Fuelling the future

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Fuel cells, the power source of the future, are already a multi-million dollar market. Sandra Curtin discusses their primary uses and the potential opportunities for industrial minerals in fuel cell development

Honda's FCX Clarity FCEV (pictured) is a hydrogen fuel cell electric vehicle that generates electricity and emits only water vapour and heat into the air

Fuel cells, the clean energy powerhouse you've heard about for years, are available for purchase *today* and early market sales are steadily growing. Twenty-four thousand fuel cell units were shipped in 2009, an increase of 41% compared to 2008, and annual global sales were more than $750m. in 2010[1] - anticipated to exceed $1bn by 2014.[2] This growth is opening markets for industrial minerals suited to the specific chemistries of high, mid and low temperature fuel cells.

Fuel cells are well-suited to materials handling applications, with more than 1,000 fuel cell-powered forklifts already deployed at warehouses across the USA. Major telecommunications companies worldwide have deployed more than 1,000 fuel cells to ensure reliability on networks, providing highly reliable primary or back-up power to cell phone towers and substations. An increasing number of supermarkets, wastewater treatment plants, universities and corporate campuses are relying on fuel cells to provide clean, efficient, low cost, power that delivers energy even when the power grid goes down.

The US Department of Energy has helped to stimulate early markets by providing funding assistance through the American Reinvestment and Recovery Act (ARRA) to deploy fuel cell-powered forklifts and fuel cell power at telecommunication towers. This investment is paying off - once companies try fuel cell power, they like it; several companies have placed follow-on orders to purchase dozens of additional fuel cell units. Fuel cells are proving a highly reliable, and economical, alternative to battery power in these applications.

The excitement is worldwide. Japan's Ministry of Economy, Trade and Industry (METI) New Energy Program has set targets to implement stationary fuel cell power - 10,000 MW by 2020 and 12,500 MW by 2030. Commercial fuel cell energy systems for Japanese homes are produced and sold by a number of Japanese energy companies; by March 2010, these companies had sold more than 5,000 units to homeowners. The South Korean government is also facilitating the development of fuel cell energy systems and anticipates the installation of 2m. residential fuel cell units by 2020. Fuel cells powered by natural gas have just earned a prime spot within the pricing mechanism of Korea's new Renewable Portfolio energy standard.

Daimler, General Motors, Toyota, Honda, and Hyundai have announced that they plan commercial production of fuel cell vehicles by 2015, with Toyota and Hyundai citing a cost comparable with many battery-powered vehicles (under $50,000). In support of the 2015 roll out of fuel cell vehicles by major manufacturers, Germany plans to open 1,000 hydrogen fueling stations. Denmark, Sweden and Norway are also working to develop a Scandinavian hydrogen highway.

Ten Japanese energy companies committed to build up to 100 hydrogen stations in four Japanese cities to support commercial sales of fuel cell vehicles from Toyota, Nissan and Honda. Mercedes-Benz and Honda fuel cell vehicles are currently being leased by customers in California, which has 20 hydrogen fueling stations and many more planned.

Fuel cell types and materials used

Fuel cell types	PEM	DMFC	PAFC	MCFC	SOFC
Catalysts	Platinum	Platinum/ ruthenium	Platinum	Nickel	Nickel/yttria-stabilised zirconia (YSZ)
Electrolytes	Perfluoro-sulphonic acid (PFSA) membrane	Perfluoro-sulphonic acid (PFSA) membrane	Phosphoric acid	Lithium and potassium carbonates	YSZ
Bipolar plates	Graphite	Graphite	Graphite	Stainless steel	Doped lanthanum & yttrium chromites
Operating temperature	<100°C	<100°C	150-200°C	600-700°C	600-1,000°C
Power range (scalable)	Watts to one megawatt (MW)	Watts	Kilowatts (kWs) to MWs	kWs to multi-MWs	kWs to multi- MWs
Applications	• Primary power • Back-up power • Portable power • Motive power	• Portable power	• Power plants • Combined heat and power (CHP)	• Power plants • CHP	• Power plants • CHP

Finding the market

So why are fuel cells so popular? Fuel cells generate electricity with low to zero emissions and operate more efficiently than combustion systems. Electricity is produced electrochemically. In structure, a fuel cell operates like a battery, but a battery stores energy while a fuel cell generates energy. A fuel cell does not run down or require recharging. It will continue to produce electricity as long as fuel is supplied.

Fuel cells are flexible in that they can operate using a wide variety of hydrogen rich fuels, ranging from fossil fuels to biofuels to industrial process gas to hydrogen derived from renewable resources such as solar, wind, and geothermal power. The high efficiency of fuel cells delivers economic and environmental benefits even when the hydrogen source is natural gas or another fossil fuel.

