Introduction to fuel cells and hydrogen technology

by Brian Cook

Whereas the 19th century was the century of the steam engine and the 20th century was the century of the internal combustion engine, it is likely that the 21st century will be the century of the fuel cell. Full cells are now on the verge of being introduced commercially, revolutionising the way we presently produce power. Fuel cells can use hydrogen as a fuel, offering the prospect of supplying the world with clean, sustainable electrical power..

A fuel cell by definition is an electrical cell, which unlike storage cells can be continuously fed with a fuel so that the electrical power output is sustained indefinitely.[1] It converts hydrogen, or hydrogen-containing fuels, directly into electrical energy plus heat through the electrochemical reaction of hydrogen and oxygen into water. The process is that of electrolysis in reverse:

overall reaction: $2H_2(\text{gas}) + O_2(\text{gas}) \rightarrow 2H_2O + \text{energy}$ (1)

Because hydrogen and oxygen gases are electrochemically converted into water, fuel cells have many advantages over heat engines. These include: high efficiency, virtually silent operation and, if hydrogen is the fuel, there are no pollutant emissions. If the hydrogen is produced from renewable energy sources, then the electrical power produced can be truly sustainable.

The two principal reactions in the burning of any hydrocarbon fuel are the formation of water and carbon dioxide. As the hydrogen content in a fuel increases, the formation of water becomes more significant, resulting in proportionally lower emissions of carbon dioxide (Fig. 1). As fuel use has developed through time, the percentage of hydrogen content in the fuels has increased. It seems a natural progression that the fuel of the future will be 100% hydrogen.

History of fuel cells

The 'gas battery'

Sir William Grove (1811–96), a British lawyer and amateur scientist, developed the first fuel cell in 1839. The principle was discovered by accident during an electrolysis experiment. When Sir William disconnected the battery from the electrolyser and connected the two electrodes together, he observed a current flowing in the opposite direction, consuming the gases of hydrogen and oxygen (Fig. 2). He called this device a 'gas battery'. His gas battery consisted of platinum electrodes placed in test tubes of hydrogen and oxygen, immersed in a bath of dilute sulphuric acid. It generated voltages of about 1V. In 1842 Grove connected a number of gas batteries together in series to form a 'gas chain'. He used the electricity produced from the gas chain to power an electrolyser, splitting water into hydrogen and oxygen (Fig. 3). However, due to problems of corrosion of the electrodes and instability of the materials, Grove's fuel cell was not

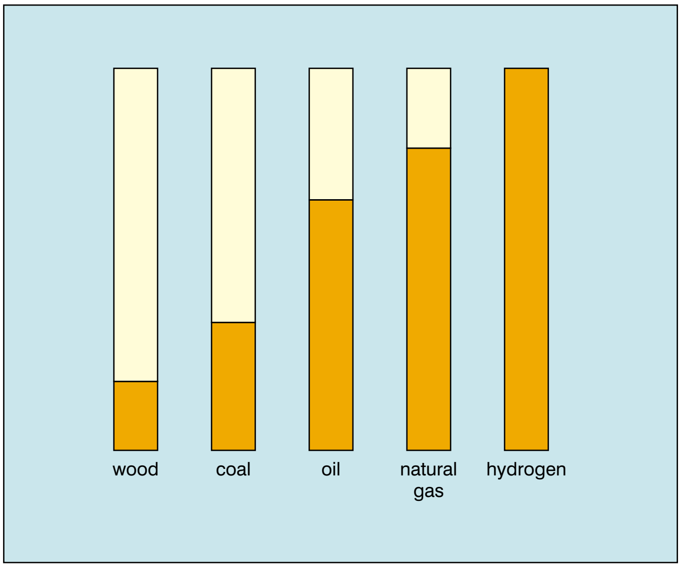

Fig. 1 Trends in the use of fuels. As fuel has developed through time, the percentage of hydrogen content in the fuel has increased

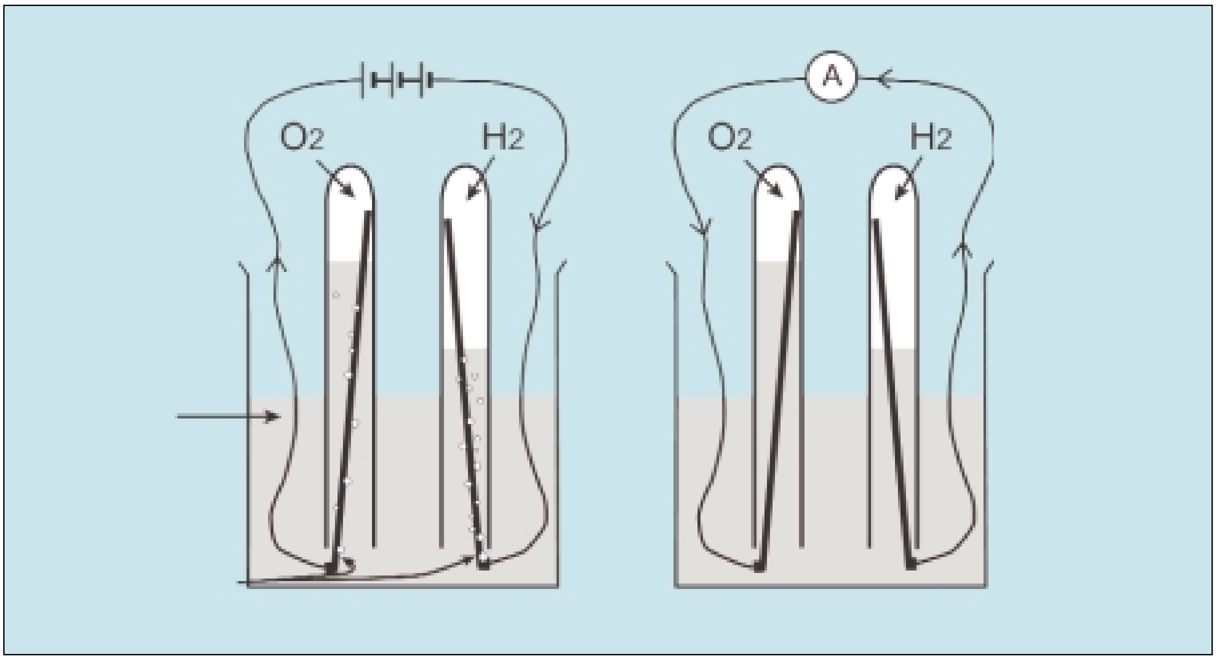

Fig. 2 Principle of an electrolyser (left) and a fuel cell (see Reference 2)

practical. As a result, there was little research and further development of fuel cells for many years to follow.

