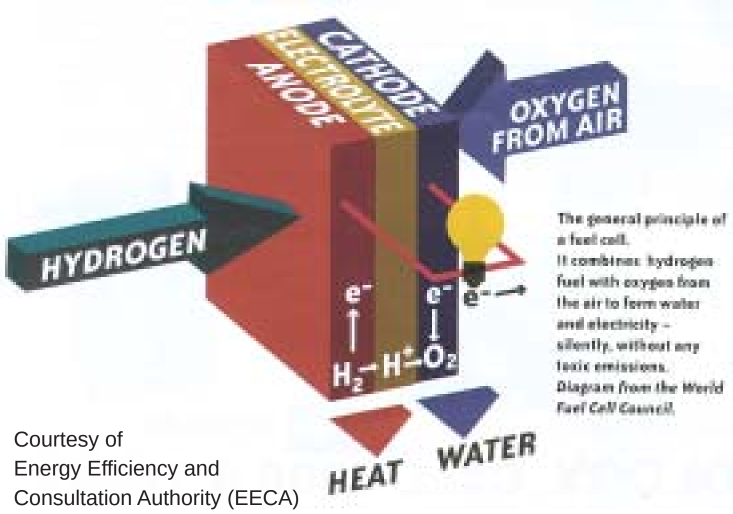
ALPHA 118

HYDROGEN → FUEL CELLS → ENERGY

the ROYAL SOCIETY of NEW ZEALAND

"… water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable." *Jules Verne The Mysterious Island – 1874.*

In June 2002, the New Zealand Government announced a $6 million investment for the development of New Zealand's hydrogen energy technology. The aim is to produce hydrogen (e.g. via electrolysis or fossil fuel conversion) which can then be converted to energy (e.g. via fuel cells). The prediction then being that leading research by energy research and development company, CRL Energy, and Crown Research Institute, Industrial Research Ltd (IRL) could see New Zealand powered by 'clean green' hydrogen energy in the foreseeable future.



Courtesy of
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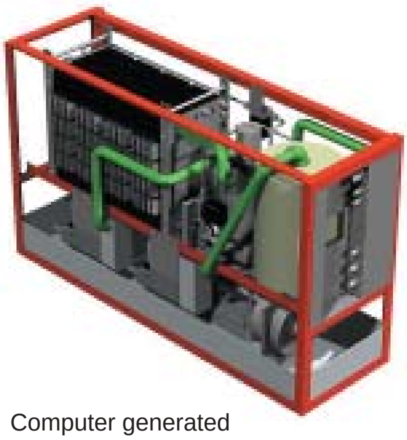

Computer generated image of IRL's DC11200 pre-commercial prototype fuell cell

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In August 2002, General Motors in the United States unveiled the world's first driveable hydrogen-powered concept car, the Hy-Wire, and announced plans to mass produce similar vehicles by 2010. In October 2002, Berlin opened its first hydrogen filling station, preparing the way to turn part of its public transport over to fuel-cell powered buses. Other countries have quickly followed.

The European Commission has allocated €18.5 million to the Clean Urban Transport for Europe (CUTE) demonstration project to support nine European cities in introducing hydrogen into their public transport system: Amsterdam (Netherlands), Barcelona and Madrid (Spain), Hamburg and Stuttgart (Germany), London (United Kingdom), City (Luxembourg), Porto (Portugal), and Stockholm (Sweden). This project will see 27 fuel-cell powered buses, running on locally produced and refilled hydrogen within the next few years.

In April 2003, Iceland opened its first hydrogen fuel station. The station, run by Royal Dutch/Shell, will be used to fuel three Daimler-Chrysler buses in Reykjavik under a project partly funded by the European Union. Iceland eventually wants other vehicles, including cars and boats, to use hydrogen fuel.

The future is being moved forward faster than anyone expected.

It now looks likely that researchers in New Zealand will have hydrogen-powered fuel cell prototypes in the field within the next six years, initially to produce electricity at small sites, such as high-rise buildings, remote rural areas, or factories.