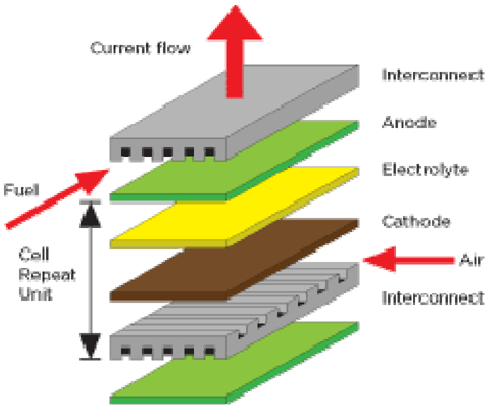
Emissions depend upon the choice of fuel, but are always lower than combustion systems. When using pure hydrogen, the emissions are zero (other than heat and water). When using natural gas, the emissions are still very low; much lower than combusting fuel. Based on measured data, a fuel cell power plant may create less than one ounce of pollution per 1,000 kWh of electricity produced - compared to 25 lbs of pollutants for conventional combustion-generating systems.

Fuel cells attain 40-50% or greater fuel-to-electricity efficiency when using hydrocarbon fuels such as natural gas or pure hydrogen. High efficiency is an inherent advantage for fuel cells because they use the chemical energy of a fuel directly, without combustion.

Hybrids, such as systems that combine high temperature fuel cells with a turbine, can operate at electrical efficiencies estimated at more than 60% - higher than even the most efficient combined cycle turbine plants now available. When the fuel cell is located near the point of use waste heat can be captured for cogeneration, where it can be used to provide steam, hot water, space heating, or cooling. This CHP installation can deliver 80-90% overall fuel efficiency.

Fuels cells are distinguished by different operating temperatures, catalysts, membrane materials and electrolytes. A variety of industrial metals and minerals are employed within the various fuel cells.

Cross section of a fuel cell stack



Fuel cell designs: PEM and DMFC

Many people are familiar with the proton exchange membrane (PEM) fuel cell, also known as a polymer electrolyte membrane fuel cell, which is used in automotive, small stationary and portable applications.

PEM fuel cells offer high energy density and fast start up in a compact package. PEMs are scalable, delivering power for portables or small stationary power (residential energy and heating, power for soldiers and first responders, back-up power), and motive power (cars, buses, forklifts, unmanned vehicles). PEM fuel cells use pure hydrogen gas as fuel, operate at temperatures of 100ºC (212¡F) or less, and deliver power at 40-50% efficiency.

The PEM fuel cell is composed of a negatively charged electrode (anode), a positively charged electrode (cathode) and an electrolyte membrane. A catalyst at the anode causes hydrogen to split into positively-charged protons and a negatively-charged electron. The proton passes through a non-conducting membrane from the anode to the cathode, while the electron travels a circuit to the cathode, creating current. At the cathode, the protons and electrons combine with oxygen from air to form a pure water byproduct.

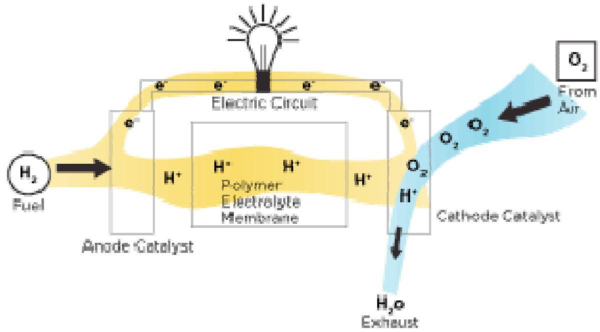
Direct methanol fuel cells (DMFCs) are similar to PEMs, in that both typically use a polymer membrane as the electrolyte. However, in the DMFC, the anode catalyst itself draws the hydrogen from the liquid methanol, eliminating the need for a fuel reformer. Efficiencies are about 40%. The operating temperature is between 120-190¡F, a relatively low range, making this fuel cell attractive for small to mid-sized applications, ranging from cellular phones and laptops, to forklifts and auxiliary power units for vehicles (such as campers).

Platinum is the most reactive and stable catalyst for low temperature fuel cells, and is used at both the anode and cathode of PEMs and DMFCs. However, the high cost of platinum, and its sensitivity to carbon oxide contaminants in hydrogen fuel, has led to efforts to increase platinum's catalytic activity on the membranes and to reduce the amount of platinum used - one way of accomplishing this is by depositing platinum nanoparticles onto carbon supports.

