

**AN INTRODUCTION TO FUEL CELLS AND HYDROGEN TECHNOLOGY**

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# AN INTRODUCTION TO FUEL CELLS AND HYDROGEN TECHNOLOGY

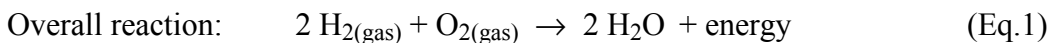
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Whereas the 19<sup>th</sup> Century was the century of the steam engine and the 20<sup>th</sup> Century was the century of the internal combustion engine, it is likely that the 21<sup>st</sup> Century will be the century of the fuel cell.

Full cells are now on the verge of being introduced commercially, revolutionizing 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.

## 1. WHAT IS A FUEL CELL?

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 (Connihan, 1981). They convert 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.



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 principle 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.

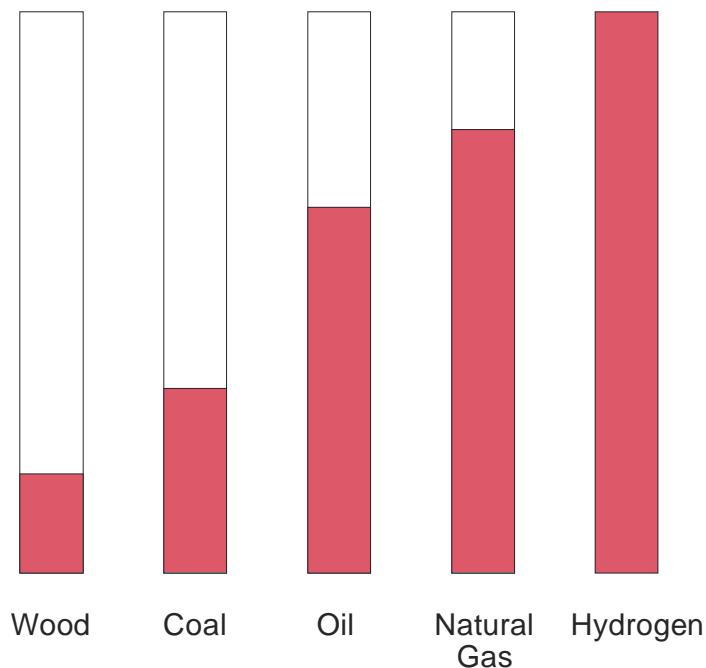


Figure 1. Trends in the use of fuels. As fuel use has developed through time, the percentage of hydrogen content in the fuel has increased.

## 2. HISTORY OF FUEL CELLS

### 2.1 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 electrolyzer 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

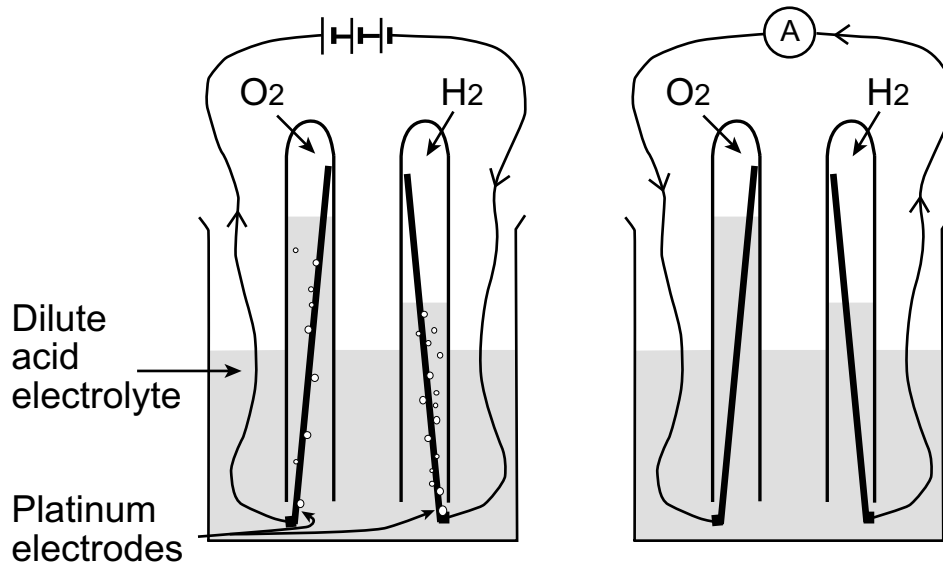


Figure 2. The principle of an electrolyzer, shown left; of a fuel cell, shown right. (Larminie, 2000).