Engineer,Ben McQueen,with IRL's demonstration fuel cell system; this alkaline fuel cell system supplied 400 W of energy to 12 spotlights.

The abundance of hydrogen

Hydrogen, the first element on the periodic table and the smallest known atom, is thought to be the most plentiful in the universe. Although abundant, hydrogen is rarely found on Earth as an element. Instead it combines with other elements (such as carbon and oxygen) and must be separated from these before being utilised. Hydrogen could be harvested from water (H_2O) using a process known as electrolysis. Electrolysis uses electricity to split water molecules to create pure hydrogen and oxygen. This process has advantages: if renewable energy is used to drive the electrolysis process, it takes away our reliance on fossil fuels, and can be done anywhere. However, the disadvantage is that the process requires electricity which must be sourced from somewhere. It is more likely, at least in the short term, that hydrogen will be harvested by reforming

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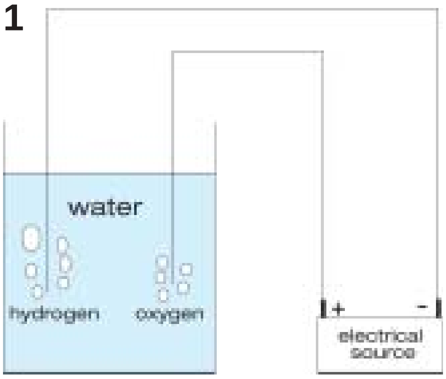

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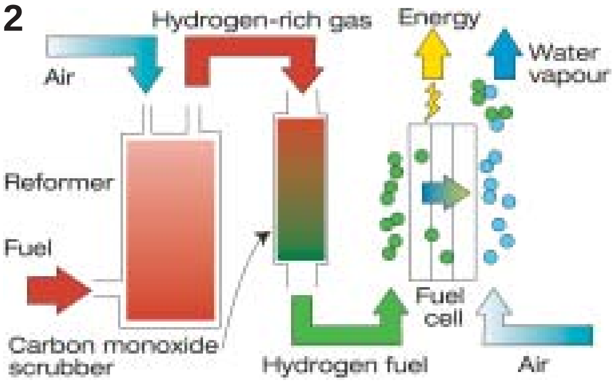


Two ways to make hydrogen.

1. Electrolysis: electricity spills water molecules to release pure hydrogen and oxygen.

2. Reforming: hydrogen is split off from hydrocarbons such as methane or natural gas

Courtesy of Energy Efficiency and Consultation Authority (EECA)

fossil fuels such as coal or methane (CH_4). Methane has twice the number of hydrogen atoms per molecule as water. Using a device called a fuel processor or a reformer, hydrogen can be split off the carbon in a hydrocarbon relatively easily compared to electrolysis.

Because it has to be generated, hydrogen is not a *source* of energy, but is an *energy carrier*, similar to electricity. Energy is produced by reacting hydrogen with oxygen from the air within an electrochemical energy conversion device called a fuel cell. This creates water vapour as a by-product, along with electricity and heat. Hydrogen can also be burnt in internal combustion engines to produce power and heat, although at lower efficiency than in a fuel cell.

1 Hydrogen fueling dispenser at the Las Vegas Energy Station

Photos 1& 2 courtesy of Air Products and Chemicals Inc. http://www.airproducts.com

Extraction process could produce polluting by-products

Harvesting hydrogen from fossil fuels still places a reliance on non-renewable resources for our energy requirements and still produces greenhouse gas by-products – namely carbon dioxide. The point of pollution has been shifted from the motor vehicle exhaust pipe to the plant where hydrogen is produced. However, scientists at CRL Energy say that a ‘zero emissions’ process can be achieved if careful attention is paid to the disposal of carbon by-products when hydrogen is removed. It is much easier to capture carbon by-products from large processing plants than it is from individual cars.

CRL Energy and IRL are currently researching the capture of carbon by-products such as carbon dioxide. This is a process known as carbon sequestration. Carbon dioxide must be captured so that it does not escape into the atmosphere to add to greenhouse problems. Storage is achieved through such methods as injecting captured carbon dioxide into geological formations, including depleted oil and gas reservoirs, deep coal seams and deep aquifers.

