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energy center

Report

193-1

Fuel Cells for Distributed Generation

A Technology and Marketing Summary

March 2000

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Abstract

Fuel cells have the potential to provide distributed power generation. Four types of fuel cells are currently receiving the most development attention: proton exchange membrane fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and solid oxide fuel cells. This document summarizes technical and marketing information from a report entitled “Review of State-of-the Art Fuel Cell Technologies for Distributed Generation” (ECW report number 193-2). The intended audience for this document is the informed lay reader. This document summarizes both the technical status and the anticipated commercial markets of the “near-term” fuel cell technologies.

Technology Summary

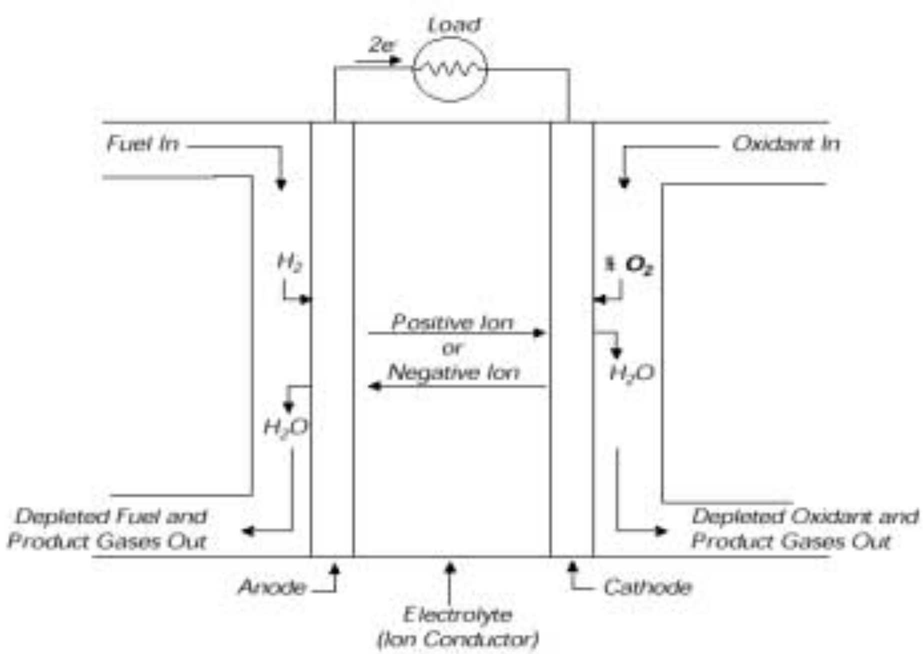
Fuel Cell Description

A fuel cell is an electrochemical device that converts the chemical energy of a fuel directly into electrical energy. Intermediate conversions of the fuel to thermal and mechanical energy are not required. All fuel cells consist of two electrodes (anode and cathode) and an electrolyte (usually retained in a matrix). They operate much like a battery except that the reactants (and products) are not stored, but continuously fed to the cell.

Fuel cells were first invented in 1839, but the technology largely remained dormant until the late 1950s. During the 1960s, NASA used precursors to today's fuel cell technology as power sources in spacecraft.

Figure 1 shows the flows and reactions in a simple fuel cell. Unlike ordinary combustion, fuel (hydrogen-rich) and oxidant (typically air) are delivered to the fuel cell separately. The fuel and oxidant streams are separated by an electrode-electrolyte system. Fuel is fed to the anode (negative electrode) and an oxidant is fed to the cathode (positive electrode). Electrochemical oxidation and reduction reactions take place at the electrodes to produce electric current. The primary product of fuel cell reactions is water.

Figure 1: Schematic of an individual fuel cell (Hirschenhofer et al, 1998)

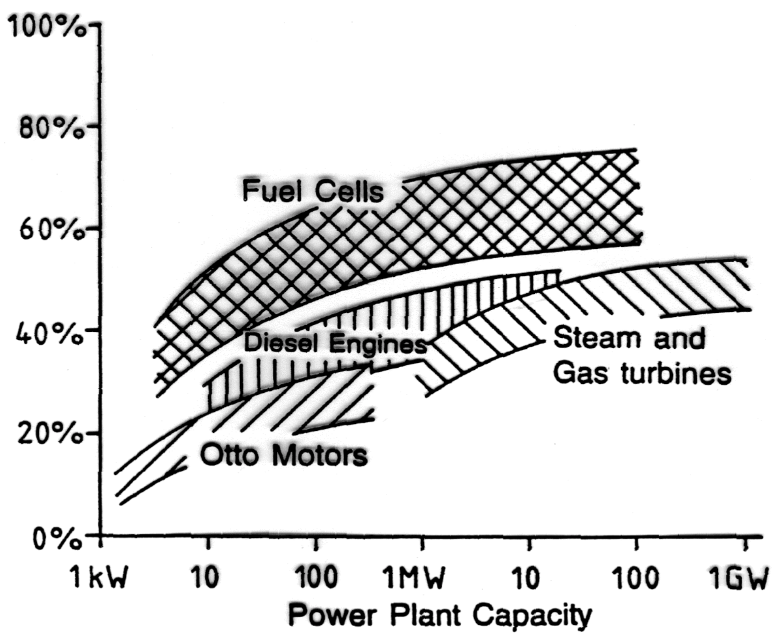


Advantages of Fuel Cells

Fuel cells have a number of advantages over conventional power generating equipment:

- High efficiency (see Figure 2)
- Low chemical, acoustic, and thermal emissions
- Siting flexibility
- Reliability
- Low maintenance
- Excellent part-load performance
- Modularity
- Fuel flexibility

Figure 2: Comparison of power plant efficiency (Kordesch and Simader, 1996)



Due to higher efficiencies and lower fuel oxidation temperatures, fuel cells emit less carbon dioxide and nitrogen oxides per kilowatt of power generated. And since fuel cells have no moving parts (except for the pumps, blowers, and transformers that are a necessary part of any power producing system), noise and vibration are practically nonexistent. Noise from fuel cell power plants is as low as 55 dB at 90 feet (Appleby, 1993). This makes them easier to site in urban or suburban locations. The lack of moving parts also makes for high reliability (as demonstrated repeatedly by the U.S. Space Program and the Department of Defense Fuel Cell Program) and low maintenance.