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

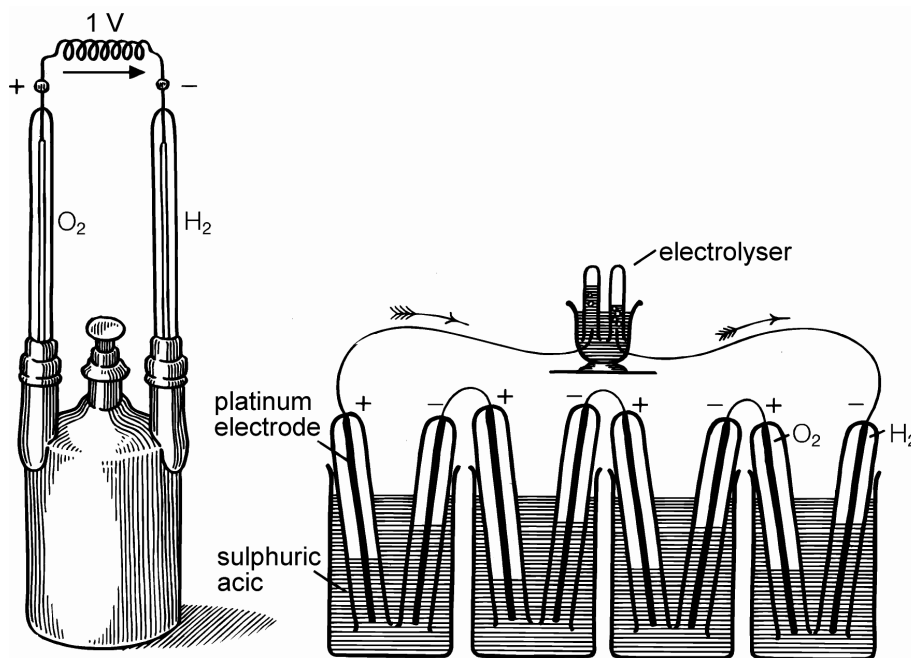


Figure 3. Grove’s ‘gas battery’ (1839) produced a voltage of about 1 volt, shown left. Grove’s ‘gas chain’ powering an electrolyzer (1842), shown right. (Photo courtesy of Berry, 2000)

## 2.2 The “Bacon fuel cell”

Significant work on fuel cells began again in the 1930s, by Francis Bacon, a chemical engineer at Cambridge University, England. 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, the use of nickel was much less expensive than that of platinum.

Alkaline fuel cell:



Figure 4. Bacon’s laboratory, at the Department of Chemical Engineering, Cambridge University (1955). A fuel cell stack can be seen being assembled on the left of the photograph (Photo courtesy of Department of Chemical Engineering, University of Cambridge).

### 2.3 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 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 1.5 kilowatts 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 (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 of the electrical needs during flight. There are no backup batteries on the space