As for reliance on fossil fuels, New Zealand has at present an abundance of coal, enough for 1000 years according to some reports. It is possible that at least in the short term, we may take the option of producing hydrogen from coal during our transition to a pure hydrogen economy where energy is eventually produced only from renewable sources.

2 The world’s first hydrogen energy station featuring the co-production of hydrogen fuel and electric power. The project is a public-private partnership between the United States Department of Energy, the City of Las Vegas, Air Products and Chemicals, Inc., and Plug Power, and will serve as a commercial demonstration of hydrogen as a safe and clean energy alternative.

Hydrogen from coal

Coal is a complex hydrogen and carbon-rich compound. It is ironic that coal, which for at least a decade has had a dubious reputation as a high-level greenhouse gas polluter when burned, contains the most likely source of hydrogen – the cleanest known fuel in the world.

Recent CRL Energy work on newly developed and experimental advanced coal conversion technologies shows that many New Zealand coals are particularly suited for hydrogen-rich gas production. Sewage, agricultural effluent, and gas fields are also possible sources of methane for hydrogen production, although the quantities available are unlikely to equal that provided by coal. Woody biomass can also be used to provide hydrogen. According to a United Kingdom Energy Saving Trust report released in May 2003, four million acres, 25% of the United Kingdom's agricultural land, could produce enough willow trees to provide a renewable hydrogen source by 2050.

Development of fuel cells

As billions of dollars are being poured into fuel-cell research around the world it is unlikely that New Zealand will develop it's own fuel cells. However, IRL has been working with a fuel cell company in Europe to make other components that fit around fuel cells such as gauges, humidity units, and other 'balance-of-system' components. IRL has already demonstrated the operation of the first 5 kW fuel cell in New Zealand and, along with it's European partners, has developed a 6.6 kW fuel-cell stack specifically designed for the extreme weather conditions found in Western Australia, with an upgraded heat and humidity management unit.

Millerton coal infeed near Westport.
Photo courtesy of SolidEnergy

Future research at IRL will initially focus on small-scale technologies for hydrogen production from sustainable energy sources so that we can eventually move to a pure hydrogen economy. A key issue for fuel cells is hydrogen quality. Fuel cells which operate at relatively low temperatures are intolerant of any impurities that are produced in the reforming process, whereas fuel cells which operate at much higher temperatures are more tolerant of impurities, which are burnt off. IRL will focus on the best way to obtain hydrogen gas of sufficient purity for use in fuel cells installed to provide distributed electricity generation. Research will include the production of hydrogen through electrolysis, hydrogen storage, and the clean-up of hydrogen produced by reformers which extract hydrogen from methane for immediate use by fuel cells.

Wairakei geothermal power station. CRW

Why do we want to change from a fossil fuel economy to a hydrogen economy?

Currently, New Zealand and most of the developed world functions in what is called the fossil fuel economy. Our cars, trains and planes are fuelled almost exclusively by petroleum products like petrol and gas. Although around 60 –70% of our power generation in New Zealand is from hydropower, we are also reliant on natural gas and coal (coal is becoming increasingly important as the Maui gas field runs down). In other parts of the world many power plants use oil, natural gas and coal to generate electricity. The transport of goods and people is dependent on oil. If the flow of oil was cut off, economies would crumble. There would be no way to transport the

Industrial pollution – Cleveland, CRW

Pollution hiding Mt Fujiyama. CRW

products that factories produce and no way for people to drive to work.

Fossil fuels have revolutionised society and have fuelled the great industrial age, but also create problems. Air pollution is perhaps the biggest concern. When an engine burns petrol or diesel it creates unwanted by-products such as carbon monoxide, carbon dioxide, nitrogen oxides (city smog), and unburned hydrocarbons.