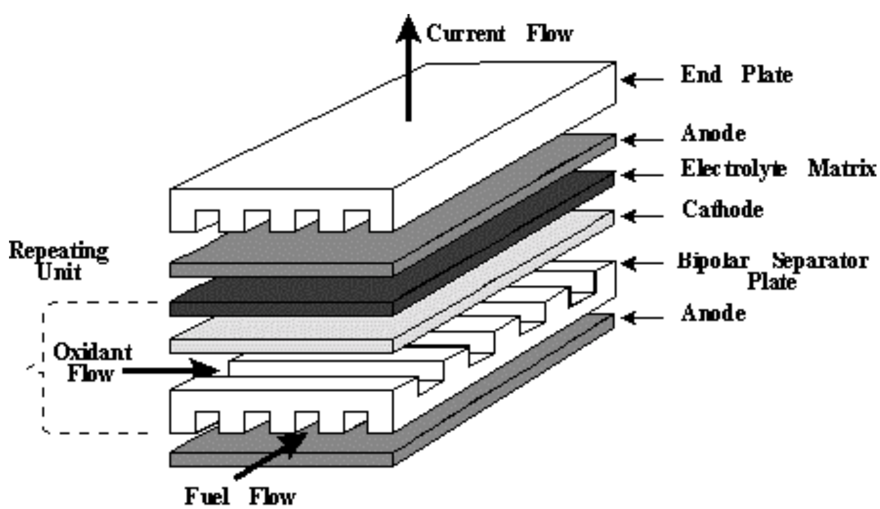
Another advantage of fuel cells is that their efficiency increases at part-load conditions, unlike gas and steam turbines, fans, and compressors. Finally, fuel cells can use many different types of fuel such as natural gas, propane, landfill gas, anaerobic digester gas, JP-8 jet fuel, diesel, naptha, methanol, and hydrogen. This versatility ensures that fuel cells will not become obsolete due to the unavailability of certain fuels.

Fuel Cell Stacks

A single fuel cell will produce less than one volt of electrical potential. To produce higher voltages, fuel cells are stacked on top of each other and connected in series. As illustrated in Figure 3, cell stacks consist of repeating fuel cell units, each comprised of an anode, cathode, electrolyte, and a biploar separator plate. The number of cells in a stack depends on the desired power output and individual cell performance; stacks range in size from a few (< 1 kW) to several hundred (250+ kW).

Reactant gases—typically, desulphurized, reformed natural gas and air—flow over the electrode faces in channels through the bipolar separator plates. Because not all of the reactants are consumed in the oxidation process, about 20 percent of the hydrogen delivered to the fuel cell stack is unused and is often “burned” downstream of the fuel cell module.

Figure 3: Components of a fuel cell stack

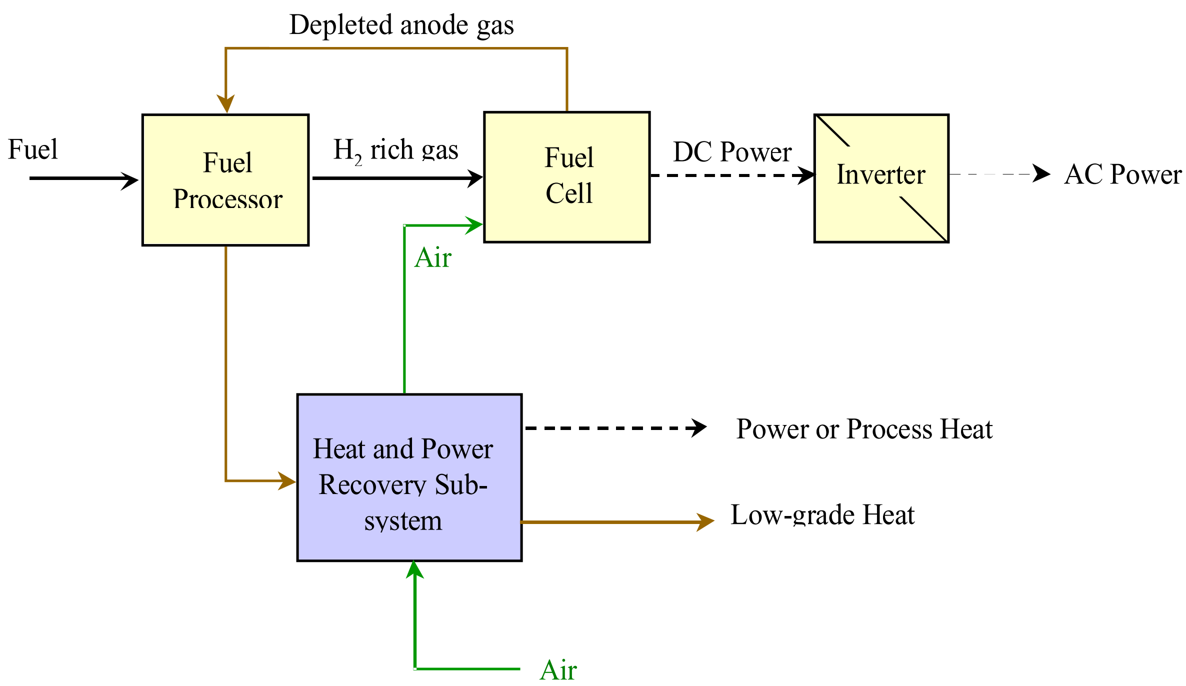


Fuel Cell Systems

Since all fuel cells use hydrogen fuel—which is not readily available—fuel cell systems must have fuel-processing equipment. Figure 4 shows a diagram of a generic fuel cell system. Fuel, in this case natural gas, enters the plant and is delivered to the fuel-processing subsystem. Fuel processing equipment removes sulfur from the fuel, preheats the fuel near the operating temperature of the cell, and reforms it to a hydrogen-rich gas stream.

After processing, the gas is delivered to the fuel cell where it is electrochemically oxidized to produce electricity (and heat). Electrical efficiencies range from 36–60 percent, depending on the type of fuel cell and the configuration of the system. By using conventional heat recovery equipment, overall efficiency can be as high as 85 percent.

Figure 4: Diagram of a generic fuel cell system (adapted from Blomen and Mugerwa, 1993)



Fuel Cell Types

Currently, there are at least six different fuel cell types in varying stages of development. Four of these are receiving the most development attention. In general, electrolyte and operating temperature differentiates the various fuel cells. Listed in order of increasing operating temperature, the four fuel cell technologies currently being developed are:

- Proton exchange membrane fuel cell (PEMFC)—175°F (80°C)
- Phosphoric acid fuel cell (PAFC)—400°C (200°C)
- Molten carbonate fuel cell (MCFC)—1250°F (650°C)
- Solid oxide fuel cell (SOFC)—1800°F (1000°C)

The following tables give a summary of the characteristics and fuel requirements of these fuel cell types.