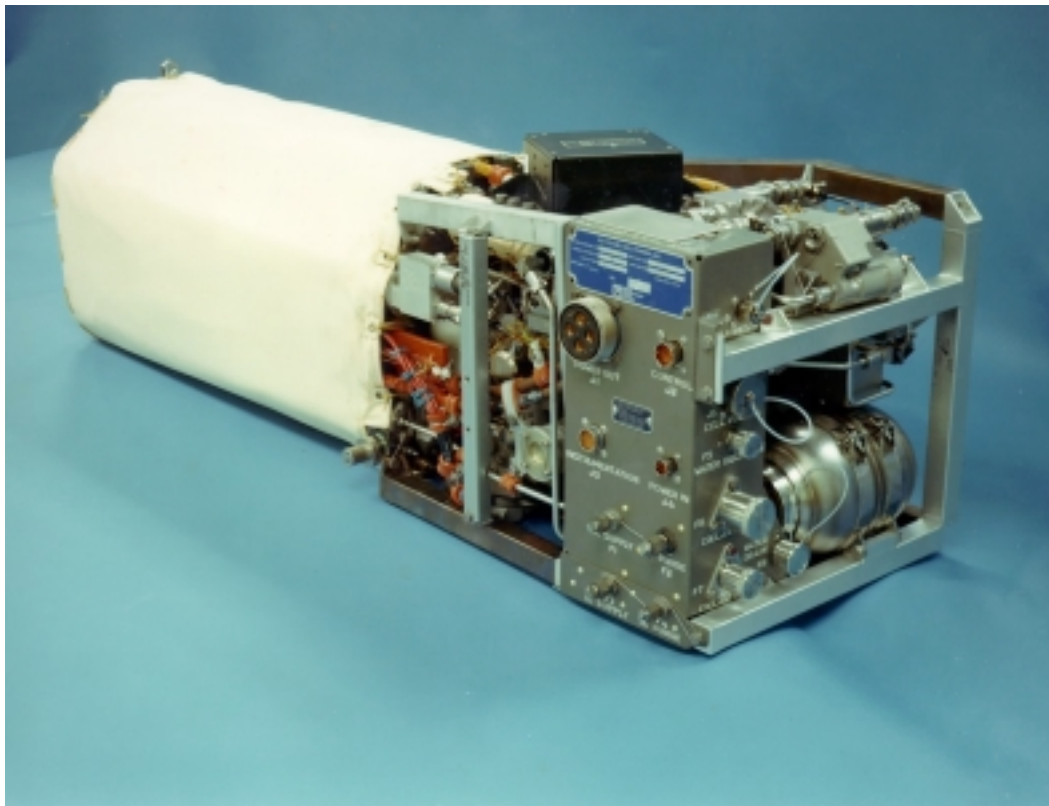


Figure 5. NASA Space Shuttle Orbiter fuel cell. One of three fuel cells aboard the Space Shuttle. These fuel cells provide all of the electricity as well as drinking water when Space Shuttle is in flight. It produces 12 kilowatts electricity, and occupies 154 litres. (Photo courtesy of NASA).

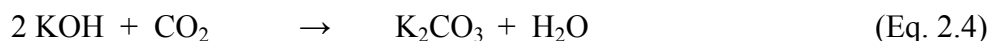


shuttle, and as such, the fuel cell power plants must be highly reliable. The power plants are fuelled by hydrogen and oxygen from cryogenic tanks and provide both electrical power and drinking water. Each fuel cell is capable of supplying 12 kilowatts continuously, and up to 16 kilowatts for short periods. The Orbiter units represent a significant technology advance over Apollo, producing about ten times the power from a similar sized package. In the Shuttle program, 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 (NASA).

#### **2.4 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 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 reformat 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 equation of carbon dioxide reacting with a potassium hydroxide electrolyte is shown below:



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 which 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 (PEM) fuel cells.

## 2.5 The 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, they invented and developed the first polymer electrolyte membrane (PEM) fuel cell. It was initially developed under a program with the US Navy's Bureau of Ships and U.S. 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 program 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 watts (NASA).

### 2.5.1 Ballard Power

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 1983, Geoffrey Ballard a Canadian geophysicist, chemist Keith Prater and engineer Paul Howard established the company, Ballard Power. Ballard took the abandoned GE fuel cell, whose patents were running out and searched for ways to improve its power and build it out of cheaper materials (Koppel, 1999).

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 recognized that fuel cells could be made smaller, more powerful and cheaply enough to eventually replace conventional power technologies.

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

#### *2.5.2 Los Alamos National Laboratory*

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 (Los Alamos National Laboratory).

### **3. FUEL CELL APPLICATIONS**

#### **3.1 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 program requires that beginning in 2003, ten percent of passenger cars delivered for sale in California from medium or large sized manufacturers must be Zero Emission Vehicles, called ZEVs. Automobiles 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 is considerably lower.



Figure 6. Two prototype automobiles powered by fuel cells, the NECAR 5 and JEEP Commander, from DaimlerChrysler (Photo courtesy of DaimlerChrysler).

The NECAR 5 drives and feels like a “normal” car. It has a top speed of over 150 km/hr (90 mph), with a power output of 75 kW (100 horsepower). 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, Ford, Shell and Texaco. The primary objective was to help commercialize fuel cell technology for vehicles through joint demonstration programs by the partners. Since then new participants have included General Motors, Honda, Hyundai, Nissan, Toyota, Volkswagen, British Petroleum, Exxon Mobil, Xcellsis, US Department of Energy and US Department of Transportation. To date seven of the world’s ten 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, trucks and trains all powered with fuel cell engines. In 2000, Ballard completed a two-year program testing six fuel cell buses, three in Vancouver, British Columbia and three in Chicago. The design and maintenance requirements of fuel-cell vehicles as well as public acceptance were included in the study. The results of the tests were exemplary. Thirty new buses powered by Ballard's fuel cell will be introduced to 10 European cities beginning in 2002 for additional field testing. The resulting data will be used to further develop a commercial fuel cell bus.

