocably altering the price structure of the energy generating markets.

Environmental Legislation

California Air Resources Board

In 1967 the Mulford-Carrel Air Resources Act, signed into law by Governor Ronald Reagan, created the California Air Resources Board (ARB) by combining the California Motor Vehicle Pollution Control Board and Bureau of Air Sanitation to address the pollution problems in the state. The Sacramento-based agency is made up of 10 part-time members and a full-time chairman. The state governor appoints all 11 board members. The Chairman has a full-time staff of scientists, engineers, and other professionals.

The Air Resources Board's mission is 'To promote and protect public health… through the effective and efficient reduction of air pollutants'

The ARB's mission is:

"To promote and protect public health, welfare and ecological resources through the effective and efficient reduction of air pollutants while recognising and considering the effects on the economy of the state."

The agency is specifically charged with "systematically attacking" pollution caused by motor vehicles and overseeing the 35 local air quality districts that regulate most non-vehicular sources of air pollution, e.g. refinery and power plant emissions. In addition to conducting research and education the ARB is also responsible for clean air regulation and enforcement and as such its decisions carry the force of law.

The ARB's success in reducing pollution has been tangible: 25 years ago in some parts of the state air contaminants measured:

(1) 30% more ground-level ozone (O3)

(2) twice as much carbon monoxide (CO)

(3) four times more sulphur dioxide (SO2)

(4) 35 times more lead (Pb)

Source California Air Resources Board.

The Air Resources Board has a long and successful record on environmental regulation

These numbers are even more impressive when set against the fact that over the same period the population of California has increased around 60% to 32 million, the number of cars has doubled and total vehicle miles travelled has gone up by a factor of 2.5. ARB regulations have forced automotive OEMs to develop and deploy a variety of technologies including catalytic converters, fuel injection systems and on-board diagnostics to improve emissions from internal combustion engines. The agency itself contends that not even the cleanest petrol motors envisioned in its regulations can sufficiently reduce emissions in the Los Angeles region to meet federal ozone requirements. Hence the push to Zero Emission Vehicles (ZEVs). It is precisely this mandate, formulated in 1990 that has extended the ARB's reputation well beyond its own borders.

The ARB's Zero Emissions mandate has had the most profound impact on the development of fuel cell technology

The ZEV mandate dictates that beginning in model year 2003 at least 10% of the passenger cars and lightest light-duty trucks produced by large and medium-volume manufacturers and delivered for sale in California must be ZEVs. Large-volume OEMs are allowed to satisfy up to 6% of the 10% ZEV requirement with a proportionately larger number of vehicles reflecting a near-zero emitting profile, or so-called partial credits. Intermediate volume manufacturers may meet the entire 10% obligation via that route.

Near-zero emitting vehicles are vehicles that are not ZEVs but, given their extremely low tail pipe emissions, are awarded a partial ZEV credit. Fuel cell vehicles using pure hydrogen as the fuel are obviously ZEVs. Less obvious is that fuel cell vehicles using methanol as the source of hydrogen attract a partial credit of 0.6. In the event that a medium sized OEM were to deploy methanol fuel cell vehicles to meet the ARB's mandate then 16% of its California sales would need to meet the partial credits to comply with the 10% rule.

In September the board unanimously reconfirmed its commitment to its 2003 Zero Emissions mandate

The Board's unanimous decision on 8 September to leave the mandate unchanged was taken after two days of hearings that included taking evidence from the auto industry itself as well as other stakeholders. The decision clearly reflects the ARB's belief that the technology(ies) is at or near commercial viability such that its goals can be realised starting in 2003. Indeed, it is reasonable to assume that the Board's decision to push on with ZEVs by mid-2003 will further accelerate the development of fuel cell technology. It is widely believed that, the Air Resources Board, and particularly its latest Chairman, Dr. Alan Lloyd, has done more to motivate the development of fuel cell systems than any other regulatory agency.

Massachusetts and New York have committed themselves to the ARB's ZEV mandate

It should be noted that the North Eastern states of New York and Massachusetts will also implement the California regulations in 2003. The states of Main and Vermont are currently in the process of finalising the process to implement the Zero Emissions Mandate. More states are expected to sign up to ZEV legislation in due course.

The Demand for Stationary Electricity

(1) Energy Demand in the Developing Economies

Growth in the developing world requires significant amounts of energy

According to the U.S. DoE annual world net electricity consumption will expand by 76% to 21,746 billion kW hours in 2020 from 12,260 billion in 1997. Impressive as this growth is, particularly in developing Asia, which accounts for more than 50% of the world's population, this region will still represent a fraction of the First-world's electricity consumption in 2020. Asia's absolute net consumption is forecast to grow 4.5 times faster than in the industrialised world, yet by the end of the period Asia will still consume 6.7 times less electricity on a per capita basis. As developing economies grow, demand for electricity for both industrial and residential consumption looks set to expand for some considerable time to come. But more to the point, development of electricity markets in the non-industrialised world may well emulate its development in telecommunications, from no phones to mobile phones and from little and low quality electricity to high quality distributed power. Why install a massively costly distribution network? What is more, as noted above, fuel cells in stationary applications will run on natural gas, a commodity available in many third world economies.