The 'Bacon fuel cell'

Significant work on fuel cells began again in the 1930s, by Francis Bacon, a chemical engineer at the University of Cambridge, UK. In the 1950s Bacon successfully produced the first practical fuel cell, which was an alkaline version (Fig. 4). It used an alkaline electrolyte (molten KOH) instead of dilute sulphuric acid. The electrodes were constructed of porous sintered nickel powder so that the gases could diffuse through the electrodes to be in contact with the aqueous electrolyte on the other side of the electrode. This greatly increased the contact area contact between the electrodes, the gases and the electrolyte, thus increasing the power density of the fuel cell. In addition, nickel was much less expensive than platinum. The chemical reactions in the alkaline fuel cell are:

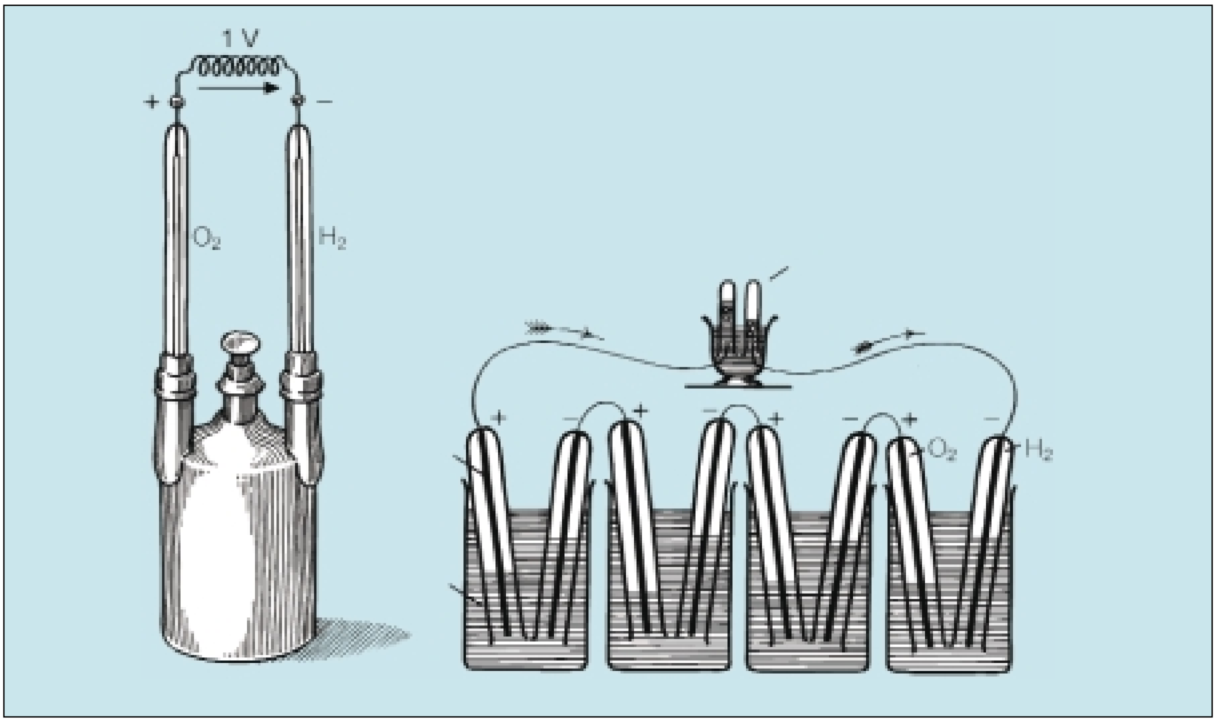

Fig. 3 Grove's 'gas battery' (1839) produced a voltage of about 1V (left); Grove's 'gas chain' powering an electrolyser (1842) (see Reference 3)

Fig. 4 Bacon's laboratory at the Department of Chemical Engineering, University of Cambridge (1955). A fuel cell can be seen being assembled on the left of the picture (photo: courtesy of Department of Chemical Engineering, University of Cambridge)

anode reaction: $2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$ (2)
cathode reaction: $O_2 + 4e^- + 2H_2O \rightarrow 4OH^-$ (3)
overall reaction: $2H_2 + O_2 \rightarrow 2\,H_2O$ (4)

Fuel cells for NASA

For space applications, fuel cells have the advantage over conventional batteries in that they produce several times as much energy per equivalent unit of weight. In the 1960s, International Fuel Cells in Windsor, Connecticut, USA, developed a fuel cell power plant for the Apollo spacecraft. The plant, located in the service module of the spacecraft, provided both electricity as well as drinking water for the astronauts on their journey to the moon. It could supply 1·5kW of continuous electrical power. Fuel cell performance during the Apollo missions was exemplary. Over 10 000 hours of operation were accumulated in 18 missions, without a single in-flight incident (Internet source: IFC).

In the 1970s, International Fuel Cells developed a more powerful alkaline fuel cell for NASA's Space Shuttle Orbiter (Fig. 5). The Orbiter uses three fuel cell power plants to supply all the electrical needs during flight. There are no backup batteries on the Space Shuttle, and as such, the fuel cell power plants must be highly reliable. The power plants are fuelled by hydrogen and oxygen from cryogenic tanks and provide both electrical power and drinking water. Each fuel cell is capable of supplying 12kW continuously, and up to 16kW for short periods. The Orbiter units represent a significant technology advance over Apollo, producing about ten times the power from a similar sized package. In the Shuttle programme, the fuel cells have demonstrated outstanding reliability (over 99% availability). To date, they have flown on 106 missions and clocked up over 82 000 hours of operation (Internet source: NASA).

Alkaline fuel cells for terrestrial applications

Compared with other types of fuel cells, the alkaline variety offered the advantage of a high power to weight

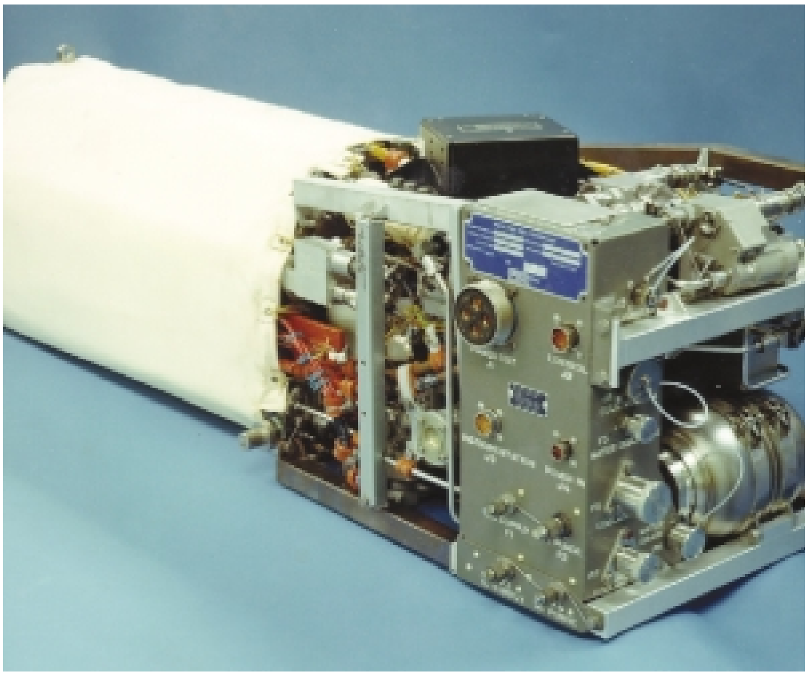

Fig. 5 NASA Space Shuttle Orbiter fuel cell, one of three fuel cells aboard the Space Shuttle. These fuel cells provide all the electricity as well as drinking water when the Space Shuttle is in flight. It produces 12kW(e) and occupies 154 litres (photo: courtesy of NASA)