Researchers are also examining the use of platinum alloys with other transitional metals, such as nickel, chromium, ruthenium, cobalt and palladium, but there are concerns about the long-term stability of these alloy catalysts. Platinum-ruthenium catalysts have shown promise due to the alloy's higher tolerance of carbon monoxide (CO) contamination.

In addition, researchers are investigating lower cost, non-platinum catalysts. These include other platinum group metals (palladium, ruthenium, iridium) and abundant, less costly non-noble catalysts, such as transition metal oxides, chalcogenides and macrocycles. However, these have shown lower catalytic activity and stability compared to platinum.

PEM fuel cell operation



Phosphoric acid fuel cells

Like PEMs, phosphoric acid fuel cells (PAFCs) use a carbon-supported platinum catalyst, but operate at a somewhat higher temperature of around 200¡C (392¡F), making them less sensitive to fuel impurities than PEMs. This higher CO tolerance permits a wider choice of fuels, using hydrogen extracted from fossil fuels, typically natural gas or biogas. PAFC systems offer lifetimes greater than 60,000 hours and deliver 40% fewer greenhouse gas emissions than typical US coal-fired power plants when operated using natural gas.[3]

PAFCs offer an electrical efficiency of about 40% and, when the heat byproduct is used for CHP, the combined electrical and thermal efficiency can reach nearly 80%.

As the name implies, PAFCs utilise a liquid phosphoric acid electrolyte located within a silicon carbide matrix. The anode and cathode reactions are similar to PEMs, using platinum or platinum alloy catalyst on the electrodes and a perfluorinated membrane. However, researchers have developed a promising polybenzimidazole (PBI) membrane doped with phosphoric acid that allows higher temperature PAFC operation, is stable and tolerates higher levels of CO. The higher operating temperature permits the use of a less expensive catalyst, such as nickel.

PAFCs have undergone R&D since the 1980s. Commercial systems are operating today at sites such as hospitals, grocery stores, hotels, office buildings, and manufacturing facilities. Installations are generally in the 200-400 kW range, with power scalable to the end-user’s needs by linking multiple fuel cell units.

Molten carbonate fuel cells

Molten carbonate fuel cells (MCFCs) operate at temperatures of 600-700ºC and do not require noble metals to catalyse the electrochemical reaction. The electrolyte comprises a molten mixture of lithium and potassium carbonates in a lithium-aluminate matrix. Anode materials use nickel-chromium or nickel-aluminium alloys, and cathodes use nickel oxide doped with magnesium or iron. Nickel oxide erosion is an issue at the positive electrode, but this may be reduced through the addition of calcium, strontium or barium carbonates.

The high operating temperature of MCFCs yields high operating efficiencies, ranging from 50-60% electrical efficiency, to 85% thermal efficiency when waste heat is captured for cogeneration. The higher operating temperature permits fossil fuels to be reformed internally, eliminating the need for an external fuel processor. Emissions are extremely low, with near zero nitrogen oxides (NO_x) and sulphur oxides (SO_x), and lower carbon dioxide (CO_2) emissions than competing technologies.

MCFCs can be scaled from several hundred kilowatts to multi-megawatt systems. Commercial units are sold today for use in larger facilities, such as wastewater treatment plants, universities, hotels, manufacturing facilities, prisons and hospitals.

Solid oxide fuel cells

Solid oxide fuel cells (SOFCs) operate between 600-1,000ºC, and sometimes higher. At these high temperatures solid materials are used for the anode, cathode and electrolyte. Nickel-YSZ (yttria-stabilised zirconia) typically is used at the anode, while the cathode employs strontium-doped lanthanum manganite (LSM). YSZ also serves as the electrolyte.

SOFCs deliver an electrical efficiency of up to 60%, and as high as 70-80% when waste heat is captured for cogeneration. SOFCs are also capable of reforming natural gas internally.

Work is underway to develop anodes that will directly oxidise methane and other fuels, using gadolinium-doped ceria electrolyte on a nickel-copper alloy anode. This would help to reduce SOFC cost by eliminating the need for an internal fuel reformer.

Researchers are also developing lower temperature SOFCs (<700ºC) that will permit a wider choice of fuel cell materials. Gadolinium-doped ceria or strontium and magnesium-doped lanthanum gallate are used as alternative electrolytes that can attain sufficient conductivity at lower temperatures. Reducing the thickness of the YSZ electrolyte membrane also improves efficiency.

Fuel cell stack components

Bipolar plates, or interconnects, separate adjacent fuel cells within fuel cell stacks. The interconnects are used to conduct current and channel the flow of gases and heat to and from the cell, and are commonly made of graphite, aluminium, nickel, titanium or stainless steel in low to moderate temperature fuel cells (PEMs, DMFCs, PAFCs).