Table 1: Fuel cell characteristics (adapted from Penner, 1995)

	PEMFC	PAFC	MCFC	SOFC (tubular)
Operating temperature	<210°F	~400°F	~1250°F	~1800°F
Operating pressure	1–5 atm	1–8 atm	1–3 atm	1–15 atm
Construction materials	Graphitic carbon	Graphitic carbon	Ni and stainless steel	Ceramics and metals
Power density (pounds/kW)	8–10 (DOE goals)	~25	~60	~40
Efficiency (LHV)	35-40%	35-40%	50–55%	45-50%
Cooling medium	Water	Boiling water	Excess air	Excess air

LHV = lower heating value basis

Efficiency = (net AC power)/(LHV fuel in)

Table 2: Fuel cell requirements (adapted from Penner, 1995)

	PEMFC	PAFC	MCFC	SOFC (tubular)
H_2	Fuel	Fuel	Fuel	Fuel
CO	Poison*	Poison at ≥ 2% (vol.)	Fuel	Fuel
CH_4	–	–	Fuel	Fuel
NH_3	Poison	Poison	–	Fuel
Cl_2	Poison	Poison	Poison	Poison?
S_2	Poison	Poison	Poison	Poison
Special problems	Moisture control in the membrane	High-voltage operation Cell life	High fuel utilization Cell life	High oxidant utilization

* A poison is a substance that harms fuel cell performance or longevity.

Proton Exchange Membrane Fuel Cells (PEMFCs)

PEMFCs are currently being developed primarily for sizes less than 500 kW. Applications for PEMFCs include:

- Light duty (50–100 kW) and medium duty (200 kW) vehicles
- Residential (2–10 kW) and commercial (250–500 kW) power generation
- Small and/or portable generators and battery replacements

Construction Materials, Cell Operation, and Performance

The PEMFC's electrolyte is a solid polymeric membrane fitted between two platinum-catalyzed porous electrodes. PEMFCs typically operate at about 80–85°C (185°F), a temperature determined by both the thermal stability and the ionic conductivity characteristics of the polymeric membrane (Srinivasan et al, 1993). To get sufficient ionic conductivity, the proton-conducting polymer electrolyte requires liquid water. Thus, temperatures are limited to less than 100°C. The low-operating temperature allows the PEMFC to be brought up to steady-state operation rapidly.

PEMFCs can operate at elevated air pressures—up to eight atm have been used—which allows for higher power densities from the cell stack. (However, the need for larger compressors and therefore higher parasitic power requirements may offset this advantage.) The solid polymer membrane also can support substantial differential reactant pressures, which provides some flexibility in the system design (Penner, 1995; Prater, 1994).

As with many of the lower temperature fuel cells, PEMFCs require a pure hydrogen source for operation. Since hydrogen is not readily available, it is typically obtained by reforming a hydrocarbon fuel, such as methanol or natural gas. The reformed fuel often contains other gasses such as carbon monoxide that are detrimental to fuel cell operation. Carbon monoxide levels of 50 ppm or greater poison the catalyst, causing severe degradation in cell performance. Therefore, all carbon-containing fuels (for example, natural gas, methanol, and propane), require additional fuel processing.

Fuel processing in general represents a significant challenge to the commercialization of fuel cells; this is particularly true for PEMFCs due to their susceptibility to electrocatalyst poisoning from low-level carbon monoxide levels. However, given sufficient fuel processing, PEMFCs are expected to operate using hydrogen, methanol, propane, and natural gas fuels (and eventually gasoline).

PEMFCs have an electrical efficiency of nearly 50 percent (McClellen, 1998). However, because the temperature of the waste heat from the fuel cell is too low be used in the fuel reforming process, overall system efficiencies have been limited to 42 percent (Rastler et al, 1996). Depending on the type of reforming process, PEMFC systems may have the lowest electrical efficiencies of all fuel cell systems.

The main technical issues that PEMFC developers face are:

1. Electrocatalyst poisoning by low-level carbon monoxide concentrations in the fuel
2. Water management and membrane operating temperature limits

3. Membrane and system balance-of-plant costs (“balance-of-plant” includes all ancillary plant equipment outside the fuel cell power module)

4. Cell life

Target Markets and Manufacturers

Low operating temperature, rapid start-up, light weight, high power density, and simplicity make PEMFCs attractive for transportation applications. However, many technological barriers remain and it is expected that PEMFCs will be marketed first in stationary applications. The same characteristics that make the PEMFCs attractive for transportation also make them attractive in remote, standby, and premium power onsite markets. PEMFCs are not suitable for most cogeneration applications because the low temperature operation results in low-grade waste heat and makes thermal integration with fuel processing equipment difficult. However, companies such as Plug Power in Latham, NY are developing residential PEMFC units that are expected to meet some hot water demands. It is not clear how well PEMFCs will meet thermal loads in cogeneration applications without auxiliary combustion equipment.

Ballard Power Systems of Vancouver, British Columbia is the leader in PEMFC technology and is pursuing both transportation and stationary applications.

Table 3: Target market for selected fuel cell manufacturers (adapted from Rastler et al, 1996)

Manufacturer / vendor	Target market
1. Ballard Power Systems	**Transportation:** Light duty (automobiles); medium duty (transit buses), **stationary:** Commercial (250kW initially)
2. Plug Power	**Transportation, stationary:** Distributed power (including residential)
3. Energy Partners	**Transportation, stationary:** Distributed power
4. H-Power	**Transportation, stationary:** 2–5kW residential & dispersed; battery replacement
5. International Fuel Cells	**Transportation**
6. Honeywell (Allied Signal)	**Transportation, stationary:** Distributed power
7. American Fuel Cell Corporation	**Transportation, stationary**
8. ElectroChem	OEM component supplier, small distributed power
10. Delphi (Division of GM)	**Transportation**
11. Northwest Power Systems	**Stationary**: Remote power, residential
12. Avista Labs	**Stationary:** Residential, commercial, and industrial
13. DCH Technology	**Portable power**

Status of Development and Commercialization

Daimler-Chrysler and Ford Motor Company have committed $750 million for research in PEMFC development and cost reduction. With this infusion of capital, PEMFCs are expected to overcome technical and economic hurdles within the next five years. Both companies have announced plans to offer commercial fuel cell powered vehicles in 2003. This is expected to accelerate stationary power development as well.

To date, several PEMFC power plants have been developed for both transportation and stationary applications. The most visible plants are those developed for transportation. Ballard Power Systems has PEMFCs in several demonstration transit buses in the Chicago Transit Authority and British Columbia transit systems and in Daimler-Chrysler NECARs I-IV. Ballard Power Systems also has demonstrated prototypes of 10 and 30 kW stationary systems. Now they are developing a 250 kW onsite generation unit for market entry in 2000.