(2) Rising First-World Demand for Premium Electricity

Demand for clean power in the West is rising

While demand for electricity is forecast to explode in the non-industrialised world, demand for electricity in the industrialised world is set to expand at a significantly more modest pace. But the macro numbers belie the fact that demand for premium electricity is rising in the industrialised countries. At a time when the quality of supply is starting to deteriorate in some major economies, particularly in the U.S., which is further down the road of deregulation than most other economies. One commentator described the U.S. as being a first world economy, with a third world grid.

US grid disruption costs estimated at US$50bn pa

There have been media reports over the past few months, of the U.S grid being over-stretched owing to surging electricity demand. According to the US-based Electro Power Research Institute grid disruptions cost U.S. business around US$50bn per annum. Consequently, we would expect to see continued high growth rates in the uninterruptible power supply (UPS) market.

Internet hotels and data centres can ill afford brown-outs, much less black-outs

The advent of internet and the continued expansion in the service sectors world-wide is occurring at a time when investment in electricity infrastructure is suffering from a lack of policy direction and increased uncertainty in the wake of deregulation. There is higher potential today than at anytime over the last few decades that some disturbance will occur on the grid, be it a brown out ie voltage drop or black out. Data centres banks and Internet hotels can ill afford to suffer such network disturbances.

Decentralised power is being debated

There is a debate emerging about the benefits of distributed energy generation. One group advocates decentralised plant supporting the existing grid. Another argues that energy reliability and quality can best be guaranteed by the marriage of fuel cells with solar and wind power in a local power network.

Fuel cells offer the chance to go off-grid

Aside from the long-term nature of energy generation fuel cells look set to offer the prospect of companies fundamentally reviewing and changing how they manage and protect mission critical operations. Such companies may well choose to deploy fuel cells to replace the batteries and Gen-Sets currently used. The quality and reliability fuel cells offer may induce some companies to consider eventually abandoning the grid completely to protect their businesses.

Utilities are looking ahead…

Many electrical utilities are aware of this eventuality and have taken options on the technology. For example the US utilities Avista Corp. Idacorp, and Detroit Eddison amongst others are all involved in the further development of fuel cell systems. In Europe, and particularly Germany, some electricity companies are alive to the potential of fuel cells. RWE, E.on, Bewag and EWE Oldenburg are all pursuing fuel cell options.

---as are gas companies

Meanwhile, gas companies are also investing in fuel cells, which can be no surprise given stationary fuel cell applications will run on natural gas. Gasunie of Holland, Gas Euskadi of Spain, Germany's Thyssengas and Japan's Tokyo Gas are all involved in on-site demonstration trials of stationary fuel cell units. Fuel cells would appear to be taking these companies into unfamiliar territory. These could be the first indications that business models in established industries are coming under review.

Products and Markets

Fuel cells can power mobile phones to industrial plant

The potential for fuel cells may be summed up thus:

If a device can be powered by electricity, then that device can be powered by a fuel cell, anywhere.

This statement captures the true potential of the technology: Fuel cells can power submarines and spaceships and all manner of devices in between. We estimate that the annual fuel cell market, including reformers and power conditioning equipment could be worth in the range of US$50 to US$100bn by 2010.

The range of markets fuel cells will compete in can be categorised as follows

(1) Portable

(2) Stationary

(3) Automotive

The above list is ranked loosely according to power requirements. We now briefly describe each of the markets indicating some targeted product applications, infrastructure requirements and the timing of market entry.

Portable Power Market

Batteries will be challenged by DMFCs

The portable power market is generally considered to include a huge array of applications covering a power range from a few watts to low double digit kilowatts. We restrict ourselves to a consideration of the genuinely portable end of the spectrum, which runs to a few hundred watts at most, in all likelihood supplied by Direct Methanol Fuel Cells. Such applications encompass products such as consumer electronic devices like Nokia's Communicator and laptop computers as well as military devices such high-capacity tactical field computers, helmet-mounted visual display units and laser range finders. The unique attraction of fuel cells in these applications is that they operate as long as fuel is supplied. They are supplied with a externally source of liquid fuel, which by its very nature packs considerably more power weight for weight than batteries ever could.

The price paid for portability makes batteries a highly-attractive target

Mobility carries an enormous premium and as such we anticipate Portable margins will be far superior to any other set of applications, bar none. The hydrogen for these devices will be stored in methanol/water cartridges, similar in dimension to a fountain pen refill and sold through existing retail networks. Infrastructure is unlikely to be an issue. Commercial market entry is currently expected around 2004 following the introduction of pre-commercial demonstration trials within the next 18 months to two years.

Stationary Power Markets

Stationary power ranges from homes to commerce to industry

Encompasses low power requirements for single and multi-family homes, medium power used in commercial enterprises like banks, hospitals and hotels as well as the multi-megawatt demands of industrial plant such as the steel and auto industries. These markets can be served by all the electrolytes. Margins in stationary will vary widely according to application. We would expect price in the industrial markets to be lowest, though still substantially above automotive applications.

The non-industrialised world may avoid installing a grid

Stationary applications will not be limited to the industrialised world. We believe that developing economies, and particularly those with gas reserves and infrastructure will by-pass the construction of large distribution infrastructure, much like the case in telecommunications, and go straight for quality distributed power. Penetration of these markets would be significantly accelerated should the Kyoto Protocol come into force.