Sunrise with pollution, Jakarta. CRW

Environmental disasters are another problem – oil spills or pipeline explosions are regular occurrences. The process of transporting and storing oil has a big impact on the environment whenever something goes wrong. Coastlines are wrecked and wildlife is devastated whenever an oil tanker springs a leak, and cleaning up can cost millions of dollars.

While the scientific jury is still deliberating on the full impacts of climate change, burning fossil fuels emits carbon dioxide into the atmosphere. This greenhouse gas is causing the Earth's temperature to slowly warm. The worst case scenario for climate change is that the sea level will rise and coastal communities and islands will be threatened.

Perhaps one of the most immediate predicaments of fossil fuel use is the dependence issue and security of supply. Most developed countries do not produce enough oil to meet their demand, and so are reliant on imports from oil-rich countries. Middle Eastern countries have most of the world's oil reserves. Demand is now outgrowing production which results in volatility of supply and prices. Recent political unrest in Iraq and elsewhere places a greater energy security risk on every country dependent on oil from the Middle East.

Another reason to move to alternative energy supplies is one of energy efficiency. According to scientists at CRL Energy, hydrogen produces little or no contamination when converted to energy for heat, power and transportation. By weight it contains 3.3 times the energy of diesel fuel. Conversion efficiencies for fuel cells are over twice those of conventional hydrocarbon-fuelled engines and close to 80% energy conversion efficiency can be achieved through combined heat and power at the point of use. These are reasons why hydrogen has long been seen as an ideal fuel.

However, scientists warn that there are many problems to overcome. Because hydrogen is light, it has a very low energy density and because the molecules are so small, storage is a problem. To the tiny hydrogen atoms, most materials are like a sieve – they can even seep through solid steel. When liquid hydrogen is stored in a cryogenic vessel there is a 1% boil off per day due to heat leakage into the vessel. None is lost from a compressed gas cylinder. There are also problems to work through internationally to improve fuel-cell technology, reduce costs, and manage the infrastructural changes that are necessary to store and deliver hydrogen.

The General Motors Hy-Wire car

General Motor's car, the Hy-Wire, is a sporty four-door sedan, although the chassis can take a range of alternative 'clip-on' car bodies from sports car to station wagon. All the propulsion and control systems are contained within the 80 mm thick skateboard-like chassis. There is no engine to see over, no pedals to operate – just a single unit called X-drive that can be set to either a left or right driving position.

To show off this radically new architecture, the front and rear panels are made of transparent glass.

"The most dramatic view of this car may be from the driver's seat," says Ed Welburn, executive director of GM Design for Body-on-Frame Architectures. "Imagine having no engine, instrument panel or foot pedals in front of you – an open, yet secure cockpit with a floor-to-ceiling view. It's like being in my living room looking out of my picture window."

The hydrogen-driven fuel-cell stack produces a continuously available electric power of 94 kilowatts and is installed in the back of the chassis. An electric motor drives the front wheels and is installed transversely between them. Three cylindrical hydrogen storage tanks (with hydrogen compressed to 350 bars) are located centrally in the chassis.

"Someday, Hy-Wire could be displayed in a museum side-by-side with the first horseless carriages of Carl Benz or Gottlieb Daimler, or next to Henry Ford's Model T," says Larry Burns, GM's vice president of research, development and planning.

Problems with changing to a 'hydrogen economy'

Scientists say that infrastructure is an issue in New Zealand as it is for any country. Given that a considerable proportion of New Zealand's energy needs are supplied by low cost fossil fuels, a rapid change to non-fossil energy sources would result in disruption to the energy supply infrastructure, with substantial consequences for the economy.

Moving towards a hydrogen economy means that we would eventually have to change all our vehicles from petrol or diesel-driven engines in cars, truck and buses, to hydrogen-powered fuel cell vehicles. We would also have to change our petrol stations to hydrogen stations and solve problems of how to generate, store and transport hydrogen. Mechanics would have to learn how to work on fuel cells as there would be no more combustion engines. This replacement of vehicles and pumps at the petrol/hydrogen stations would come as a gradual phasing in as stock is replaced, rather than a rapid change from one type of technology to another.