Plug Power is developing PEMFCs from 5–50 kW. Their first product is a 7 kW residential power unit to be offered commercially in 2000. H-Power has developed 10 kW PEMFCs for Ford and is currently working on three-kilowatt residential units which they expect to sell for about $5,000 in moderate volume (New York Times, June 17, 1998). Additionally, H-Power has developed the first wholly unsubsidized, fully commercial fuel cell unit for a trailer-mounted, electric-powered highway construction sign (New York Times, June 17, 1998). Northwest Power Systems is developing 7–10 kW residential power generators.

To be successful in the transportation sector, it is widely believed that PEMFCs will have to cost $150/kW or less. In fact, automakers believe that in light duty applications they will need to cost around $25–50/kW. This means that the current cost of $500/kW will have to be reduced by another order of magnitude. To accomplish this, production volumes on the order of one million units per year are necessary.

Many people believe that stationary onsite fuel cell systems will have to cost $1500/kW to be competitive. Because PEMFCs have lower system efficiencies than other fuel cell types, utility experts believe they will need to cost less or will have to offer other benefits to potential customers in order to compete against phosphoric acid fuel cells in commercial markets (Rastler et al, 1996).

Phosphoric Acid Fuel Cells (PAFCs)

PAFCs are the only commercially available fuel cell today (made by ONSI, a subsidiary of International Fuel Cell Corporation). Worldwide, PAFC technology has been demonstrated at levels ranging from 50 kW to 11 MW, with most demonstration units between 50 and 200 kW. PAFCs can be used for onsite power generation in hospitals, hotels, schools, and commercial buildings requiring heat, high power quality, or premium power services.

Construction Materials, Cell Operation, and Performance

PAFCs have electrolytes of phosphoric acid. They typically operate near 200°C (400°F). Cooling of the fuel cell stack is accomplished with pressurized boiling water. As with all fuel cell types, PAFCs operate on hydrogen that is typically delivered from a natural gas-supplied reformer, though International Fuel Cell's PC25 units have operated on propane, landfill gas, and anaerobic digester gases. PAFCs can operate at elevated pressures (up to eight atm); however, the current packaged, commercially available PC25 unit operates at ambient pressures.

The electrolyte material consists of 100 percent phosphoric acid, which acts as a transport fluid for the migration of dissolved hydrogen ions from the anode to the cathode and conducts the ionic charge between the two electrodes in order to complete the electric circuit. Because the electrolyte is a liquid, evaporation and migration must be carefully controlled. Like PEMFCs, PAFCs also employ platinum electrocatalysts in the cell electrodes. This limits the amount of carbon monoxide the cell can tolerate before performance degradation sets in. The present limit is about two percent (by volume) before cell voltage begins to decay. Corrosion (by the acidic liquid electrolyte) of the carbon components, primarily the carbon support for the catalyst layer and the separator (or bipolar) plate, causes reduced cell life in PAFCs. Other factors that affect PAFC performance decay are sintering of platinum particles and electrolyte flooding, both due to changes in material properties at elevated temperatures.

PAFCs are the only fuel cell to consistently achieve demonstrated lifetimes of 40,000 hours or better under production conditions. Field units have been operated at ambient temperatures of –32°C to 49°C and altitudes of one mile. Additionally, the PC25 units operating in California have been exempted from the air pollution permitting process because their emissions have been so low.

PAFCs achieve electric efficiencies between 37–42 percent (lower heating value), employ high cost platinum electrocatalysts, and require external reformers to produce a hydrogen-rich gas feed from a hydrocarbon feedstock. The near 200°C operating temperature of PAFCs is sufficient to provide low-grade thermal output in the form of 140°–250°F hot water or low-pressure (15 psi) steam. Use of the thermal output for cogeneration applications, such as hotel, hospitals, and schools, is particularly attractive.

In comparison with other fuel cell types, the electrical efficiency of PAFCs is low. This disadvantage is offset by their tolerance to fuel contaminants, cogeneration potential, and technology readiness.

Target Markets and Manufacturers

PAFC developers are targeting commercial sector applications where waste heat can be used. These applications include hospitals, hotels, schools, and high value commercial buildings requiring high power quality or premium power services. The potential U.S. market is estimated at 10–125 MW/year if the installed costs of PAFCs can be reduced to $1500–$2000/kW. The market increases to 250 MW/year if the cost is brought down to $1000/kW (Rastler et al, 1996).

PAFC development historically included transportation applications, such as transit buses. However, due to the rapid advancements of PEMFCs, PAFCs are not likely to compete in light and medium duty vehicular transportation. Future applications for PAFCs may be found in marine, locomotive, or space applications.

ONSI Corporation, a subsidiary of International Fuel Cells Corporation (IFC), is the only U.S. PAFC developer. Foreign PAFC developers include Fuji Corporation, Mitsubishi Electric Co., and Toshiba Corporation. Ansaldo in Europe has obtained licensing rights from ONSI to sell and eventually build 200 kW units (Rastler et al, 1996).

Status of Development and Commercialization

Of all the fuel cell types, PAFC technology is most developed. There are no technical hurdles to a viable PAFC product since the technology has been “commercial” for about five years. IFC has been selling (with Department of Defense subsidies) 200 kW packaged, PAFC cogeneration units since about 1993 and has filled about 160 orders, with over 130 units operating in the field (Scheffler et al, 1998). ONSI claims that in over two million hours of total operation, their PAFCs have demonstrated better than 95 percent reliability and a mean time between forced outage of 2200 hours—a figure that bests onsite, diesel-powered generators (Hall et al, 1998).

However, costs are still two to three times higher ($3000/kW or $4000/kW installed) than the commercial market will sustain. Thus, the only hurdle to the complete commercialization of PAFCs is cost reduction. To achieve 50–65 percent cost reductions, developers need higher sales volumes and design improvements in the power plant itself. Costs associated with every element of the power plant must be reduced—including fuel processor, cell-stack design, power conditioning and control, and ancillary components (Penner, 1995).

Molten Carbonate Fuel Cells (MCFCs)

MCFCs are high temperature fuel cells that offer several advantages for onsite or utility-scale power generation. They produce high quality waste heat that can be used for fuel processing and cogeneration, internal methane reforming, and conventional production of electricity. The waste heat is of sufficient temperatures to produce high pressure steam for industrial processes. Developers are targeting commercial markets such as hotels, schools, small to medium sized hospitals, and shopping malls, as well as industrial applications (chemical, paper, metal, food, and plastics) for onsite power generation.

Construction Materials, Cell Operation, and Performance

MCFCs are a liquid electrolyte-based fuel cell that makes use of flat, planar-configured fuel cell stacks. MCFCs typically consist of a lithium-potassium or lithium-sodium based electrolyte. After the cathode reaction, carbonate ions migrate through the electrolyte to the anode side of the cell to complete the fuel oxidation. Because of the carbon dioxide requirement at the cathode, and production of it at the anode, carbon dioxide must be transferred from the anode exhaust to the cathode inlet. This is normally accomplished through mixing of the anode exhaust with incoming air or by physically separating the carbon dioxide from the other exhaust gas species through a "product exchange device" (Srinivasan et al, 1993).