### **3.2 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% (IEA., 1997), and in developing countries it is approximately 6% (Khatib., 1998). How can these energy demands be met responsibly and safely? Distributed power plants using fuel cells can provide part of the solution.

Distributed or "decentralized" power plants, contrasted with centralized 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 by-product 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 percent, 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.

### *3.2.1 Grid-connect applications*

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 stand-by 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 versus typically nine hours for a conventional battery-bank UPS (HDR Engineering). For industries where UPS systems are critical, such as banking, minimizing down time is of up most importance.

### *3.2.2 Non-grid connect applications*

Other applications for fuel cell distributed power plants are also possible e.g. stand-alone back-up power generators. The 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 Figure 7 is a prototype fuel cell distributed power plant, by Ballard Power. This unit provides 250 kilowatts 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 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.



Figure 7. A fuel-cell distributed power plant. This unit, produced by Ballard Power provides 250 kilowatts heat and electricity which is enough power for an industry, a school or a community of up to 50 homes. (Photo courtesy of Ballard Power)

Eventually as an infrastructure for hydrogen develops, these units could be powered with hydrogen directly without the need of 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 after which commercial introduction is planned (Ballard Power).

### **3.3 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 of the electricity required by a modern-day home.

Ballard Power has developed a one-kilowatt fuel cell 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 seven kilowatts of electrical power to the home plus heat, using either natural gas or propane as the fuel (Fig. 8). This is enough power to supply the electrical needs of a modern energy efficient house. At present, these units are designed to be used in parallel with the grid. This means the fuel cell will supply base-load power and the utility grid will handle momentary power surges. Should the electric grid fail, the fuel cell operates as a back-up generator providing power for the home's critical requirements.



Figure 8. A fuel-cell power plant for residential applications provides 7 kilowatts heat and electricity, enough power for a modern energy efficient home. (Photo courtesy of Plug Power)



Second generation products will be designed to run independent of the grid. During 2000, Plug Power installed and tested 52 systems in the field and accumulated over 133,000 hours of system run-time. General Electric which is marketing Plug Power's unit, has announced that commercial introduction of this home fuel cell power plant is expected in 2002 (Plug Power).

### 3.4 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.



Figure 9. A prototype portable fuel cell provides 50 watts electrical power. The supply of hydrogen for this unit, by Heliocentris, is stored in the attached metal hydride canister.

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.