When we start using fuel cells to generate electricity for domestic and commercial power usage, power plants might change as will the way we deliver the electricity. In the future, we might become less reliant on fossil-fuel and nuclear power plants. Photovoltaic or solar-powered cells might become a common feature on roof tops as an energy source for electrolysis of hydrogen.

For the most part, oil companies are gearing themselves for the changes. BP changed its name to Beyond Petroleum some years ago, and is jockeying to position itself as a hydrogen technology provider and distributor. Already the company has signed a deal with Singapore's Economic Development Board to build hydrogen refuelling stations for future Singaporean motorists driving hydrogen-powered vehicles. Shell Hydrogen, a division of the Royal Dutch/Shell Group of companies, in partnership with Daimler-Chrysler and Norsk Hydro amongst others, is currently involved in a project with the Icelandic Government to transform Iceland into a 'hydrogen society' where hydrogen is produced via renewable energy sources. The aim is to completely eliminate the use of hydrocarbon fuels and eventually become a net exporter of hydrogen produced using surplus renewable energy. Countries and businesses that have long been providers of oil products are somewhat more nervous about the prospects of a hydrogen future.

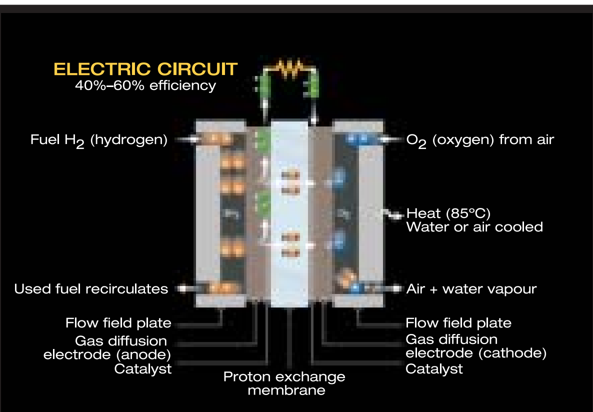
How do you store and transport hydrogen?

Hydrogen is a bulky gas, and it is not nearly as easy to store as petrol or oil. Compressing the gas requires energy, and compressed hydrogen contains far less energy than the same volume of petrol. One solution being developed is to store hydrogen in a solid form in a substance called sodium borohydride created from borax. This solid dissolves readily in water to make a non-flammable liquid fuel that will only liberate hydrogen when passed over a catalyst. As sodium borohydride releases its hydrogen, it turns back into borax which can be recycled. Hydrides such as sodium borohydride, have energy storage densities similar to other liquid fuels and may provide one solution for the safe use of hydrogen as a transport fuel. IRL is actively investigating ways to lower the cost of the production of hydrides.

Another solution that is being researched is filling up cars with methanol, and extracting hydrogen with reformers built into motor vehicles which will supply hydrogen to fuel cells as required. However, although this creates a more energy-efficient vehicle, it will still contribute to pollution because of the carbon-based waste products from the reformation process. There is also the issue of the amount of space a reformer would take up inside a motor vehicle. Eventually, standardised storage devices for hydrogen will be developed to pump hydrogen at the point of sale, but at present there is considerable debate on which storage option is preferable.

Once the storage problem is solved and standardised, a network of hydrogen stations and the transportation infrastructure will develop. However, this is unlikely until there is a storage technology that clearly dominates the marketplace.