A protective carbon coating, or a metal-based coating using noble metals, metal nitrides, oxides or carbides, is added to the interconnect plates to improve resistance to corrosion. Gold and chromium are among leading candidates.

MCFC interconnects are stainless steel alloys coated with nickel. However, high temperature operation and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Researchers have found that adding chromium or aluminium to stainless steel or nickel-based alloys used at electrodes and bipolar plates increases corrosion resistance.

Similarly, SOFCs require the use of plate and coating metals that are stable at high temperatures and resist corrosion. At higher temperature operations (above 900ºC), doped lanthanum or yttrium chromites are used, while intermediate temperature SOFCs (less than 900ºC) can use metal alloys, like ferritic stainless steels, which are lower cost and offer better conductivity. Lanthanum chromites, lanthanum manganites or yttrium manganites serve as coatings. Researchers are working to further improve corrosion resistance and improve mechanical stability.

Hydrogen generation

Hydrogen generation technologies - fuel reforming and electrolytic hydrogen generation from water - require industrial minerals to catalyse reactions.

Reformers generate hydrogen from hydrogen-rich fuels. Nearly all hydrogen generated today is reformed from natural gas used in large facilities. However, small-scale, on-site reforming technologies are also in development. Both reforming methods typically use nickel or platinum group metals as catalysts.

Electrolysers, which use electricity to split water into oxygen and hydrogen, and gas clean-up processes, which remove trace contaminants from reformate gases, also typically utilise nickel or platinum group metals as catalysts.

Fuel cell market outlook

The commercialisation of fuel cells in an array of market applications has and will continue to present a growing opportunity for industrial mineral suppliers. Johnson-Matthey's general manager, Peter Duncan, recently commented that platinum-bearing fuel cells "have entered a phase of commercialisation in mobile phone chargers and increasingly into the stationary back-up power generation markets. Even at the moment, the fuel cell is quite a driver of platinum demand, and it's very much an important demand sector for the future".[4]

In addition, the US Geological Survey's *Mineral Commodity Summaries* 2010 states that "large-scale fuel-cell applications are being developed that could consume as much graphite as all other uses combined".[5]

Researchers are expanding upon the industrial minerals currently used in fuel cells, looking for lower cost, more abundant minerals that are stable, reactive, and resistant to corrosion. In addition, the family of fuel cell technologies is expanding. Distinctions among fuel cell types are blurring, particularly between the PAFC and PEM fuel cells, as researchers develop higher and lower temperature systems.

Other pathways being pursued include alkaline, direct borohydride and direct carbon fuel cells, to name but a few. All this leads to one conclusion - an array of industrial minerals will play a big role in both fuel cells and in the clean energy future.

Contributor: Sandra Curtin, research director, Fuel Cells 2000. Fuel Cells 2000 is an activity of the Breakthrough Technologies Institute (BTI), a non-profit, independent, educational organisation that identifies and promotes environmental and energy technologies that can improve the human condition. BTI was established in 1993.

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Fuel cell market applications

Owing to fuel cells' versatile nature, early market applications include:

- Motive power: passenger vehicles, forklifts, unmanned aerial vehicles;
- Backup power: cell phone towers, emergency communications;
- Portable power: chargers for hand-held electronics, soldier power;
- Primary power: data centres, wastewater treatment plants, hospitals, hotels, universities, supermarkets.

Power applications may also include combined heat and power (CHP) systems that provide cogenerated cooling, heating and hot water using the fuel cell's heat by-product.

Who is using fuel cells?

Walmart, Coca-Cola, Whole Foods Market, Hilton Hotels, Sprint Nextel, Google, Sierra Nevada brewery, Cabela's, FedEx, Cox Communications, Safeway, eBay, Wegmans, Fujitsu, Staples, Sysco, NestlŽ Waters, AT&T, Bridgestone-Firestone, Motorola, Kimberly-Clark, Cox Enterprises, Price Chopper, Sutter Home Family Vineyards, Starwood Hotels, and Verizon, among many others.

Fuel cells are being sold today to power forklifts, supermarkets, data centres, cell phone towers, wastewater treatment plants, hospitals, hotels, universities and corporate campuses.

[1] Pike Research. "Fuel Cell Industry is Poised for Major Change and Development in 2011." Press Release, 2 Feb. 2011. 3 Feb. 2011. < http://www.pikeresearch.com/newsroom/fuel-cell-industry-is-poised-for-major-change-and-development-in-2011>.

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[3]

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