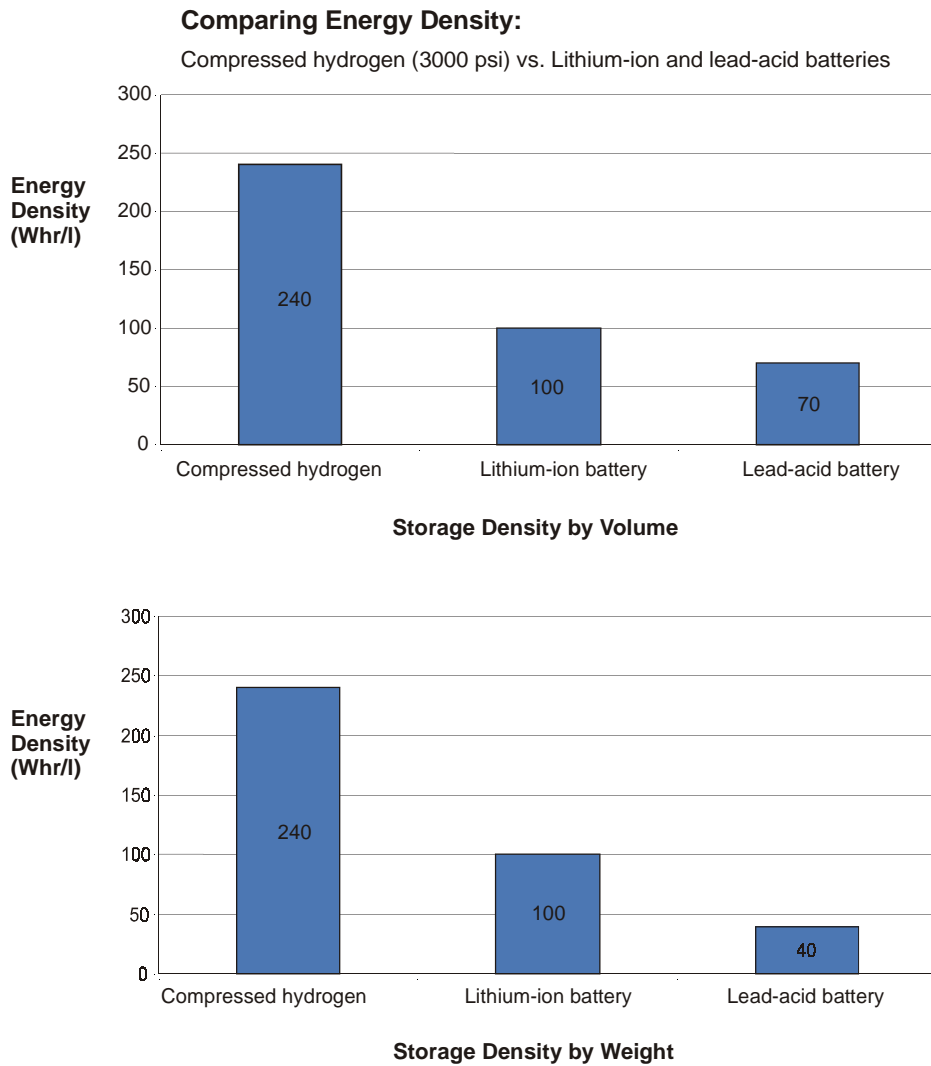


Figure 10. Graphs comparing the energy density of compressed hydrogen (3000 psi) versus lithium-ion and lead acid batteries.

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

#### *3.4.1 Direct methanol fuel cells for portable power*

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, 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.

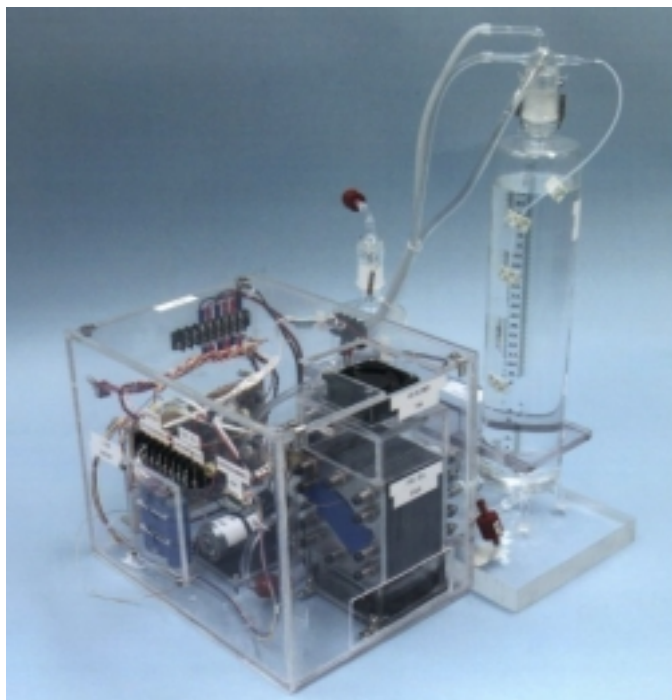


Figure 11. A prototype direct methanol fuel cell used as a lithium battery charger provides up to 20 watts electrical power. (Photo courtesy of Jet Propulsion Laboratory/NASA)

#### **4. THE SCIENCE OF THE PEM FUEL CELL**

##### **4.1 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 electrolyzer, 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.