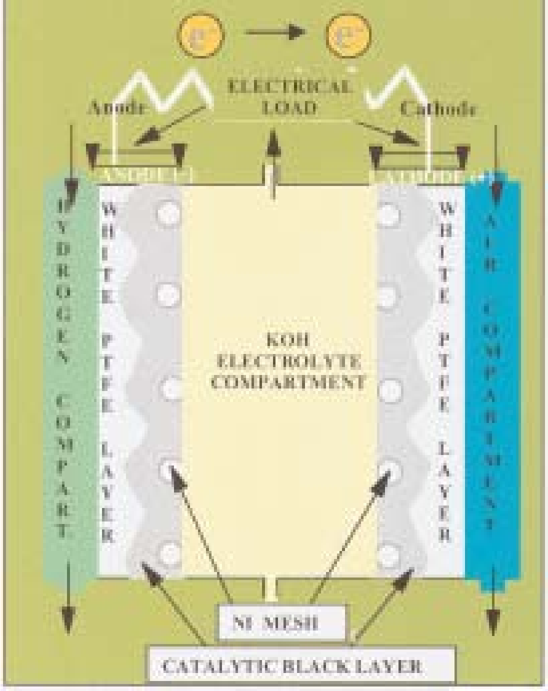
Courtesy of Energy Efficiency and Consultation Authority (EECA)



A POLYMER ELECTROLYTE MEMBRANE (PEM) FUEL CELL
When hydrogen reaches the catalyst layer, it separates into protons (hydrogen ions H^+) and electrons (e-). The free electrons produced at the anode, are conducted in the form of a usable electric current through the external circuit. At the cathode, oxygen (O_2) from the air, electrons from the external and protons combine to form water and heat. – Ballard Power systems

How do fuel cells work?

Fuel cells are the devices needed to convert hydrogen into useful forms of energy. A problem at present is the high cost of producing fuel cells for everyday use. For vehicle applications they cost around 50 times more than an equivalent petrol or diesel engine. However, as manufacturing volumes increase and technology is improved



The structure of an alkaline fuel cell.
With permission from IRL. www.irl.cri.nz

the costs will drop (as with the tumbling price of computers). There are niche applications available now where fuel cells are economically competitive. These include uninterruptible power supplies for hospitals and factories and, combined with wind or solar power, as power supplies for remote areas. (It can cost around $25,000 per kilometre for wires, poles and labour, to connect a remote house to the national grid).

Fuel cells are very efficient converters of chemical energy to electricity and they run quietly – unlike most petrol or diesel generators. Fuel cells act in a similar way to car batteries, but instead of using electricity to recharge they use hydrogen and oxygen. In turn they give off a direct current (DC) voltage that can be used to power electric motors, lights or other electrical appliances. The only waste product from the reaction is water vapour.

Fuel cells are usually classified by the type of electrolyte they use. One of the oldest types is the alkaline fuel cell which has been used in the United States space programme since the 1960s. This type of fuel cell is relatively inexpensive but is sensitive to contamination from impure hydrogen and carbon dioxide in the air. IRL have been working with a European alkaline fuel cell manufacturer to develop balance-of-system components for distributed generation applications. Other types of fuel cells include the phosphoric acid and solid oxide fuel cells which operate at higher temperatures (over 1000°C for solid oxide). These are most suitable for stationary power systems because the expense, the longer time frame to warm up and the high operating temperature make them unsuitable for use in vehicles.

The polymer electrolyte membrane (PEM), fuel cell is the most likely type of fuel cell to power cars and buses. They operate at a comparatively low temperature, about 80°C, which means they warm up quickly and don't require expensive containment structures. However, they are more sensitive to contaminants in the hydrogen and require very precise humidity control.

There are four basic elements of a polymer electrolyte membrane fuel cell.

- The **anode**, or positive electrode of the fuel cell, attracts electrons that are freed from the hydrogen molecules so that they can be used in an external circuit.
- The **cathode**, or negative electrode of the fuel cell, attracts positively-charged hydrogen atoms through the membrane and directs electrons back from the external circuit to the catalyst where they can recombine with the hydrogen ions and oxygen to form water. The cathode has channels etched into it that distribute the oxygen to the surface of the catalyst.
- The **polymer** electrolyte membrane looks similar to a piece of plastic lunch wrap. This specially treated material blocks electrons and conducts positively-charged ions.
- The **catalyst** facilitates the reaction of oxygen and hydrogen. It is usually made of platinum powder very thinly coated onto carbon paper or cloth which is wrapped around the electrolyte. The platinum-coated side of the catalyst faces the electrolyte.