Stationary plant can run on a wide variety of fuels

Stationary fuel cell plant will run on a variety of fuels, but mostly natural gas, making full use of the existing infrastructure. But these units are also well suited to use so-called opportunity fuels such as bio-gases from waste water and sewage plants as well as the methane produced in city dumps. Another interesting application being considered is to use fuel cells to capture gas from oil wells that has been traditionally flared, which is now banned. This application has the added benefit of attracting CO_2 credits.

We believe commercialisation is just a few years away

In our view residential and commercial plant (ie from 1kW units to 250kW units) will start to enter the markets on a commercial basis in two to three year's time. Large industrial plant, employing correspondingly large high-temperature fuel cell plant is some three to four years from commercial availability.

Automotive Power Markets

The infrastructure problem will not be the same for all users

The substantive point here is that there exist significant barriers to the successful deployment of Fuel Cell systems in the wider automotive market (as detailed on page 12). But, California notwithstanding, it would be foolhardy to dismiss the potential that does exist within sub-sectors that offer a clearer path to market. These include defined cycle fleet markets such as urban buses, postal and local delivery trucks and taxis. Another attractive early market, not requiring a nationwide refuelling infrastructure, is the captured fleet market. This sector includes, agricultural and airport vehicles (which number 100,000I in the US alone) as well as fork lift trucks.

The large defined cycle and captured fleet markets face relatively few problems

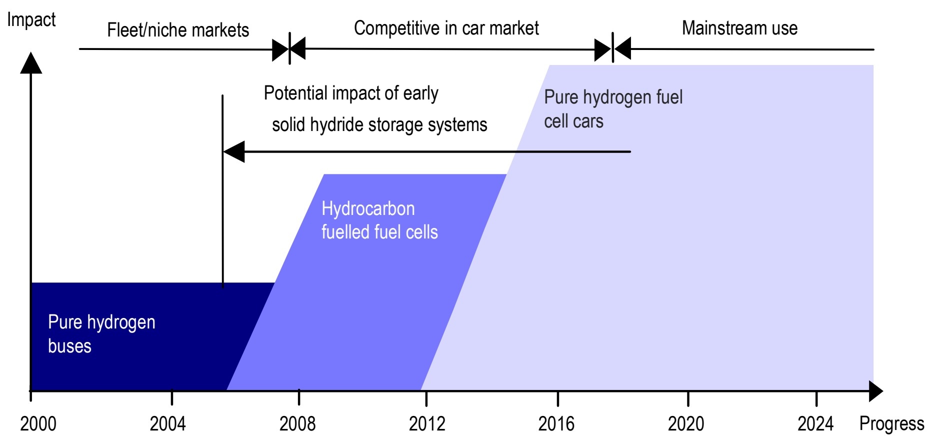
By way of an example of the potential size of defined cycle markets, the US Postal Service notes in its latest annual report that it owns some 200,000 delivery vehicles. Environmental pressure is highlighted by the fact that UPS operates 7,500 compressed natural gas vehicles within its fleet and began to take delivery of 10,000 flexible fuel ethanol vehicles this year. It has not been possible to estimate the size of the local delivery markets in detail, though we believe the examples given above hint that they could be substantial, as well as attractive. Indeed, local delivery markets are expected to be boosted by internet-driven orders. One of the benefits to in-town delivery offered by fuel cell motors, to both private homes and stores, is the fact that they are quiet and unlikely to fall foul of local noise abatement rules and hence could expand fleet operating times.

Europe's transit agencies signing up to significant bus trials

An indication of the European concern with environmental issues is reflected in the fact that nine major European cities are in negotiations with Daimler Chrysler to take delivery of three hydrogen-powered fuel cell buses each at an unsubsidised unit price of €1.2m per unit. In addition to this, the cities will bear the cost of installing the necessary hydrogen refuelling facilities. It is also believed that Melbourne in Australia is negotiating a similar contract. These buses will be used in demonstration programmes ahead of full commercialisation some time around 2003.

The following diagram is one possible scenario of how hydrogen will evolve in the automotive sector:

Chart 11: Advance of Hydrogen Technology in the Automotive Sector



Source: Shell Hydrogen

One scenario is that mainstream use will occur before 2020

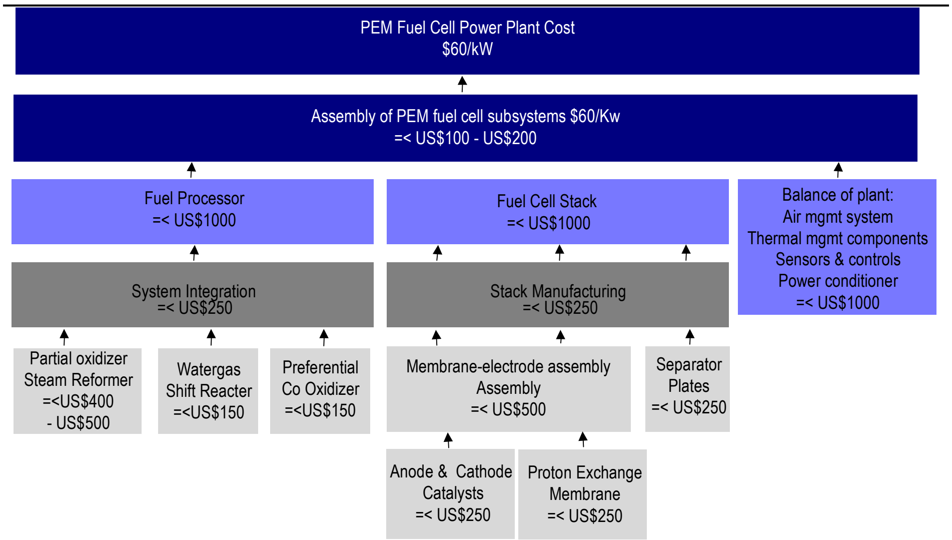
The graphic above depicts a scenario in which fuel cell powered fleet and niche markets, employing pure hydrogen systems, will be the first to be commercialised. This is followed by the passenger car markets becoming competitive some time after 2008, initially making use of on board reforming devices to extract the required hydrogen. Pure hydrogen systems are not anticipated for another 15 to 20 years from now.