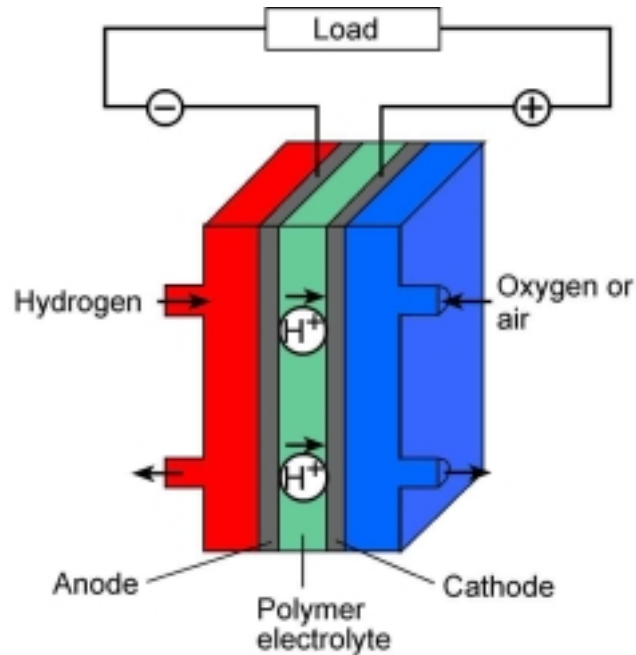


Figure 12. Diagram of a single PEM fuel cell. When an electrical load is attached across the anode and the cathode of the fuel cell a redox reaction occurs. The working voltage produced by one cell in this process is between 0.5 and 0.8 volts, depending on the load. To create practical working voltages, individual fuel cells are stacked together in series to form a fuel cell stack.

#### PEM Fuel Cell:



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 ( $\text{H}_3\text{O}^+$ ). 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 -286 kilojoules of energy per mole of water formed. The free energy available to perform work decreases as a function of temperature. At 25° C, 1 atmosphere the free energy available to perform work is about -237 kilojoules per mole. This energy is observed as electricity and heat.

#### **4.2 The Polymer Electrolyte 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 between 50 to 175 microns thick, or around the thickness of 2 to 7 sheets of paper.

A common PEM material used today is Nafion<sup>®</sup>. Developed in the 1970s by Dupont, Nafion consists of Polytetrafluoroethylene (PTFE) chains, commonly known as Teflon<sup>®</sup> forming the backbone of the membrane. Attached to the Teflon chains, are side chains ending with sulphonic acid (HSO<sub>3</sub>) 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.

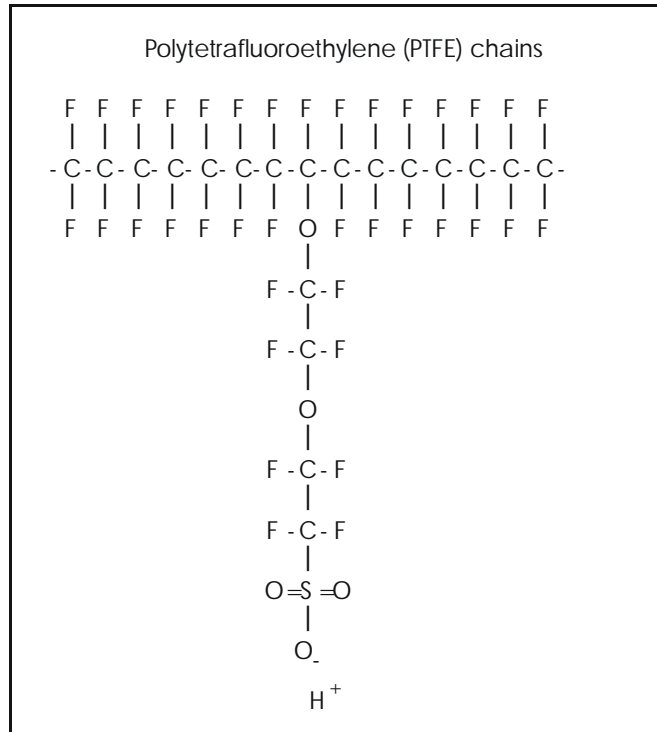


Figure 13. Chemical structure of a PEM fuel cell membrane. Long chains of PTFE (Teflon®) with side chain ending with sulphonic acid (HSO<sub>3</sub>). (Source: Larminie & Dicks, February 2000)