Fig. 6 Two prototype automobiles powered by Ballard fuel cells, the NECAR 5 and JEEP Commander, from DaimlerChrysler (photo: courtesy of DaimlerChrysler)

ratio. This was primarily due to intrinsically faster kinetics for oxygen reduction to the hydroxyl anion in an alkaline environment. Therefore alkaline fuel cells were ideal for space applications. However, for terrestrial use, the primary disadvantage of these cells is that of carbon dioxide poisoning of the electrolyte. Carbon dioxide is not only present in the air but also present in reformate gas, the hydrogen rich gas produced from the reformation of hydrocarbon fuels.

In the poisoning of an alkaline fuel cell, the carbon dioxide reacts with the hydroxide ion in the electrolyte to form a carbonate, thereby reducing the hydroxide ion concentration in the electrolyte. This reduces the overall efficiency of the fuel cell. The chemical equation for carbon dioxide reacting with a potassium hydroxide electrolyte is:

$$2KOH + CO_2 \rightarrow K_2CO_3 + H_2O \qquad (5)$$

Because of the complexity of isolating carbon dioxide from the alkaline electrolyte in fuel cells for terrestrial applications, most fuel cell developers have focused their attention on developing new types using electrolytes that are non-alkaline. These fuel cells include: solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC) and polymer electrolyte membrane or proton exchange membrane (PEM) fuel cells.

PEM fuel cell

In the early 1960s, General Electric (GE) also made a significant breakthrough in fuel cell technology. Through the work of Thomas Grubb and Leonard Niedrach, the company invented and developed the first polymer electrolyte membrane (PEM) fuel cell. It was initially developed under a programme with the US Navy's Bureau of Ships and US Army Signal Corps to supply portable power for personnel in the field.

Attracted by the possibility of using GE's PEM fuel cell on the Apollo missions, NASA tested its potential to provide auxiliary power onboard its Gemini spacecraft. The Gemini space programme consisted of 12 flights in preparation for the Apollo missions to the moon. For lunar flights, a longer power source was required than could be provided by batteries, which had been used on previous space flights. Unfortunately, the GE fuel cell, model PB2, encountered technical difficulties prior to launch, including the leakage of oxygen through the membrane. As a result the Gemini missions 1 to 4 flew on batteries instead.

The GE fuel cell was redesigned and a new model, the P3, successfully operated on the Gemini flights 6 to 12. The Gemini fuel cell power plant consisted of two fuel cell battery sections, each capable of producing a maximum power of about 1000 W (Internet source: NASA).

A further limitation of the GE PEM fuel cell at that time was the large quantity of platinum required as a catalyst on the electrodes. The cost of PEM fuel cells was prohibitively high, restricting its use to space applications.

In 1979, Geoffrey Ballard, a Canadian geophysicist, chemist Keith Prater and engineer Paul Howard established the company Ballard Power Systems. In the early 1980s, Ballard took the abandoned GE fuel cell, whose patents had expired and searched for ways to improve its power and build it out of cheaper materials.[4]

Working on a contract from the Canadian Department of National Defence, Ballard developed fuel cells with a significant increase in power density while reducing the amount of platinum required. From these developments it was recognised that fuel cells could be made smaller, more powerful and cheaply enough to eventually replace conventional power technologies.

Ballard Power Systems has since grown to become recognised as a world leader in PEM fuel cell technology, developing fuel cells with power outputs ranging from 1 kW, for portable and residential applications, through to 250 kW for distributed power. Ballard has formed alliances with a wide range of companies, including DaimlerChrysler, Ford, EBARA in Japan and ALSTOM in France.

In the late 1980s and early 1990s Los Alamos National Laboratory and Texas A&M University also made significant developments to the PEM fuel cell. They also found ways to significantly reduce the amount of platinum required and developed a method to limit catalyst poisoning due to the presence of trace impurities in the hydrogen fuel (Internet source: Los Alamos National Laboratory).

Fuel cell applications

Transportation

The California Low Emission Vehicle Program, administered by the California Air Resources Board (CARB), has been a large incentive for automobile manufacturers to actively pursue fuel cell development. This programme requires that, beginning in 2003, 2% of passenger cars delivered for sale in California from medium or large-sized manufacturers must be zero emission vehicles, called ZEVs. Either automobiles powered by batteries or those powered by fuel cells meet these requirements, as the only output of a hydrogen fuel cell is pure water.

The NECAR 5 (Fig. 6) is the latest prototype fuel cell automobile by DaimlerChrysler. This automobile is fuelled with liquid methanol which is converted into hydrogen and carbon dioxide through use of an onboard fuel processor. The vehicle has virtually no pollutant emissions of sulphur dioxide, oxides of nitrogen, carbon monoxide or particulates, the primary pollutants of the internal combustion engine. The efficiency of a fuel cell engine is about a factor of two higher than that of an internal combustion engine and the output of carbon dioxide, when fuelled with a hydrocarbon fuel, is considerably lower.

The NECAR 5 drives and feels like a 'normal; car. It has a top speed of over 150 km/h (90mph), with a power output of 75 kW (100hp). It is also believed that this vehicle will require less maintenance. It combines the low emission levels, the quietness and the smoothness associated with electric vehicles, while delivering a performance similar to that of an automobile with an internal combustion engine.

In April 1999 the California Fuel Cell Partnership was developed. Founding members included DaimlerChrysler, the California Air Resources Board, the California Energy Commission, Ballard Power Systems, Ford, Shell and Texaco. The primary goals of the partnership are to:

Fig. 7 PEM fuel-cell distributed power plant. This unit, produced by Ballard Power Systems, provides 250kW heat and electricity which is enough power for a small building, a school or a community of up to 50 homes (photo: courtesy of Ballard Power Systems)

- Demonstrate vehicle technology by operating and testing the vehicles under real-world conditions in California.
- Demonstrate the viability of alternative fuel infrastructure technology, including hydrogen and methanol stations.
- Explore the path to commercialisation, from identifying potential problems to developing solutions.
- Increase public awareness and enhance opinion about fuel cell electric vehicles, preparing the market for commercialisation.