But price is also demanding

Apart from the hurdles outlined above, a significant issue in automotive applications in the price sensitivity of this market. A price of US$60 per kW is held to be the price at which fuel cell power will be competitive with existing internal combustion engines (ICEs). At this price, a 50kW or almost 70bhp engine would come in at US$3,000, the price for an average ICE. The US$60 per kW price requirement is evenly split between the engine's three major components – assuming the hydrogen is extracted from a carbonaceous fuel such as petrol or methanol – namely the fuel cell stack, the fuel reformer and the so-called balance of plant (BOP). The BOP mainly consists of air and heat management systems as well as a power conditioner and sensors and controls.

The following chart is a detailed breakdown of the total cost of a fuel cell engine for automotive use.

Chart 12: Detailed Cost Breakdown of Fuel Cell Engines



Source: 'Fuel Cell Technical Advisory Panel' report to the California Air Resources Board, 1998.

Conventional Technologies

In the following pages we compare fuel cells with the conventional technologies they will seek to displace. When comparing fuel cells with automobile engines and electricity generating plant the appropriate yardstick is efficiency, whereas for batteries weight is the more appropriate measure of comparison.

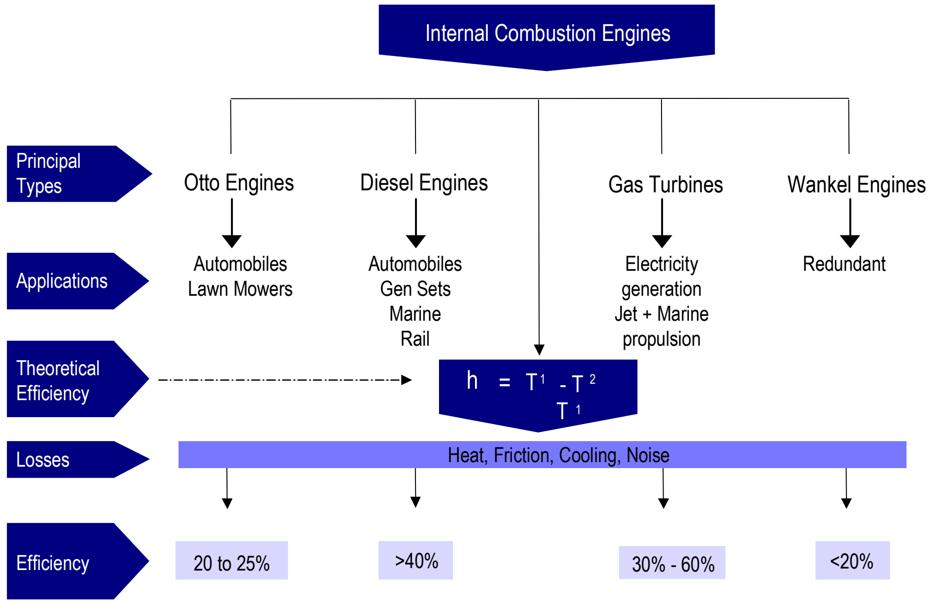
Internal Combustion Engines

ICEs offered flexibility and efficiency

The earliest energy conversion devices (ECDs) were waterwheels and windmills, used for grinding grain and later to drive sawmills, pumps and any number of other industrial processes. The Industrial Revolution created the need for new sources of power, independent of location or weather conditions. Subsequently wind and water conversion technologies were overtaken by the advent of heat engines, which convert the chemical energy stored in a fuel, normally a hydrocarbon by burning it. Early thermal devices were steam engines, which represented the first practical means for converting heat energy into mechanical energy. Later the invention of the internal combustion engine (ICE) largely supplanted tremendously inefficient steam engines.

Within the internal combustion group of heat engines four principal types have been developed, namely; the Otto engine, invented in the 1870s; the Diesel engine dating from the 1890s, gas turbines devised around 1900 and the rotary engine made in the 1950s. The following diagram details the four internal combustion engines:

Chart 13: Principal Internal Combustion Engine (ICE) Types



Source: UBS Warburg

The four-stroke Otto engine is widely regarded as the first practical ICE, and together with the Diesel engine, powers the vast majority of the world's automobiles. Gas-turbines, which are widely used for the generation of electricity, make use of compressed air, heated by the combustion of a hydrocarbon fuel. The rotary engine employs a three-cornered rotor turning in an oval combustion chamber in contrast to the pistons used in Otto and Diesel motors. A line of Wankel-rotary engines was produced in Japan in the early 1970s, but owing to their poor fuel economy and high emissions this technology is not widely employed and will not be discussed further.