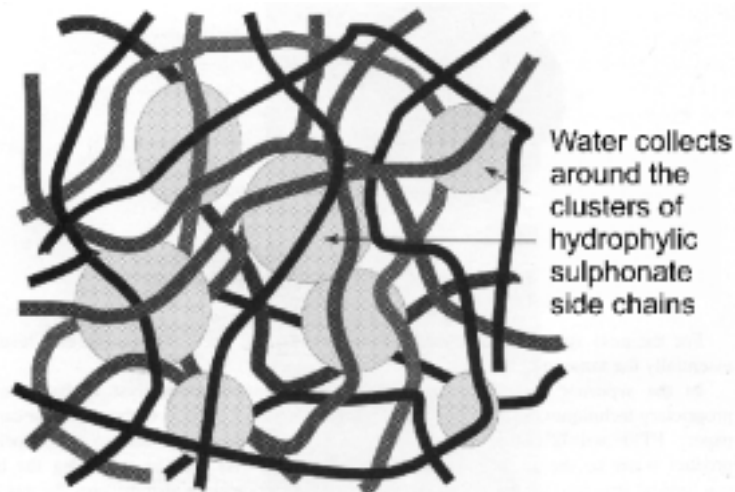


Figure 14. Close-up of a PEM fuel cell membrane. Diagram shows long spaghetti-like chain molecules of Teflon surrounding clusters of hydrated regions around the sulphonate side chains. The Teflon chains form the backbone of the membrane. The hydrated regions around the sulphonate side chains become the electrolyte. (Source: Larminie & Dicks, February 2000)

### 4.3 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, 1 atmosphere, 1.23 volts. As the fuel cell heats up to operating temperature, around 80° C the ideal cell voltage drops to about 1.18 volts. 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 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

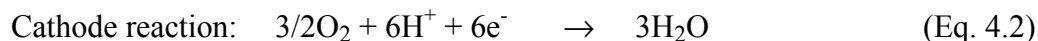
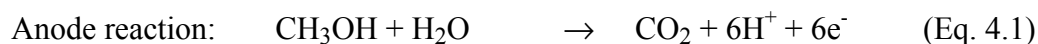


immediately available at the catalyst sites. With the build up of water at the cathode, particularly at high currents, catalyst sites can become clogged, restricting oxygen access. It is therefore important to remove this excess water, hence the term mass transport.

## 5. 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.

Direct Methanol Fuel Cell:



## 6. WHERE WILL THE HYDROGEN COME FROM?

One of the most important questions to be asked is: where the hydrogen will 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 electrolyzers 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 & pollutants into the environment. If on the other hand the electrolyzer 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. The choice has yet to be made as to which method of hydrogen production will dominate as the fuel cell industry grows.

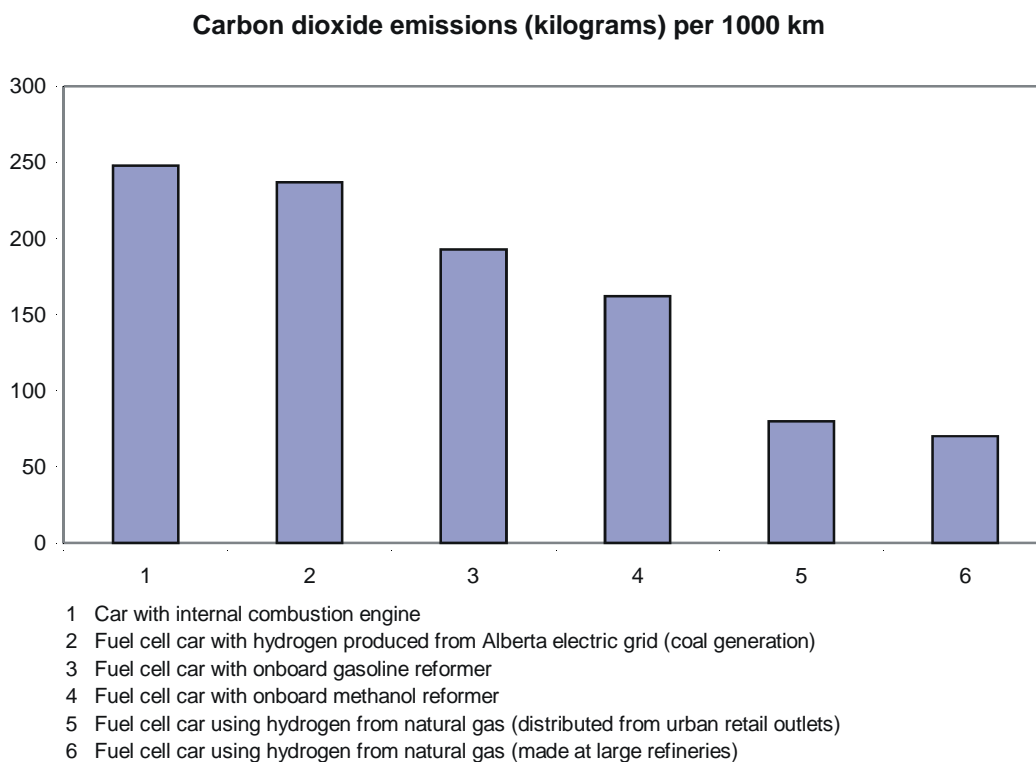


Figure 15. Graph comparing carbon dioxide emissions of cars, using different types of fuel sources. (Reprinted by permission from Pembina Institute)