Pressurised hydrogen gas (H_2) enters the fuel cell on the anode side. This gas is forced through the catalyst. When a hydrogen molecule comes in contact with the platinum on the catalyst, it splits into two H^+ ions and two electrons (e^-). The electrons are attracted to the anode, then conducted through an external circuit to power a motor or other electrical device. The electrons return to the cathode side of the fuel cell.

On the cathode side of the fuel cell, oxygen (O_2) is forced through the catalyst, where it forms two oxygen atoms. The oxygen atoms attract H^+ ions, so that two H^+ ions combine with an oxygen atom and two electrons return from the external circuit to form a water molecule (H_2O).

Chemistry of a PEM fuel cell

Anode side: $2H_2 \Rightarrow 4H^+ + 4e^-$

Cathode side: $O_2 + 4H^+ + 4e^- \Rightarrow 2H_2O$

Net reaction: $2H_2 + O_2 \Rightarrow 2H_2O$

This reaction in a single fuel cell produces only about 0.7 volts or less when loaded. To increase this voltage, many separate fuel cells need to be combined to form a fuel-cell stack. A polymer electrolyte membrane fuel-cell stack the size of a small suitcase can power a car.

Glossary

Anode – the positive electrode of an electrolytic cell, towards which negative particles are attracted.
Borax – hydrous sodium borate, a salt found as soft white crystals around hot springs and dry salt lake beds. It is often used in making glass, china, antiseptic, bleaches, washing powder, and detergent.
Cathode – the negative electrode.
Catalyst – a substance which produces chemical change in other substances or speeds up the rate of chemical reactions without itself undergoing change.
Cryogenic container – an insulated, vented container for storing cold liquids.
Electrochemical – chemical elements which have the ability to easily lose electrons to form cations (positive ions). **Electrochemicals** can form electrolytes.
Electrode – a terminal, either an anode or a cathode, through which electricity enters or leaves the electrolyte.
Electrolysis – chemical decomposition or change by passing an electric current through a solution (electrolyte) resulting in the migration of ions to the electrodes.
Electrolyte – a solution able to conduct an electric current.
Fuel cell – cell producing electricity direct from chemical reaction. It works on the same principle as a battery but is continuously fed fuel (such as hydrogen) to sustain the process.
Fuel-cell stack – an assemblage of individual fuel cells.
Greenhouse gas – gases such as carbon dioxide, methane, and nitrous oxide which contribute to the greenhouse effect, a phenomenon of the Earth's atmosphere by which solar radiation trapped by the Earth and re-emitted from the surface is prevented from escaping by the various gases in the air. The overall effect is a rise in the Earth's surface temperature, leading to climate variation and rising sea levels.

Resources

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General Motors: http://www.gm.com
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(These Web pages at MfE are only available temporarily. you could contact MfE for copies of the proceedings.)
Plug Power: http://www.plugpower.com
Plug Power is a United States company which manufactures fuel cells and the site has information about their development and history, check the 'news' section, then look under 'press releases'.
Rocky Mountain Institute: http://www.rmi.org/sitepages/pid171.php
The Rocky Mountain Institute in Colorado is headed by Professor Amory Lovins – a world renowned expert in the development of hydrogen and fuel cell technologies. A particularly interesting article is 'A strategy for the hydrogen transition'.
United States Department of Energy – National Hydrogen Energy Roadmap: http://www.eren.doe.gov/hydrogen/features.html
Hydrogen and fuel cells have the potential to solve several major challenges facing America today: dependence on petroleum imports, poor air quality, and greenhouse gas emissions. The site outlines the United States Government's Hydrogen, Fuel Cells and Infrastructure Technologies Programme. This site also has a special section for students and teachers explaining the basics of hydrogen and fuel cells or to view an animation of a fuel cell in action.

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Cover Photos: *Top*, With permission NorskeHydro Electrolysers, Norway www.electrolysers.com *Bottom*, IRL's AFC System seen here in its container – the first to be exported from New Zealand to Western Australia and a world first proof-of-concept connecting an AFC in parallel with a wind turbine.

Photos: As credited

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