Fig. 8 Fuel-cell cogeneration power plant for residential applications, providing 7kW heat and electricity, enough power for a modern energy efficient home (photo: courtesy of Plug Power)

Fig. 9 Prototype portable fuel cell providing 50W electrical power, produced by Heliocentris. The fuel cell is contained in the upper compartment; the hydrogen is stored in a metal hydride canister in the lower compartment

Since then new participants include General Motors, Honda, Hyundai, Nissan, Toyota, Volkswagen, British Petroleum, Exxon Mobil, US Department of Energy and US Department of Transportation. To date five of the world's leading auto manufacturers have announced that they plan to introduce fuel cell automobiles beginning in the 2003 to 2005 timeframe.

There are also plans for buses and trucks all powered with fuel cell engines. In 2000, Ballard completed a two-year program of in-service field testing with six fuel cell buses, three in Vancouver, British Columbia, and three in Chicago. Objectives of the field test included gathering data on performance and maintenance for use in Ballard's future heavy-duty engine designs, assessing public acceptance, and determining the needs of transit authorities and users of the buses.

The results of the tests were exemplary—the six buses travelled almost 75 000 miles and carried over 200 000 passengers. Thirty new transit buses powered by Ballard's heavy-duty fuel cell engines will be introduced to ten European cities beginning in 2003 for additional demonstration. The resulting data will be used to further develop a commercial fuel cell bus.

Distributed power generation

Electrical energy demands throughout the world are continuing to increase. In Canada the demand is growing at an annual rate of approximately 2·6%. In America the rate is about 2·4%[5], and in developing countries it is approximately 6%.[6] How can these energy demands be met responsibly and safely? Distributed power plants using fuel cells can provide part of the solution.

Distributed or 'decentralised' power plants, contrasted with centralised power plants, are plants located close to the consumer, with the capability of providing both heat and electrical power (a combination known as 'cogeneration'). Heat, the byproduct of electrical power generation, is transferred from the fuel cell to a heat exchanger. The exchanger transfers the heat to a water supply, providing hot water to local customers. The overall efficiency of a cogeneration system can be in excess of 80%, comparatively high compared to a system producing electricity alone. An increase in efficiency naturally corresponds to a decrease in fuel consumption.

Distributed power plants have many additional advantages. For example, they can provide power to a remote location without the need of transporting electricity through transmission lines from a central plant. There is also an efficiency benefit in that the cost of transporting fuel is more than offset by the elimination of the electrical losses of transmission. The ability to quickly build up a power infrastructure in developing nations is often cited. Using fuel cell power plants obviates the need for an electrical grid.

Distributed power plants can provide either primary or back-up power. In primary applications they can provide base-load power, operating virtually continuously from the consumption of natural gas, reducing the demand from the electrical grid. This not only decreases the cost of displaced power, but can also result in a reduction of demand charges imposed by the utility. Should the power plant provide an excess of electricity, the excess can be fed back into the electrical grid, resulting in additional savings.

In case of a power outage on the grid, a distributed power plant can continue to provide power to essential services; eliminating the need for both an uninterruptible power supply (UPS), presently handled by lead-acid battery banks, and a standby generator, for extended periods of power outage. An additional quality of a fuel cell power plant for UPS applications is that the average 'down time' is anticipated to be low, 3·2 to 32 seconds per year against typically nine hours for a conventional battery-bank UPS (Internet source: HDR Engineering). For industries where UPS systems are critical, such as banking, minimising down time is of utmost importance.

Other applications for fuel cell distributed power plants are also possible, e.g. stand-alone back-up power generators. The PEM fuel cell plant can be started in seconds, supplying power for as long as required from stored hydrogen, producing electrical power cleanly and virtually silently.

Shown in Fig. 7 is a prototype fuel cell distributed power plant, by Ballard Power Systems. This unit provides 250 kW of electricity and an equivalent amount of heat. This is enough power for a community of about 50 homes, or a small hospital or a remote school. This particular unit incorporates a fuel processor so that natural gas can be used as a fuel. The fuel processor converts the natural gas, through the

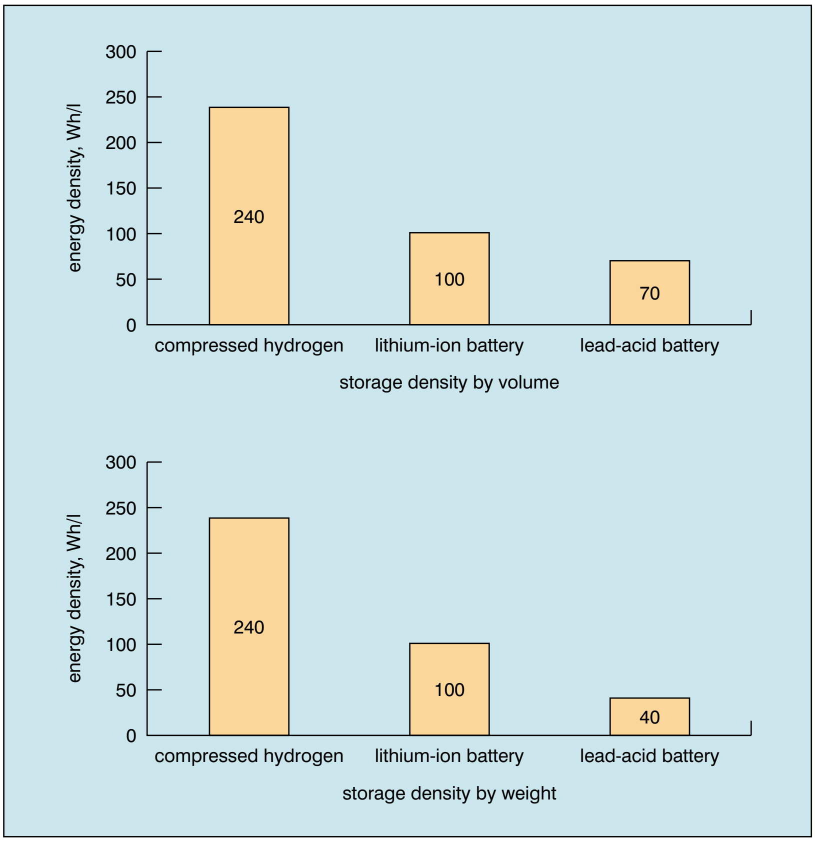

Fig. 10 Comparison of the energy density of compressed hydrogen (3000 psi) against lithium-ion and lead-acid batteries

process of reformation, into a hydrogen-rich gas composed primarily of hydrogen and carbon dioxide. The hydrogen is used by the fuel cell and the carbon dioxide is released into the atmosphere.