Efficiency: Heat Engines

Heat engine efficency is fixed by the Carnot cycle

Sadi Carnot formulated the theoretical upper efficiency limit of a heat engine in 1824. Carnot's theorem shows that the theoretical maximum amount of heat energy available for conversion into useable energy in an idealised engine. It is determined by the difference between the maximum heat in the system and the temperature at which the exhaust heat is ejected. This idea is expressed by the following equation:

$$\eta = (T_1 - T_2) / T_1$$

Where η = engine efficiency, T_1 and T_2 = maximum and exhaust temperature respectively, measured on the Kelvin scale.

The exhaust (T_2) is unlikely to be below room temperature of around 290K and will always be relatively large. Assuming an ideal engine operated at 500C (T_1 = 773K) with an exhaust temperature of 55C (T2 = 328K) then it would have a theoretical efficiency of 57%. It thus follows that raising the operating temperature relative to the exhaust temperature raises the theoretical efficiency of a heat engine. (See Chart 14 below)

Carnot defined the borders

This general, theoretical formulation provided firm ground for the understanding of how thermal engines actually function and could best be designed. In other words it showed the thermodynamic borders within which heat engines operate (see chart 14 below). Once these parameters were understood, efficiency could be optimised subject to the constraint of energy losses through heat dissipation, mechanical friction and noise.

Efficiency: Electrochemical Conversion

Electrochemical efficiency does not conform to Carnot restrictions

Given fuel cells convert the chemical energy bound in a fuel directly into useful energy, they are not subject to the Carnot restriction and are thus capable of extracting more useful energy from the conversion process at significantly lower temperatures. In essence, the total energy required to bind hydrogen and oxygen together in a water molecule (H_2O) is less than the total amount of energy required to maintain hydrogen and oxygen in their natural diatomic states, ie H_2 and O_2. Thus when the gases are electrochemically rearranged in a fuel cell, this 'spare' energy is released. The relevant equation to measure the energy available for conversion is given as follows:

$$\Delta G = (\Delta H - T\Delta S) / \Delta H$$

Where ΔG is the energy available to do work which in the case of a fuel cell is the power or electrons fed to the load. ΔH is defined as the total energy contained in the fuel, which differs depending on the choice of fuel. T is absolute temperature as measured on the Kelvin scale and ΔS is the entropy or the small amount of energy unavailable for useful conversion.

Assuming a reaction where hydrogen combines with oxygen to form water ($H_2 + ½O_2 \rightarrow H_2O$), the theoretical efficiency (ΔG) is arrived at by plugging in the relevant values for ΔH and TΔS. It turns out that ΔH contains a total of 286 kilojoules of energy per mole (kJ/mol, a unit of energy accounting) with an associated non-convertible portion, TΔS, of 49kJ/mol. The theoretical efficiency of a fuel cell converting hydrogen and oxygen gases into liquid water is therefore 83%[2].

FCs do not need to operate at peak to maintain efficiency

At this point it is also worth mentioning a significant practical difference between fuel cells and heat engines: Fuel cell efficiency is relatively insensitive over a wide range of the operating range, whereas the efficiency numbers quoted for heat engines refer to the engine operating at peak. This consideration is particularly important when comparing fuel cells with conventional automotive engines.

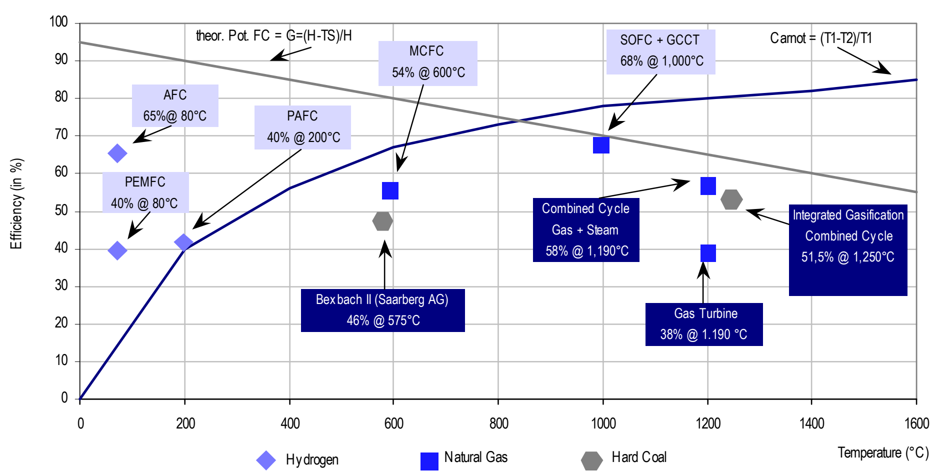
Direct energy conversion is simply superior…

Finally, the gap between the theoretical and operational efficiency is wider for thermal engines than fuel cells for the simple reason that fuel cells directly convert energy without the intermediate step of creating mechanical energy, which can be seen below.