At 650°C (1200°F), the operating temperature of MCFCs is substantially higher than that of PEMFCs or PAFCs. The higher operating temperature enables internal reforming of hydrocarbon fuels, improving system design and efficiency. Additionally, the elevated operating temperature, combined with fast electrode kinetics, eliminates the need for expensive noble metal electrocatalysts and results in the highest electric efficiency of all fuel cell types. MCFCs have a verified efficiency of up to about 44 percent and developers expect efficiencies to reach 50 to 60 percent (LHV).

MCFCs can operate on several fuel types since carbon monoxide is not poisonous to it. MCFCs have operated on reformed or synthetic natural gas and synthetic coal gas. Developers anticipate that MCFCs will also be capable of operating on ethanol, landfill gas, and military logistic fuels (JP-8 and diesel).

The disadvantage of MCFCs' high operating temperature is that the molten carbonate electrolyte makes for a more corrosive environment. Therefore, the materials used in MCFCs must withstand high operating temperatures and resist corrosion. Cell materials that demonstrate the necessary corrosion stability at reasonable costs have been primarily stainless steel alloys, ceramic composites, and semiconducting oxides.

A major technical challenge remaining in the development of MCFCs is extending the cell life to 40,000 hours. Cathode dissolution in the electrolyte, electrolyte management, and hardware corrosion are the major barriers to long cell life for MCFCs.

Target Markets and Manufacturers

U.S. MCFC developers are targeting commercial product size ranges between 250 kW to 3 MW. The leader in MCFC technology is Energy Research Corporation (ERC) in Danbury, Connecticut, followed by MC-Power in Burr Ridge, Illinois. Both manufacturers are currently in the later stages of demonstrating their respective technologies. Early production units are expected to be available beginning in the 2001–2002 timeframe.

Table 4: North American manufacturers of MCFCs (adapted from Rastler et al, 1996)

Manufacturer	Technology	Product size	Markets
Energy Research Corporation (ERC)	Externally manifolded (1 atm operation)	300 kW–2.5 MW	Commercial, light industrial, distributed power, niche, transportation (marine)
MC-Power	Internally manifolded (1–3 atm operation)	250 kW– 1 MW	Commercial, light industrial, distributed power, niche

Foreign MCFC developers include Hitachi Ltd., Ishikawajima-Harima Heavy Industries, Mitsubishi Electric Company in Japan, and BCN (Brandstofel Nederland) in the Netherlands.

Status of Development and Commercialization

MCFCs are poised to enter the commercial market as early as 2000. Both ERC and MC-Power have several demonstration plants planned for 2000. In order to penetrate the commercial markets they've targeted, developers need to address the following issues:

1. High power density (and small plant footprint). This is a must for commercialization. Developers have set power density goals of 0.18 to 0.225 W/cm^2 to reduce cost and plant footprint (Penner, 1995).

2. Cell life. Nickel oxide (cathode) dissolution in the electrolyte, electrolyte management, and hardware corrosion protection are the three major factors in establishing long life characteristics in MCFCs.

3. Cost reduction. Developers need to achieve production volumes of 200–400 MW/year to drive manufacturing costs down to $200–400/kW.

4. Systems integration and thermal management

5. Reliability and durability of stacks

Solid Oxide Fuel Cells (SOFCs)

SOFC technology can potentially span all of the traditional power generating markets (residential, commercial, industrial/onsite generation, and utility) but is likely to penetrate niche markets first, such as small portable generators and remote or premium power applications. There are two different SOFC geometries being developed: tubular and planar. The tubular design is the most advanced and is slated for large commercial and industrial cogeneration applications and onsite power generation. The planar design will serve smaller markets (less than 300 kW). SOFCs could be commercially available as early as 2002.

Construction Materials, Cell Operation, and Performance

SOFCs employ a solid state electrolyte and operate at the highest temperature (1000°C/1800°F) of all fuel cell types. The SOFC uses a solid yittra-stabilized zirconia ceramic material as the electrolyte layer. In general, the solid phase design is simpler than PAFCs or MCFCs since it requires only two phases (gas-solid) for the charge transfer reactions at the electrolyte-electrode interface. The two-phase contact simplifies the design because it eliminates corrosion and electrolyte management concerns commonly associated with the liquid electrolyte fuel cells (Murugesamoorthi et al, 1993). During operation, oxidant (usually air) enters the cathode compartment and, after the electrode reaction, oxygen ions migrate through the electrolyte layer to the anode where hydrogen is oxidized. The operating temperature of SOFCs is sufficiently high to provide the necessary heat for the endothermic reforming reaction. SOFCs, therefore, are more tolerant of fuel impurities and can operate using hydrogen and carbon monoxide fuels directly at the anode. They don't require costly external reformers or catalysts to produce hydrogen. The relative insensitivity of SOFCs to gas contaminants normally considered "poisons" to lower temperature fuel cells makes them especially attractive for unconventional fuels, such as biomass or coal gasification.

SOFCs also have the potential for high system efficiencies. When integrated with a gas turbine (SOFC-GTs), SOFC systems are expected to achieve 70–75 percent (LHV) electric efficiencies, representing a significant leap over all other energy technologies. Additionally, developers expect commercial SOFCs to have lifetimes of 10 to 20 years, two to four times longer than other fuel cells.

The disadvantage of the SOFCs high operating temperature is the stringent materials requirement for the critical cell components. Exotic ceramics, metal-ceramic composites, and high temperature alloys drive up the cost of SOFCs, as do the manufacturing techniques demanded by these materials (electrochemical vapor deposition, sintering and plasma spraying). Because of the stringent materials requirement and demanding manufacturing techniques, developers are exploring ways to reduce the operating temperature of SOFCs to the 700–900°C range.

Target Markets and Manufacturers

Tubular designs are more costly than planar geometry SOFCs. Both technologies are making headway, but the tubular design is closer to commercialization. Siemens Westinghouse, the leader in SOFC technology, is pursuing the tubular design. However, the high costs for tubular designs have helped to stimulate research interest in SOFC planar technology. SOFCo (a limited partnership between Ceramatec and McDermott Technology), Honeywell (AlliedSignal), Ztek, and TMI (Technology Management, Inc.) are the North American manufacturers pursuing planar technology.