Eventually as an infrastructure for hydrogen develops, these units could be powered with hydrogen directly without the need for a fuel processor. Ballard Power is presently field-testing five of these units in the United States, Germany, Japan and Switzerland, with four more units planned for 2002. Testing is expected to continue until 2004.

Residential power

Fuel cell power plants are also being developed by several manufacturers to provide electricity and heat to single-family homes. Fuelled by either natural gas or propane, these plants will be able to supply base-load power or all the electricity required by a modern-day home.

Ballard Power Systems, in collaboration with its associate company Ebara Ballard, partner Ebara Corporation, and co-developer Tokyo Gas, has developed a 1 kW fuel cell generator designed to supply both base-load electrical power as well as heat to a dwelling. This unit can also be fuelled by natural gas. It does not provide enough power to supply the total electrical demands of a residence, but it does shift a portion of the demand from the electrical grid to natural gas. The electrical efficiency of this fuel cell system is rated at 42% and the heat efficiency is rated at 43%. Therefore the combined cogeneration efficiency of the system can be as high as 85%. This particular generator is targeted at the Japanese residential market. Ballard's goal is to commence sales of these units in 2004.

Plug Power, based in Latham New York has developed a new fuel cell power plant that supplies 5 kW of electricity plus heat, using natural gas as a fuel (Fig. 8). Depending on the size and location of the house this could be enough power to supply the electrical demand of a modern energy efficient home. Initially these fuel cell power plants will be operated in parallel with the grid. Eventually they will be able to operate either grid parallel or grid independent, possibly supplying the entire power for a modern home. Plug Power is presently installing and testing these units in selected sites throughout North America, Europe and Japan. In 2001, 75 units were delivered to Long Island Power Authority (LIPA) to supplement the grid and provide learning experience for LIPA employees. This experience will enable LIPA to purchase and install a larger number of units in a variety of locations in the future.

Portable power

Several manufacturers are also developing fuel cell power supplies for portable applications, providing a few watts up to several kilowatts of electricity (Fig. 9). Fuelled by stored natural gas, propane, methanol or hydrogen gas, portable fuel cells may one day replace both gasoline and diesel-engine generators for portable applications as well as conventional batteries for uses such as remote lighting, laptop computers and mobile phones.

Compared with engine-driven mobile electrical generators, fuel cells have the significant advantage of being quiet and having low emissions. As they have few moving parts (only external pumps and fans) they operate virtually silently. If stored hydrogen is the fuel, again the only emission is pure water.

A significant advantage of the fuel cell over its battery counterpart is that of its energy density (Fig. 10). Portable power packs using fuel cells can be lighter and smaller in volume for an equivalent amount of energy, particularly the direct methanol fuel cell. Note that the comparison here is the fuel tank.

'The fuel cell makes sense when the energy storage required by an application represents many hours of operation at full power. The durability of batteries in this sort of application is at best a few hours. The size, weight, and cost of energy

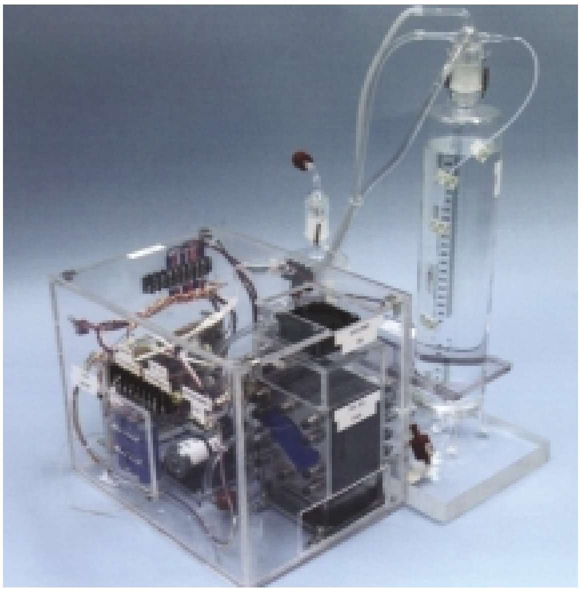

Fig. 11 Prototype direct methanol fuel cell used as a lithium battery charger provides up to 20W electrical power (photo: courtesy of Jet Propulsion Laboratories/NASA)

storage for a fuel cell power plant easily out-competes batteries. You do have the fixed cost (and size and weight) of the plant, which is a function of power. This is why it is important to note that the advantage of fuel cells is for low power, high energy applications.' (Ric Pow of Pow Consulting, 2001)

Rechargeable batteries will discharge over time; the colder the ambient temperature the quicker they

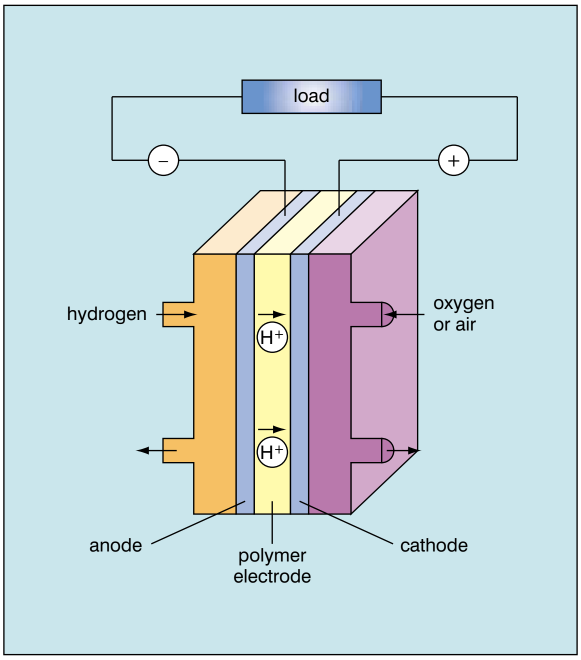

Fig. 12 Schematic of a single PEM fuel cell. When an electrical load is attached across the anode and the cathode of the fuel cell a redox reaction occurs. The working voltage produced by one cell in this process is between 0·5 and 0·8V, depending on the load. To create practical working voltages, individual fuel cells are stacked together in series to form a fuel cell stack

discharge. Also the charge capacity of a rechargeable battery decreases with the number of times of charge and discharge. Conversely, provided that the hydrogen supply is sealed correctly, a fuel cell will not discharge over time, maintaining its full charge capacity almost indefinitely.

Direct methanol fuel cells were invented and initially developed at the Jet Propulsion Laboratory in Pasadena, California. They were designed to supply electricity for field troops in the Armed Forces and for applications with NASA (Fig. 11). The direct methanol, fuel cell has the advantage over the hydrogen fuel cell in that they can use a liquid fuel, i.e. methanol without the need for external reforming. Liquid fuel is easy to store and has a high energy density compared to compressed hydrogen. At present, the direct methanol fuel cell suffers from relatively low efficiency and high cost, owing to required platinum loading compared to that of the hydrogen fuel cell. However, as this improves, it is expected that the direct methanol fuel cell will play a leading role in providing power for portable and possibly transportation applications.