Electricity Generating Plant Versus Fuel Cell Engines

Chart 14 contrasts Carnot and fuel cell efficiency boundaries with respect to temperature. The shapes of the respective boundaries reflect the equations discussed above. The chart also shows the actual efficiency of a number of working thermal electrical generators as well as the efficiencies of the five-hydrogen/air fuel cells.

Chart 14: Fuel Cell Efficiency Versus Heat Engines



Source: Pruschek, R:" Visionen einer zukünftigen Energie Versorgung".

…and is better at lower temperatures

It is noticeable that the gas turbine operating at 1190C is only 36% efficient compared to the Carnot limit of 80% at that temperature. The most efficient generator is the gas and steam combined cycle plant at 58%, but is still 22% below its Carnot limit, reflecting the inherent inefficiency owing to friction, heat loss and noise. By contrast the natural gas powered SOFC unit, making use of its exhaust

[2] The efficiency varies inversely with temperature. See Chart 14 above

heat in a combined cycle operation is not only 10% more efficient it is also operating close to its maximum limit. This clear shows the superiority of electrochemical energy conversion against thermal energy conversion It is the ability of fuel cells in general to operate so efficiently that makes them so attractive. While the traditional technologies have been under development for around 100 years, the high temperature fuel cells that are ideally suited to large power production have been under investigation for just 30 years and are now emerging from laboratories into real pre-commercial demonstrations.

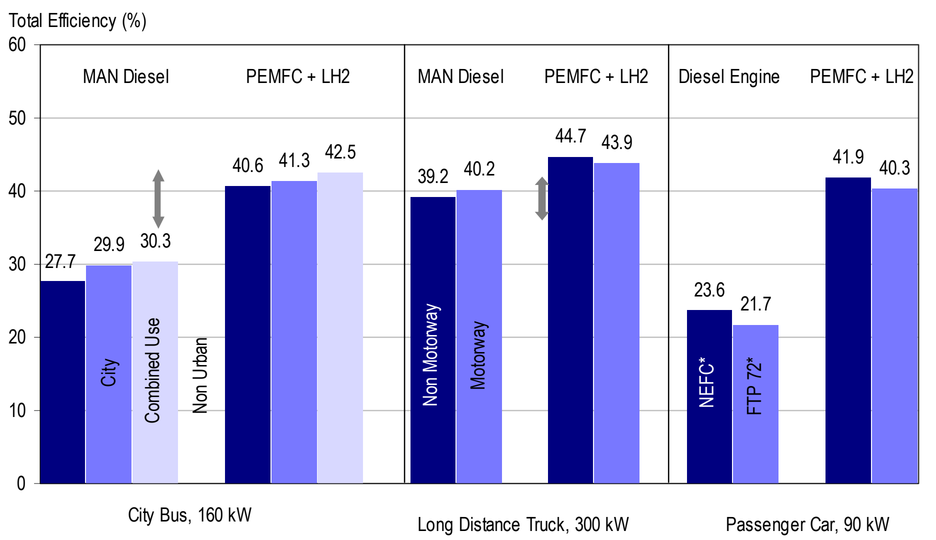
ICEs need to increase temperature to increase efficiency: the cost is pollution

One further comparison between conventional power plant and fuel cells is worth noting. According to the VIK (*Verband der Industriellen Energie- und Karftwirtschaft*), the German Federation of Industrial Energy Consumers and Self-Producers, a modern combined cycle gas turbine, operating at around 55% efficiency can be expected to produces around 560 milligrams of oxides of nitrogen (NO_x) per kilowatt hour. High temperature fuel cells, operating at 65% efficiency using natural gas, by contrast, emit less than 1mg of NO_x per kilowatt of electricity. In other words the fuel cell produces 99.88% less NO_x. Finally, it is worth noting that heat engines achieve greater efficiencies by increasing operating temperature relative to exhaust temperature with the penalty being a greater pollution problem.

Automotive Engines Versus Fuel Cell Engines

Chart 15 compares the tank to wheel efficiencies of conventionally powered buses trucks and cars with PEM fuel cells.

Chart 15: Total Efficiency 'From Tank To Wheel'



Source: MAN Nutzfahrzeuge AG. *

Automotive drive cycles lend FCs a natural advantage

It is clear from the chart that internal combustion engines have a lower tank to wheel efficiency than fuel cell engines for cars, buses and trucks. Given the different drive cycles of the vehicles highlighted above it is not surprising to see that the least difference between a conventional engine and a fuel cell engine is in long-distance trucks. This conclusion is indicative of the fact that internal combustion engines are most efficient when operated at peak, which city traffic hardly ever attains.

ICEs may be near the end of their R&D lives…fuel cells are at the beginning of theirs

The net result at the end of more than 100 years of research and development, is that the internal combustion engines powering automobiles yield efficiencies of between 20 to 25%, while PEMFC powered engines offer significantly higher fuel efficiencies. The important point here is that the fuel cell is at the beginning of its commercial development and has a long way to go before the research and development dollars even begin to approach the volumes spent on developing conventional engines.