Table 5: North American manufacturers of SOFCs (adapted from Rastler et al, 1996)

Manufacturer	Technology	Product size	Market(s)
Siemens Westinghouse	Tubular (1000°C)	1–5 MW (initial)[†] < 50 MW (long-term)	Large commercial & industrial cogeneration, distributed generation
SOFCo	Flat Planar (700–800°, 1000°C)	10– 50 kW	Commercial HVAC
Ztek	Radial planar (1000°C)	25–50 kW 250–300 kW	Commercial HVAC Commercial cogen[‡]
Honeywell (Allied Signal)	Flat & radial planar (600–800°C)	Small portable (500 W), large commercial?	Portable power, commercial SOFC-GT
TMI	Radial Planar (700–800°, 1000°C)	20–100 kW	Commercial HVAC
Global Thermoelectric	Flat Planar (700-800°)	1-150 kW	Remote, residential, commercial

† Siemens Westinghouse SureCell SOFC initial entry will be a 1.3 MW unit, but a smaller 300 kW may also be sold in international markets .

‡ Ztek's 250 kW generator unit is expected to be comprised of an SOFC integrated with a gas turbine.

Unique among fuel cell types, SOFCs provide a nearly perfect match with small gas turbines. When integrated with these turbines, SOFCs can potentially obtain electric efficiencies of 70 percent (LHV) or greater and offer the additional benefit of a small footprint. These performance and size characteristics give SOFC-GT systems a large market potential if cost reduction targets can be obtained. Early market customers include rural electric generating and transmission utilities, remote power applications (where the cost of transmission and distribution installation is exorbitant), and low emission regions such as southern California.

Status of Development and Commercialization

Current state-of-the art SOFC technology has demonstrated satisfactory efficiency and life performance. To date, Siemens Westinghouse has demonstrated 1 kW, 25 kW, 100 kW, and 250 kW tubular SOFCs and plans on releasing commercial 1–5 MW plants by 2002.

Relative to the other fuel cell types, however, SOFC development is especially dependent on materials research and manufacturing processes. The development of suitable low-cost materials and fabrication techniques represents a significant challenge for SOFCs (Hirschenhofer et al, 1998). For example, sintering is a high temperature process that adds production complexity and cost. The materials may cost $7–$15/kW, but manufacturing can drive this to $700/kW for the stack (Minh, 1991; Frist, 1992; Halpern et al, 1992). Additionally, because many geometric configurations can be developed from SOFCs' solid components, developers are proceeding in several different directions. As planar SOFC technology matures, some design conformity will eventually result, as previously occurred with PAFC and MCFC development (Hirschenhofer et al, 1998). Planar technology, while not as advanced as the tubular design, has a shorter development path; it is targeting commercial release by 2002. Most planar SOFC technologies are below 200 kW and developers are initially targeting commercial HVAC applications in the 25–100 kW size range.

If manufacturing cost targets are achieved, SOFC systems are likely to be one of the cheapest fuel cell technologies, available at $800–$1000/kW.

Development issues common to tubular and planar SOFCs include:

1. Developing lower cost, reliable manufacturing techniques for cell components

2. Establishing quality assurance criteria (non-destructive evaluation techniques to detect manufacturing flaws in cell and stack components)

3. Refining the thermal management of stack heat flows (air cooling, internal reforming, etc.)

4. Studying systems applications to best integrate and take advantage of the new technology

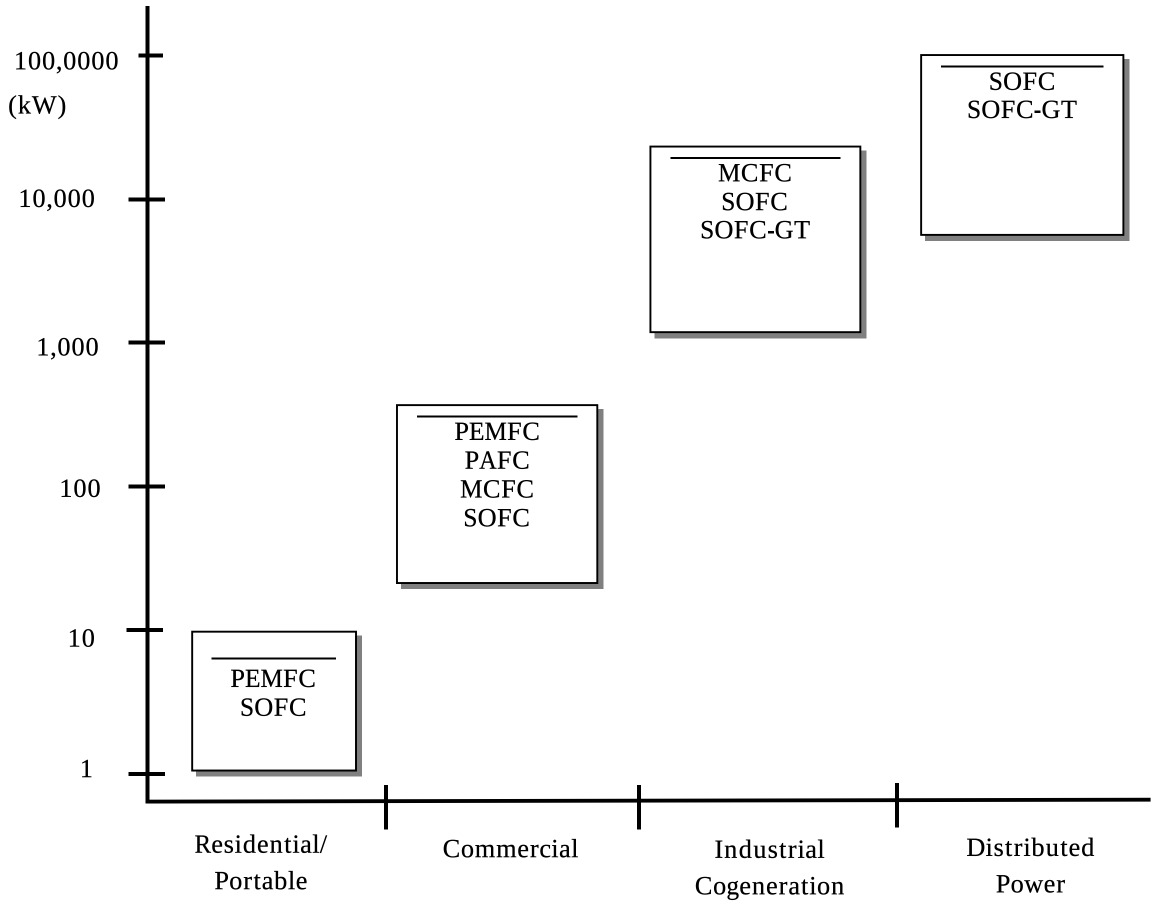
5. Developing new and/or improved materials, including

    - Contaminant tolerant fuel electrodes
    - Improved interconnect materials (stability and conductivity over range of O_2 partial pressures)
    - Establishment of physical and mechanical properties of the cell and stack components versus temperature for design and modeling of stack performance

Prospective Markets and Applications

The following figure shows the market sectors and the kW ranges of the various fuel cell technologies.