Ballard Power Systems, Motorola, the Los Alamos National Laboratory and Manhattan Scientific are all actively pursuing the development of the direct methanol fuel cell. Motorola claims that a portable cell phone will be able to remain fully charged on standby for a month rather than days. The company has also announced that it plans to have its version commercially available in three to five years.

The science of the PEM fuel cell

The chemistry of a single cell

In a PEM fuel cell, two half-cell reactions take place simultaneously, an oxidation reaction (loss of electrons) at the anode and a reduction reaction (gain of electrons) at the cathode. These two reactions make up the total oxidation-reduction (redox) reaction of the fuel cell, the formation of water from hydrogen and oxygen gases.

As in an electrolyser, the anode and cathode are separated by an electrolyte, which allows ions to be transferred from one side to the other (Fig. 12). The electrolyte in a PEM fuel cell is a solid acid supported within the membrane. The solid acid electrolyte is saturated with water so that the transport of ions can proceed. The chemical reactions for a PEM fuel cell are:

anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$ (6)
cathode reaction: $\frac{1}{2}O_2 + 2e- + 2H^+ \rightarrow H_2O_{(l)}$ (7)
overall reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O_{(l)}$ (8)

At the anode, the hydrogen molecules first come into contact with a platinum catalyst on the electrode surface. The hydrogen molecules break apart, bonding to the platinum surface forming weak H-Pt bonds. As the hydrogen molecule is now broken the oxidation reaction can proceed. Each hydrogen atom releases its electron, which travels around the external circuit to the cathode (it is this flow of electrons that is referred to as electrical current). The remaining hydrogen proton bonds with a water molecule on the membrane surface, forming a hydronium ion (H_3O^+). The hydronium ion travels through the membrane material to the cathode, leaving the platinum catalyst site free for the next hydrogen molecule.

At the cathode, oxygen molecules come into contact with a platinum catalyst on the electrode surface. The oxygen molecules break apart bonding to the platinum surface forming weak O-Pt bonds, enabling the reduction reaction to proceed. Each oxygen atom then leaves the platinum catalyst site, combining with two electrons (which have travelled through the external circuit) and two protons (which have travelled through the membrane) to form one molecule of water. The redox reaction has now been completed. The platinum catalyst on the cathode electrode is again free for the next oxygen molecule to arrive.

This exothermic reaction, the formation of water from hydrogen and oxygen gases, has an enthalpy of –286kJ of energy per mole of water formed. The free energy available to perform work decreases as a function of temperature. At 25°C, one atmosphere, the free energy available to perform work is about –237kJ/mole. This energy is observed as electricity and heat.

Polymer electrolyte (or proton exchange) membrane (PEM)

The membrane material used in a PEM cell is a polymer. PEMs are generally produced in large sheets. The electrode catalyst layer is applied to both sides, and is cut to the appropriate size. A single PEM sheet is typically 50–175µm thick, or around the thickness of 2–7 sheets of paper.

A common PEM material used today is Nafion. Developed in the 1970s by Dupont, Nafion consists of polytetrafluoroethylene (PTFE) chains, commonly known as Teflon, forming the backbone of the membrane. Attached to the Teflon chains, are side chains ending with sulphonic acid (HSO_3) groups (Fig. 13). A close-up view of the membrane material shows long, spaghetti-like chain molecules with clusters of sulphonate side chains (Fig. 14). An interesting feature of this material is that, whereas the long chain molecules are hydrophobic (repel water), the sulphonate side chains are highly hydrophylic (attract water).

For the membrane to conduct ions efficiently the sulphonate side chains must absorb large quantities of water. Within these hydrated regions, the hydrogen ions of the sulphonic acid groups can then move freely, enabling the membrane to transfer hydrogen ions, in the form of hydronium ions from one side of the membrane to the other.

Cell voltage and efficiency

If the fuel cell was perfect at transferring chemical energy into electrical energy, the ideal cell voltage (thermodynamic reversible cell potential) of the hydrogen fuel cell would be at 25°C, one atmosphere, 1·23V. As the fuel cell heats up to operating temperature, around 80°C the ideal cell voltage drops to about 1·18V. However, there are many limiting factors that reduce the fuel cell voltage further. The voltage out of the cell is a good measure of electrical

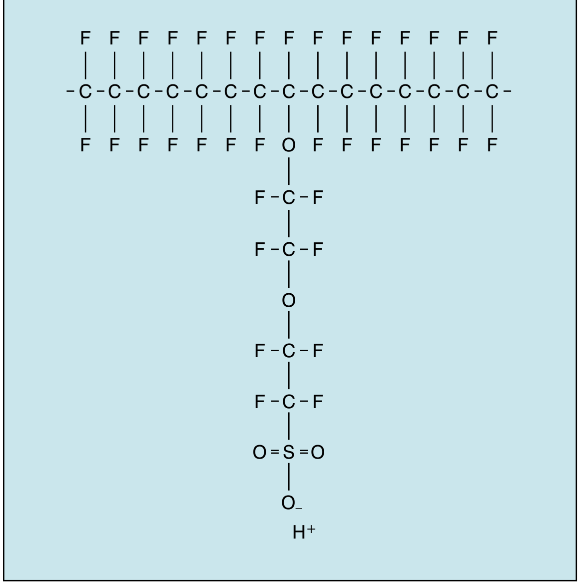

Fig. 13 Chemical structure of a PEM fuel cell membrane-long chains of PTFE (Teflon) with side chain ending with sulphonic acid (HSO_3) (source: Reference 2)

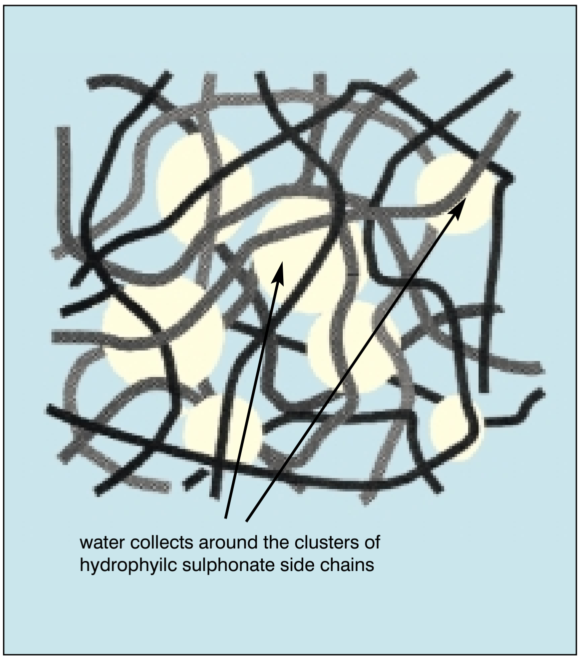

Fig. 14 Close-up of a PEM fuel cell membrane. The Figure shows long spaghetti-like chain molecules of Teflon surrounding clusters of hydrated regions around the sulphonate side chains. The Teflon chains form the backbone of the membrane. The hydrated regions around the sulphonate side chains become the electrolyte (source: Reference 2)