## 6.1 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.

## 6.2 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 electrolyzer. The electrolyzer 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 are lost to the outside environment. The water consumed by the electrolyzer 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).

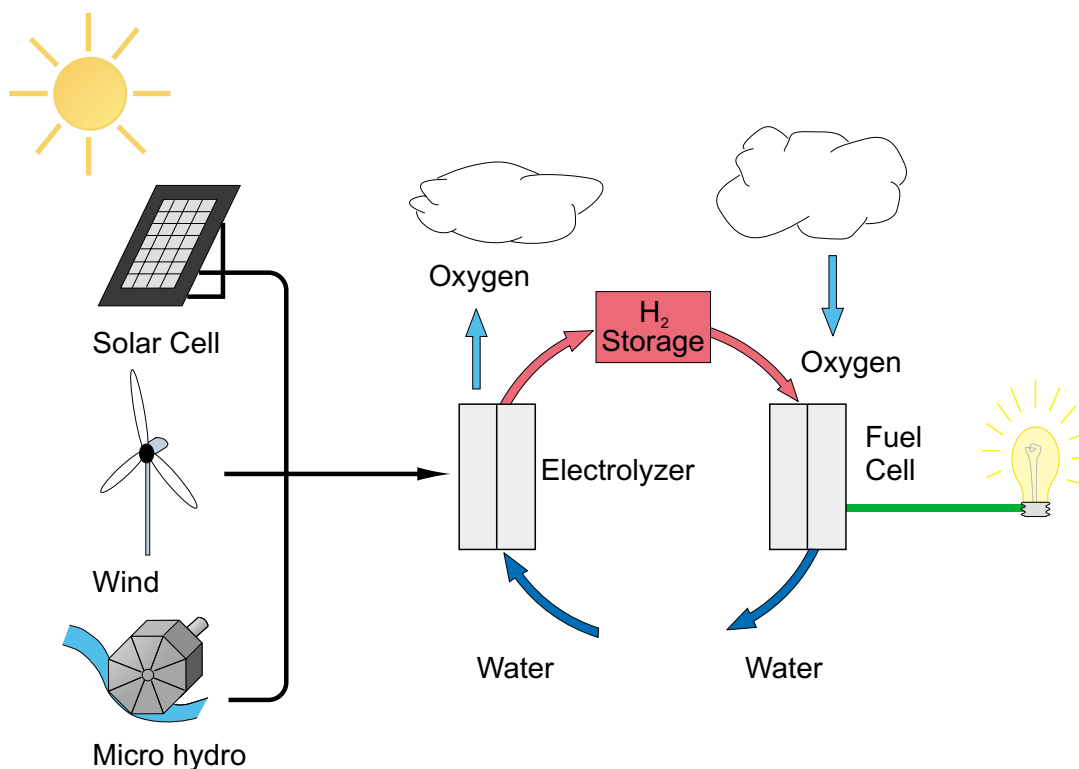


Figure 16. Electrical power from renewable energy sources. In the past, the limiting factors of renewable energy have been the storage and transport of that energy. With the use of an electrolyzer, a method of storing and transporting hydrogen gas, and a fuel cell, electrical power from renewable energy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

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

### 6.3 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 oxidize 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.

## 7. BENEFITS AND OBSTACLES TO THE SUCCESS OF FUEL CELLS AND THE DEVELOPMENT OF A HYDROGEN-BASED ECONOMY

### 7.1 Benefits

- **Fuel cells are efficient.** They convert hydrogen and oxygen directly into electricity and water, with no combustion in the process. The resulting efficiency is between 50 and 60%, 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 by-product is water (or water and carbon dioxide in the case of methanol cells).
- Fuel cells may give us the opportunity to provide the world with sustainable electrical power.

## 7.2 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 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.

## 8. 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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