Figure 5: Fuel cell market sectors (adapted from Rastler et al, 1996)



PEMFC = Proton exchange membrane fuel cell

SOFC = Phosphoric acid fuel cell

MCFC = Molten carbonate fuel cell

SOFC = Solid oxide fuel cell

SOFC-GT = Solid oxide fuel cell with gas turbine

Commercial Applications

Fuel cells for the small commercial market will supply power in the range of 25 kW to 500 kW. All fuel cell types can serve this market, which includes hotels, schools, small to medium sized hospitals, office buildings, and shopping malls. The higher temperature fuel cells will operate in a cogeneration mode, supplying heat and electricity.

Ballard Power is developing a 250 kW natural gas-fueled PEMFC unit for stationary power and plans to commercialize it by 2001. International Fuel Cell Corporation has developed the only commercially available fuel cell power plant, the PC-25C, a 200 kW, packaged cogeneration system. The advantage of the PC-25C (PAFC technology) is that it may be more efficient than PEMFC technology and more suitable for cogeneration. However, PEMFCs may cost less if they are commercialized in both stationary and transportation markets.

Two developers, ERC and MC-Power, are planning 250 and 300 kW MCFC systems, respectively. These systems may be highly efficient, but their larger footprint will limit where they can be used. Several manufacturers are developing SOFCs, which are efficient and have power densities that allow smaller plant footprints than MCFCs. Once mature, SOFCs are also expected to be less expensive than the other fuel cell types.

Fuel cells will compete in the commercial sector, not only among themselves, but also with other emerging technologies such as microturbines.

Industrial Applications

Fuel cells for the industrial market will supply power in the range of 1 MW to 25 MW. High temperature fuel cells (MCFCs and SOFCs) will serve this market, which includes the chemical, paper, metal, food, and plastic industries. The first fuel cells for this market will be small (<5 MW) but greater generating capacity will evolve as the market develops and costs are reduced.

Distributed Generation

The Electric Power Research Institute (EPRI) defines distributed generation as the “integrated or stand-alone use of small modular resources by utilities, utility customers, and third parties in applications that benefit the electric system, specific customers, or both.” (EPRI, 1998) It is synonymous with onsite generation and cogeneration.

Fuel cells for the distributed power market segment will supply power in the range of 3 MW to 100 MW. High temperature fuel cells (MCFCs and SOFCs) will serve this market, which includes traditional utilities, unregulated subsidiaries, municipal utilities, and energy service providers. Fuel cells for this market may be integrated with coal gasification after the year 2015.

The energy industry is changing to compete in a deregulated market. In order to take advantage of new technologies, meet growing energy demand, and meet stringent emission requirements, distributed generation technology is becoming a more viable option. The traditional electric utility perspective has been that large central power plants, because of their economies of scale, will continue to provide the vast majority of electric power in the U.S. for the foreseeable future (Leeper and Barich, 1998). However, many utilities (for example, Unicom and Southern California Edison) are investing in alternative generation technologies to meet future energy demands. As the market for distributed power technology matures, the cost of electricity from distributed power generation will decrease and offer many benefits that centralized utilities cannot match. Some of the often-stated advantages of distributed generation include:

1. Economy power or "peak-shaving," which allows the customer to take advantage of time-of-day pricing, effectively leveraging fuel costs against electricity prices

2. Cogeneration

3. Premium power—uninterrupted power supply and high power quality

4. Little or no transmission and distribution (T&D) expansion costs

5. Utilities can meet energy demand incrementally with a lower cost, lower risk investment—essentially enabling a "just-in-time" philosophy.

6. Niche markets—such as developing countries or remote locations where there is little or no existing T&D infrastructure and limited fuel options—could be served better.

Residential Applications

Fuel cells for the residential market will supply power in the range of 1 kW to 10 kW. PEMFCs and SOFCs operating (initially) in electric-only configurations are likely to serve single and multi-family residences.

Other Applications

Additionally, fuel cells may be appropriate for niche markets such as computer centers or other customers who require premium power quality and high reliability. There also may be a market for fuel cells in the field of renewable or "opportunity" fuels such as landfills, waste water treatment plants, and refineries.

Competing Technologies

There are many technologies competing with fuel cells, particularly in the distributed generation market (3kW–50MW). The following table shows the technologies and markets in which fuel cells will compete. The size ranges given for each technology are approximate since distributed generation technology is modular and the economics of each site will determine the number of units or mix of technologies that will be used. The markets listed in the last column reflect current targets and expectations.

Table 6: Distributed generation technology (adapted from Rastler et al, 1996)

	Types	Size	Efficiency	Markets
Fuel cells	PEM (80°C)	1–500 kW	40%	L&MT, residential, PP, RP
	PAFC (200°C)	50 kW–1.2 MW	40%	MT, commercial cogeneration, PP
	MCFC (650°C)	1–20 MW	55%	HT, PP
	SOFC (1000°C)	1 kW–25 MW	45–65%	Residential, commercial cogeneration, PP, RP
Engines	Diesel	50 kW–6 MW	33–36%	SP for commercial and small industrial, T&D support,
	Internal combustion—natural gas	5 kW–2 MW	33–35%	PP and commercial cogeneration
	Stirling cycle	1–25 kW	20%	Residential, RP
Combustion turbines	Microturbines	25–500 kW	26–30%	SP, RP, commercial cogeneration
	"Small" turbines	1–100 MW	33–45%	Industrial cogeneration, T&D support
Renewables	Solar (PV)	1–1000 kW	10–20%	RP, peak shaving, power quality, green power
	Wind			RP, peak shaving, green power
	Biomass			

"Small" turbines include cascaded humidified air turbines, advanced turbine systems, and intercooled aeroderivative cycle.

Efficiencies = electric only (no heat recovery, HV basis unknown); PV efficiency is sunlight to AC power.

L&MT—Light and medium duty transportation applications (e.g., automobiles, trucks, buses)

MT—Medium duty transportation applications (e.g., trucks, buses)

HT—Heavy duty transportation applications (e.g., rail, marine—ships, naval vessels)

PP—Premium Power

RP—Remote Power

SP—Standby Power

Market Segmentation and Drivers

Table 7 shows a breakdown of the markets for fuel cells and their competing technologies.