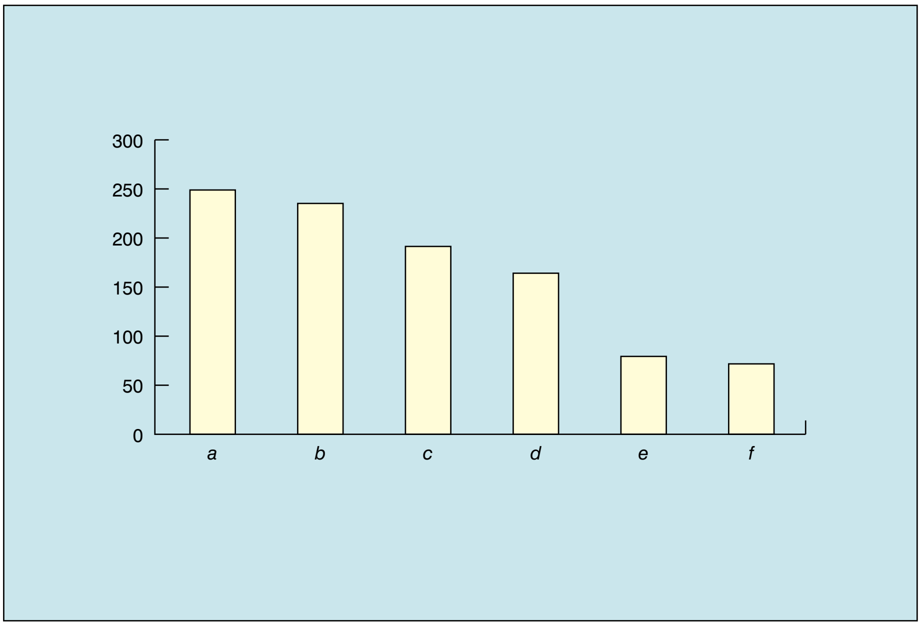

Fig. 15 Graph comparing carbon dioxide emissions of cars, using different types of fuel sources (reprinted by permission from Pembina Institute). *a* Car with internal combustion engine; *b* Fuel cell car with hydrogen produced from Alberta electric grid (coal generation); *c* Fuel cell car with onboard gasoline reformer; *d* Fuel cell car with onboard methanol reformer; *e* Fuel cell car with hydrogen produced from natural gas (distributed from urban retail outlets); *f* Fuel cell car with hydrogen produced from natural gas (made at large refineries)

efficiency; the lower the voltage, the lower the electrical efficiency and the more chemical energy is released in the formation of water and transferred into heat.

The primary losses that contribute to a reduction in cell voltage are:

- *Activation losses:* Activation losses are a result of the energy required to initiate the reaction. This is a result of the catalyst. The better the catalyst the less activation energy is required. Platinum forms an excellent catalyst; however, there is much research underway for better materials. A limiting factor to power density available from a fuel cell is the speed at which the reactions can take place. The cathode reaction (the reduction of oxygen) is about 100 times slower than that of the reaction at the anode, thus it is the cathode reaction that limits power density.
- *Fuel crossover and internal currents:* Fuel crossover and internal currents are a result of fuel that crosses directly through the electrolyte, from the anode to the cathode without releasing electrons through the external circuit, thereby decreasing the efficiency of the fuel cell.
- *Ohmic losses:* Ohmic losses are a result of the combined resistances of the various components of the fuel cell. This includes the resistance of the electrode materials, the resistance of the electrolyte membrane and the resistance of the various interconnections.
- *Concentration losses* (also referred to as 'mass transport'): These losses result from the reduction of the concentration of hydrogen and oxygen gases at the electrode. For example, following the reaction new gases must be made immediately available at the catalyst sites. With the build up of water at the cathode, particularly at high currents, catalyst sites can become clogged, restricting oxygen access. It is therefore important to remove this excess water, hence the term mass transport.

Direct methanol fuel cell

A direct methanol fuel cell also uses a PEM membrane. However, other catalysts in addition to platinum are required on the anode side of the membrane to break the methanol bond in the reaction forming carbon dioxide, hydrogen ions and free electrons. As with the hydrogen fuel cell, the free electrons flow from the anode of the cell through an external circuit to the cathode and the hydrogen protons are transferred through the electrolyte membrane. At the cathode the free electrons and the hydrogen protons react with oxygen to form water. The chemical reactions of the direct methanol fuel cell are:

anode reaction: $CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$ (9)
cathode reaction: $3/2O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$ (10)
overall reaction: $CH_3OH + 3/2O_2 \rightarrow CO_2 + 2H_2O$ (11)

Where will the hydrogen come from?

One of the most important questions to be asked is: where will the hydrogen come from? A very interesting study published by the Pembina Institute, based in Calgary, Alberta, compared total carbon dioxide emissions of fuel cell vehicles using hydrogen produced from a variety of methods (Fig. 15). The results clearly show that the choice as to which method will be used to produce the hydrogen will be a critical environmental decision.

For example, if hydrogen is produced from the electrolysis of water and the electrolysers are powered from the electrical grid, whereby the electricity is produced from a coal burning power station, then there will be no reduction in carbon dioxide emissions compared with the levels of the present day internal combustion engine. In fact, there will be an increase in metals and pollutants into the environment. If on the other hand the electrolyser is powered from a renewable energy source, through use of a solar panel, a wind turbine or a hydroelectric turbine, there will be no emissions of carbon dioxide. As the fuel cell industry grows there will likely be different approaches to making hydrogen in various areas of the world, depending on their local energy production methods.