Batteries Versus Fuel Cells

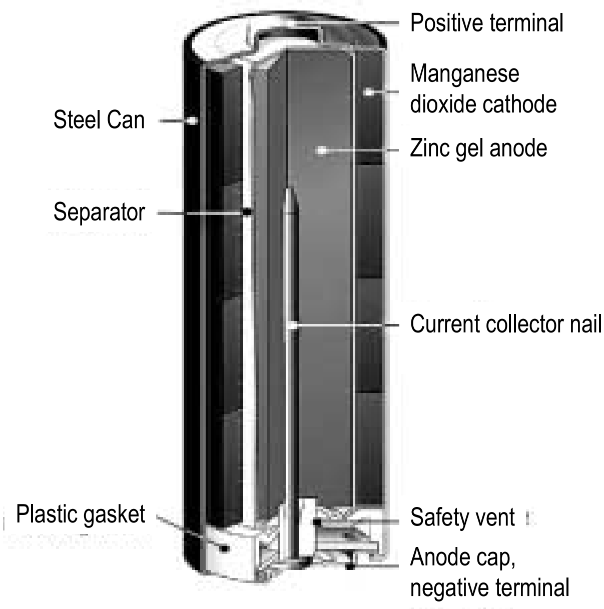
The range of battery applications is bewildering

While batteries, like fuel cells, transform chemical energy into electrical energy, essentially batteries are storage devices, converting the chemical energy of material previously stored internally. Batteries can be divided into two types, namely, rechargeable or secondary and non- rechargeable or primary batteries. Within these two subgroups there is a wide variety of batteries, which are used in a bewildering array of applications.

Like fuel cells, batteries essentially consist of two electrodes and an electrolyte, which can be either solid or liquid. The capacity of a given battery is determined by the chemicals it contains as well as their quantity and is normally measured in milli-amp-hours. The chemical agents within the cell also determine the voltage. The power the battery can deliver is the product of milli-amps multiplied by volts.

The following diagram details the structure of a long-life alkaline primary cell:

Chart 16: Structure of a Long-Life Alkaline Primary Cell



Source: Varta AG

A porous separator isolates the manganese dioxide cathode from the zinc anode. Within the electrolyte the cathode material establishes a negative potential while the anode material establishes a positive potential. The nail in the centre of the cell acts as the current collector. When the circuit to which the battery is connected is closed, electrons from the zinc flow from the negative terminal via the external load - e.g.

lamps or motors - to the positive terminal and into the manganese dioxide cathode. To complete the electrical circuit and the chemical process, ions flow through the electrolyte. Thus the energy stored in the chemical materials is released as the chemicals themselves undergo transformation, releasing electricity and heat in the process. Once the electron supply has been exhausted the cell is flat, as all the energy stored in the chemical agents has been converted into electrical energy. If it is a primary battery, it will be disposed of, or, if it is a secondary battery, it can be recharged.

During the recharging process, electrons flow in reverse, from the cathode to the anode. Again the transfer of ions through the electrolyte completes the circuit and the restores previously existing chemical state of the cell. The best-known examples are lead-acid, nickel cadmium, nickel-metal hydride and lithium-ion batteries. Under normal conditions a rechargeable battery will take between 500 and 1000 charge-discharge cycles, with each recharge contributing to some degradation of the chemical agents.

Dead Weight and Limited Capacity

The weight and capacity of batteries severely limits their use

Weight is a significant issue for batteries. While it may not be noticeable in a mobile phone, the weight of batteries has thus far proven to be a significant barrier to the wider use of batteries. The following example, though extreme, will serve to illustrate this point.

A three-day Shuttle mission uses around one megawatt of electricity, which is supplied by three Alkaline Fuel Cells. Each fuel cell weighs around 115 kilos for a total weight of some 345 kilograms. The cells consume around 450 kilograms of hydrogen and oxygen giving a system weight of 800 kilograms. Using high-powered alkaline the C-cells, used in torches, the best available battery, would require just over five metric tons to do the same job. Apart from the weight consideration, the inherent unattractiveness of batteries in all applications lies in their inability to provide continuous (ie, without the need for recharging) power.

Summary Company Profiles

This section is intended to give the briefest overview of some quoted Fuel Cell businesses and their key characteristics. Research on these and others (including suppliers) will follow. For further information, please contact us.

Ballard Power Systems (BLDP.O)

Location	Vancouver
Approx. Market Cap.	US$8,874m
Foundation / History	Founded in 1979
Electrolyte	PEM / DMFC
Core Technology / Strategy	Ballard is positioning itself as a substantial manufacturer of Fuel Cell stacks / systems.
Product / Development Progress	Cell architecture suitable for mass production (Mark 900) established; First plant for mass production to be commissioned late 2000. First products will probably be for portable power applications - expected launch in 2001. Thereafter, stationary power in 2002 and Automotive in 2004 / 5.
Key Relationships	Daimler-Chrysler; Ford, GPUI, Ebara, Coleman Powermate, Alstom, Matsushita
Other businesses	None
Comment	Ballard is very well advanced in its plans for technological development and market entry. In fact, it is the structure of the group's partner relationships in anticipation of market entry that is as impressive as its technological development. See our BALLARD review of 23 June 2000

Fuel Cell Energy (FCEL.O)

Location	Danbury, Connecticut, US
Approx. Market Cap.	US$1,109m
Foundation / History	Used to be called Energy Research Corporation, founded in 1970
Electrolyte	Molten Carbonate
Core Technology / Strategy	FCE is developing products in the 250kw - 3MW+ range and has cross-licensing agreements with MTU.
Product / Development Progress	The first components were made in 1992 with pre--commercial units being built, now. Significant testing time has already been logged. Some early problems (not associated with the cell itself). Since then, progress has been steady. FCE will attack the Stationary Power market and we expect the first commercial units should be sold in 2003 / 2004
Key Relationships	MTU; US DoE; Marubeni; Los Angeles Dept. of Water and Power, et al.
Other businesses	None
Comment	FCE has an impressive, focussed strategy as well as a technology which looks attractive.