Table 7: Markets for fuel cells and competing technologies

Residential (1–15 kW)	Light commercial (25–250 kW)	Commercial w/cogeneration (50 kW–3 MW)	Industrial & distributed (3–50 MW)
PEM	PEM	PAFC	MCFC
SOFC	PAFC	MCFC	SOFC
Solar PVs	SOFC	SOFC	Gas Turbines
Stirling Engines	Solar PVs	IC Engines	Wind Turbines
	IC Engines	Microturbines	
	Microturbines		
	Stirling Engines		

The most significant competition, both among fuel cell types and with other technologies, occurs in the light commercial sector. Fuel cells, PV, engines, and microturbines are all expected to be viable options. Light commercial markets are likely to have some cogeneration needs as well.

The residential sector seems likely to be dominated by fuel cell and solar technology. At the other end of the spectrum, gas turbines will most likely be the dominant technology in the industrial sector, with some competition from higher temperature fuel cells. Hybrid power generating systems incorporating fuel cells with microturbines are also possible in this sector.

Conclusions

Current worldwide electric power production is based on a centralized, grid-dependent network structure. This system has several disadvantages such as high emissions, transmission losses, long lead times for plant construction, and large and long term financing requirements (Blomen and Mugerwa, 1993). Distributed generation is an alternative that is gathering momentum, and modern technologies, such as fuel cells, are likely to play an increasing role in meeting ever-increasing power demands.

Fuel cells have many advantages over conventional power generating equipment: high efficiency, low emissions, siting flexibility, high reliability, low maintenance, excellent part-load performance, modularity, and multi-fuel capability. Because of their efficiency and environmental advantages, fuel cell technologies are viewed as an attractive 21st century solution to energy problems. And given the near zero supply of fuel cells (PAFCs are the only currently available commercial product), the demand is high. Several different types of fuel cells are suitable for applications in the commercial market and will compete with one another. However, it is difficult to predict the success of one fuel cell type versus another given their immature development and commercialization, high cost, and uncertainties in cell performance.

Some negative aspects of fuel cell power include short operating life, high equipment costs, and lack of field experience. In addition to these technological and cost barriers, there are external market forces that will affect fuel cells as well. These market forces include federally regulated emission standards and, in the U.S., the deregulation of the energy industry. Emissions standards could have a positive influence on fuel cell commercialization. For example, in tightly regulated emissions zones, such as California, fuel cell systems may be mandated even though their capital costs currently exceed those of other competing technologies. In contrast, the deregulation of the power industry could have a negative impact on fuel cell commercialization. Electric and gas utilities traditionally have helped pioneer new technologies but may be reluctant to champion high risk options such as fuel cells when they must compete with lower cost energy suppliers for their customers. Despite this, fuel cells have a wide range of applications that can allow them to succeed in several markets.

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Appendix A: Fuel Cell Primers

Basic

There are a few sources of basic information on fuel cells. The resources listed below are a good starting point if you want to learn how fuel cells work and what applications they can be used for.

Web Sites

Fuel Cells 2000 Web Site: www.fuelcells.org

> This site is an on-line fuel cell information center that explains how fuel cells work, the types of fuel cells that are being developed and the benefits of fuel cells. There is a section of "Frequently Asked Questions" and a gallery of fuel cell pictures. There are links to the major fuel cell developers and to other sites with fuel cell information.

Federal Energy Technology Center: www.fetc.doe.gov

> FETC implements the Department of Energy/Fossil Energy's Fuel Cell Program. They have published a brochure that describes how fuel cells work, the development status of fuel cells, and the market for fuel cells in the U.S. The brochure can be download from their site (go to "Publications" and select the fuel cell brochure).

Print Resources

The Future of Fuel Cells (1999) by A.J. Appleby, A.C. Lloyd and C.K. Dyer.

> This is a collection of three articles that appeared in a special section of the July 1999 issue of *Scientific American*. The series provides a general overview of how fuel cells work and how they might be used in the near future. "The Electrochemical Engine for Vehicles" describes fuel cells that power buses and cars, "The Power Plant in Your Basement" looks at fuel cells that could provide power for your home, and "Replacing the Battery in Portable Electronics" discusses the fuel cell that could replace the battery in your laptop computer.

Advanced

There are several sources of more technical or in-depth information on fuel cells, as well as organizations that promote fuel cells and/or renewable energy. Some of these resources are listed below.

Web Sites

American Hydrogen Association: www.clean-air.org

The American Hydrogen Association (AHA) is a non-profit organization dedicated to the advancement of inexpensive, clean and safe hydrogen energy systems.

Department of Defense Fuel Cell Demonstration Program: www.dodfuelcell.com

The DoD's demonstration program is designed to stimulate growth and economies of scale in the fuel cell industry and to determine the role of fuel cells in the DoD's long-term energy strategy.

Fuel Cell Commercialization Group: www.ttcorp.com/fccg

The FCCG's mission is to commercialize carbonate fuel cells for power generation. FCCG members are electric and gas utilities and other energy users that have recognized the opportunity and the value of early involvement in the development and commercialization of this very promising technology.

Fuel Cell Laboratory at Kettering University: www.gmi.edu/~altfuel/femain.htm

The FCL's purpose is to produce more efficient and less costly designs for all facets of fuel cell implementation. The program also provides students and faculty with knowledge and hands on experience with the future of electrical power production.

National Fuel Cell Research Center at the University of California-Irvine: www.nfcrc.uci.edu

The NFCRC promotes and supports the fuel cell industry by providing technological leadership through program of research, development and demonstration.

US Fuel Cell Council: www.usfcc.com

The US Fuel Cell Council is an industry association dedicated to fostering the commercialization of fuel cells in the United States.

World Fuel Cell Council: www.fuelcellworld.org

The WFCC serves as a communication center for fuel cell commercialization activity worldwide. The site provides links to fuel cell manufacturers and other fuel cell organizations.

Print Resources

Biomass Fuel Cell Power for Rural Development: Creating Options for Rural Communities in a Deregulated Electric Utility Market (1997) by Energy Research Corporation.

Ethanol Fuel Cells for Efficient Power Generation From Biomass—Final Report (1994) by P. Patel. The National Rural Electric Cooperatives Association (NRECA) also published this report as “Ethanol Fuel Cells for Rural Power Generation.”

Fuel Cell Handbook 4th edition (1998) by J.H. Hirschenhofer et al U.S. Department of Energy, Office of Fossil Energy, Federal Energy Technology Center, Morgantown, VA. This handbook is available on CD Rom from the FETC.

Fuel Cell Systems (1993) by Leo J. Blomen, Michael N. Mugerwa (Editor). This multiauthored report provides state-of-the-art overviews of research and development activities on each type of fuel cell with a more general system approach toward fuel cell plant technology, including plant design and economics.

Powering the Future: The Ballard Fuel Cell and the Race to Change the World (November, 1999) by Tom Koppel. This book tells the story of Ballard Power Systems journey to develop and commercialize a fuel cell that could compete with the internal combustion engine and provide a nonpolluting energy source for cars and buses.

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