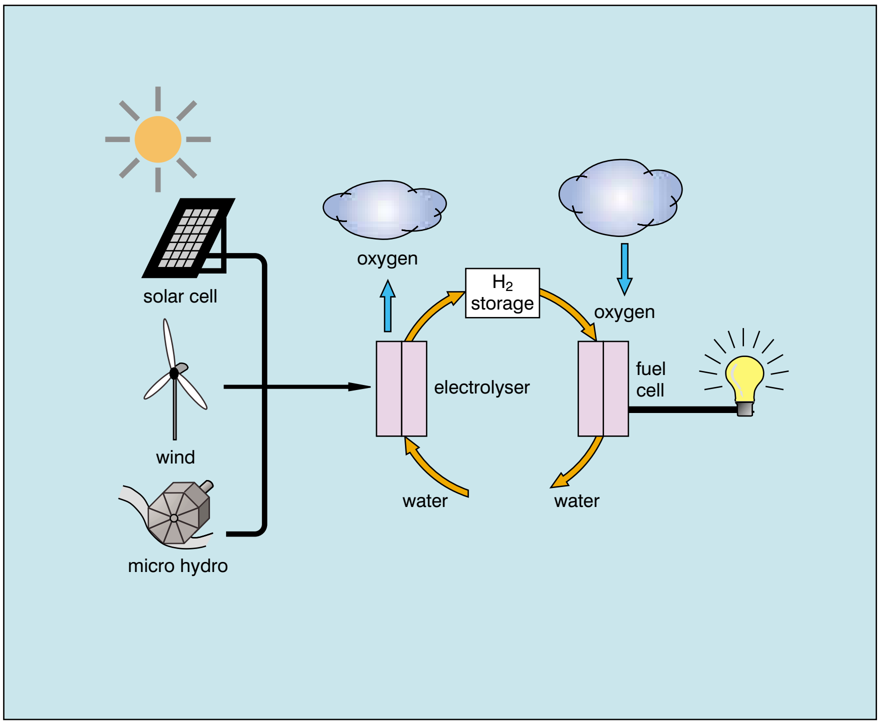

Fig. 16 Electrical power from renewable energy sources. In the past, the limiting factors of renewable energy have been the storage and transport of that energy. With the use of an electrolyser, a method of storing and transporting hydrogen gas, and a fuel cell, electrical power from renewable energy sources can be delivered where and when required, cleanly, efficiently and sustainably

Reformation of hydrocarbon fuels

For the short term, because of the abundance of natural gas, the availability of methanol and propane, and the lack of a hydrogen infrastructure, it is expected that hydrocarbon fuels will be the dominant fuels for stationary fuel cell applications. For as long as these fuels are cheaply available, reformation of a hydrocarbon fuel is the most cost efficient method of producing hydrogen. In the reformation of a hydrocarbon fuel, however, there is an emission of carbon dioxide. Although carbon dioxide is not considered a pollutant, controversy exists that man-made emissions may contribute to global warming.

Renewable energy systems

Hydrogen can be produced sustainably with no emission of carbon dioxide from renewable energy systems. An example of such a system is the use of a solar panel, a wind turbine or a micro-hydro generator to convert the radiant energy of sunlight into electrical power, which drives an electrolyser. The electrolyser breaks apart water producing hydrogen and oxygen gases. The hydrogen is stored for use by the fuel cell and the oxygen is released into the atmosphere. Thus when the sun shines, the wind blows or the water flows, the electrolyser can produce hydrogen.

A power system incorporating hydrogen from renewable sources and a fuel cell is a closed system, as none of the products or reactants, water, hydrogen and oxygen, is lost to the outside environment. The water consumed by the electrolyser is converted to gases. The gases are converted back to water. The electrical energy produced by the solar panel is transferred to chemical energy in the form of gases. The gases can be stored and transported, to be reconverted back to electricity (Fig. 16).

These systems are truly sustainable, for as long as there is sunlight there can be electrical power, available where and when required.

Biological methods

Research and development is taking place on the production of hydrogen from biological methods (biohydrogen). For example, Dr. A. Melis at the University of California, Berkeley, has discovered a metabolic switch in common green algae (*chlamydomonas reinhardtii*) that causes the algae to oxidise water and to produce pure hydrogen gas when sulphur nutrients are depleted from the growth medium. This and other biohydrogen mechanisms are presently in the R&D stage but may one day provide the world with an additional source of hydrogen.

Benefits and obstacles

Benefits

- *Fuel cells are efficient:* They convert hydrogen and oxygen directly into electricity, water and heat, with no combustion in the process. The resulting efficiency is between 50 and 80%, about double that of an internal combustion engine.
- *Fuel cells are clean:* If hydrogen is the fuel, there are no pollutant emissions from a fuel cell itself, only the production of pure water. In contrast to an internal combustion engine, a fuel cell produces no emissions of sulphur dioxide, which can lead to acid rain, nor nitrogen oxides which produce smog nor dust particulates.

- *Fuel cells are quiet:* A fuel cell itself has no moving parts, although a fuel cell system may have pumps and fans. As a result, electrical power is produced relatively silently. Many hotels and resorts in quiet locations, for example, could replace diesel engine generators with fuel cells for both main power supply or for backup power in the event of power outages.
- *Fuel cells are modular:* That is, fuel cells of varying sizes can be stacked together to meet a required power demand. As mentioned earlier, fuel cell systems can provide power over a large range, from a few watts to megawatts.
- *Fuel cells are environmentally safe:* They produce no hazardous waste products, and their only byproduct is water (or water and carbon dioxide in the case of methanol cells) and heat.
- Fuel cells may give us the opportunity to provide the world with sustainable electrical power.

Obstacles

At present there are many uncertainties to the success of fuel cells and the development of a hydrogen economy:

- *Fuel cells must obtain mass-market acceptance to succeed:* This acceptance depends largely on price, reliability, longevity of fuel cells and the accessibility and cost of fuel. Compared to the price of present day alternatives e.g. diesel-engine generators and batteries, fuel cells are comparatively expensive. In order to be competitive, fuel cells need to be mass-produced and less expensive materials developed.
- *An infrastructure for the mass-market availability of hydrogen, or methanol fuel initially, must also develop:* At present there is no infrastructure in place for either of these fuels. As it is we must rely on the activities of the oil and gas companies to introduce them. Unless motorists are able to obtain fuel conveniently and affordably, a mass market for motive applications will not develop.
- *At present a large portion of the investment in fuel cells and hydrogen technology has come from auto manufacturers:* However, if fuel cells prove unsuitable for automobiles, new sources of investment for fuel cells and the hydrogen industry will be needed.
- *Changes in government policy could also derail fuel cell and hydrogen technology development:* At present stringent environmental laws and regulations, such as the California Low Emission Vehicle Program, have been a great encouragement to these fields. Deregulation laws in the utility industry have been a large impetus for the development of distributed stationary power generators. Should these laws change it could create adverse effects on further development.
- *At present platinum is a key component to fuel cells:* Platinum is a scarce natural resource; the largest supplies to the world platinum market are from South Africa, Russia and Canada. Shortages of platinum are not anticipated; however, changes in government policies could affect the supply.

Conclusion

As our demand for electrical power grows, it becomes increasingly urgent to find new ways of meeting it both responsibly and safely. In the past, the limiting factors of renewable energy have been the storage and transport of that energy. With the use of fuel cells and hydrogen technology, electrical power from renewable energy sources can be delivered where and when required, cleanly, efficiently and sustainably.

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