Plug Power (PLUG.O)

Location	Latham, NY, US
Approx. Market Cap.	US$919m
Foundation / History	Founded 1997 as a JV between DTE Energy and Mechanical Technology. Floated October 1999.
Electrolyte	PEM
Core Technology / Strategy	PEM systems of c. 7kw - fuelled by Natural Gas, will be used for domestic applications.
Product / Development Progress	Actual stage of development is unclear - save for launch target of 2002. The target market is residential power systems. Plug claim they will have full commercial product availability in H1 2002.
Key Relationships	GE; MTI; DTE Energy; Southern California Gas
Other businesses	None
Comment	The publicity surrounding Plug's apparent failure to meet GE's expectations recently - along with changes in senior management - have not inspired confidence. The burden of proof placed on Plug, in demonstrating that it can deliver, has therefore increased.

DCH Technology (DCH)

Location	Valencia, CA, US
Approx. Market Cap.	US$125m
Foundation / History	Founded as partnership in 1994, quoted
Electrolyte	PEM
Core Technology / Strategy	Small (up to 10kw) cylindrical Fuel Cells and various types of Hydrogen sensors.
Product / Development Progress	Still pre-commercial. Demonstrators include a 3kw unit with EPRI (Electric Power Research Institute) and smaller ones with the US army. It is apparent that the company is looking at a wide range of industries inc. semiconductor manufacturing, telecommunications, automotive (electric vehicles and alternatively fuelled cars and trucks)
Key Relationships	Customers include: GE; GM; Ford; TRW; Lockheed Martin; Westinghouse; Mobil and Exxon.
Other businesses	None

H Power (HPOW.O)

Location	Belleville, NJ, US
Approx. Market Cap.	US$935m
Foundation / History	Founded in July1989
Electrolyte	PEM
Core Technology / Strategy	Small stationary (1kw to 20kw) and portable (up to 15kw) fuel cells for various general and back-up power applications.
Product / Development Progress	The company is already well advanced in its product development and has already sold cells for use in mobile road signs and is also working on fuel cells for military applications. The launch of new, residential products is imminent while development of all new product types continues apace.
Key Relationships	Various - including ECO in the US with distribution rights for stationary power units.
Other businesses	None

Global Thermoelectric (GLE.TO)

Location	Calgary, Alberta, CAN
Approx. Market Cap.	C$751m
Foundation / History	Founded in 1975, FC business started 1997
Electrolyte	SOFC
Core Technology / Strategy	Global is developing SOFC technology for the residential, small industrial co-gen and hybrid vehicles markets concentrating on1kw to 25kw power ranges.
Product / Development Progress	Global expects to have Canada's first operational pilot plant in 2001
Key Relationships	Enbrige Inc, Canada's largest gas distributor. Also supply Delphi with SOFC stacks for development of an auto APU
Other businesses	Core business of the group is thermoelectric generators for generating power in remote locations

Astris Energi (ASTS.CD)

Location	Mississauga, Ontario. Canada
Approx. Market Cap.	n/a
Foundation / History	The private company was formed in 1983
Electrolyte	Alkaline
Core Technology / Strategy	Alkaline FCs of below 10kw
Product / Development Progress	Most cells sold to date have been demonstration and educational cells as well as units for use in testing ASETS' desktop model components and system expected to be available in 2000.
Key Relationships	Sells product via Fuelcellstore.com
Other businesses	None

Medis El (MDTL.O)

Location	Israel
Approx. Market Cap.	US$342m
Foundation / History	Formed in 1992
Electrolyte	Direct Methanol
Core Technology / Strategy	Described as a 'greenhouse' for new technologies - one of which is fuel cells
Product / Development Progress	The company is concentrating its Fuel Cell efforts on developing ells for use in lap-top computers and mobile phones and believes it has a particular know-how in preventing leakage form such cells.
Key Relationships	Various academic
Other businesses	Various unrelated technologies

Manhattan Scientific (MHTX.OB)

Location	New York City, US
Approx. Market Cap.	US$288m
Foundation / History	Floated in 1998
Electrolyte	PEM
Core Technology / Strategy	Manhattan is a technology incubator involved in Direct Methanol fuelled PEM for MicroFuel Cell and H2 fuelled PEM for other (portable) applications
Product / Development Progress	The company is developing two distinct FC product ranges which address two complementary areas of the market. The direct methanol system will fuel mobile phones, pagers etc, while the H2 fuelled system will be aimed at slightly larger applications up to household power systems.
Key Relationships	Various
Other businesses	Various other technologies

UBS Warburg

This report was produced by:

UBS Warburg

+44-20-7567 8000

Head Office:

1 Finsbury Avenue
London
EC2M 2PP
United Kingdom