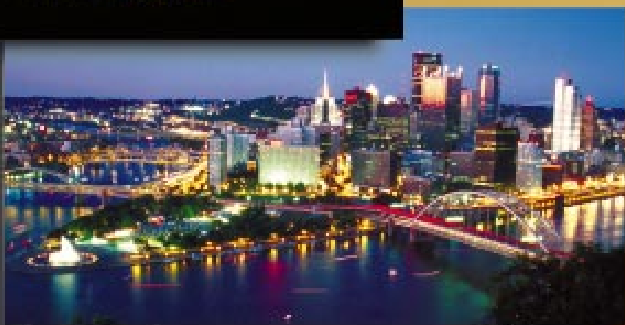
U.S. Department of Energy • Office of Fossil Energy
Federal Energy Technology Center

Fuel Cells



Opening New Frontiers in Power Generation

FETC

Fuel cells initially found application in space exploration, opening new frontiers by virtue of their inherently clean, efficient, and reliable service. Now efforts by the Department of Energy's Federal Energy Technology Center, in partnership with industry, are bringing fuel cell costs down and opening new frontiers in the power generation industry.

Fuel cells have the potential to truly revolutionize power generation. Fuel cell systems have few moving parts, making them reliable and quiet as well. No solid wastes are produced and pollutant emissions are negligible. The potential electrical efficiencies can reduce carbon dioxide emissions by 50 percent relative to existing power plants. Moreover, their modular construction and electrochemical processing allow suppliers to match demand over a range of several kilowatts to a hundred megawatts and to maintain efficiency independent of size.

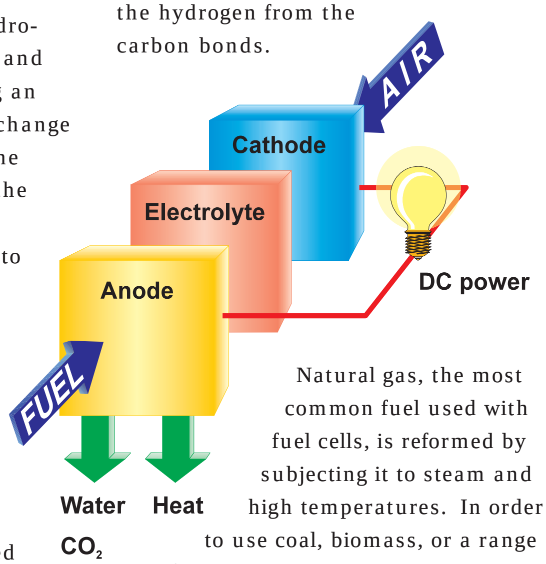
FUEL CELLS—A Revolutionary Technology

How Fuel Cell Systems Work

Fuel cells produce power electrochemically by passing a hydrogen-rich gas over an anode and air over a cathode, and introducing an electrolyte in between to enable exchange of electrical charges called ions. The natural propensity of hydrogen in the fuel gas to react with oxygen in the air causes one or the other stream to become charged, or ionized. The flow of ions through the electrolyte induces an electric current in an external circuit or load. The effectiveness of this process is strongly dependent upon the electrolyte to create the chemical reactivity needed for ion transport. As a result, fuel cells are categorized by the type of electrolyte. The anode and cathode typically use catalytic materials to enhance reactivity.

The products of the electrochemical conversion are heat, carbon dioxide (CO_2), and water. No solid waste is produced. Very low levels of nitrogen oxides are emitted, but usually in the undetectable range. The process heat can be applied to useful purposes to further enhance efficiency. The CO_2 emissions are relatively low because of high efficiency, and are in concentrated form, facilitating capture.

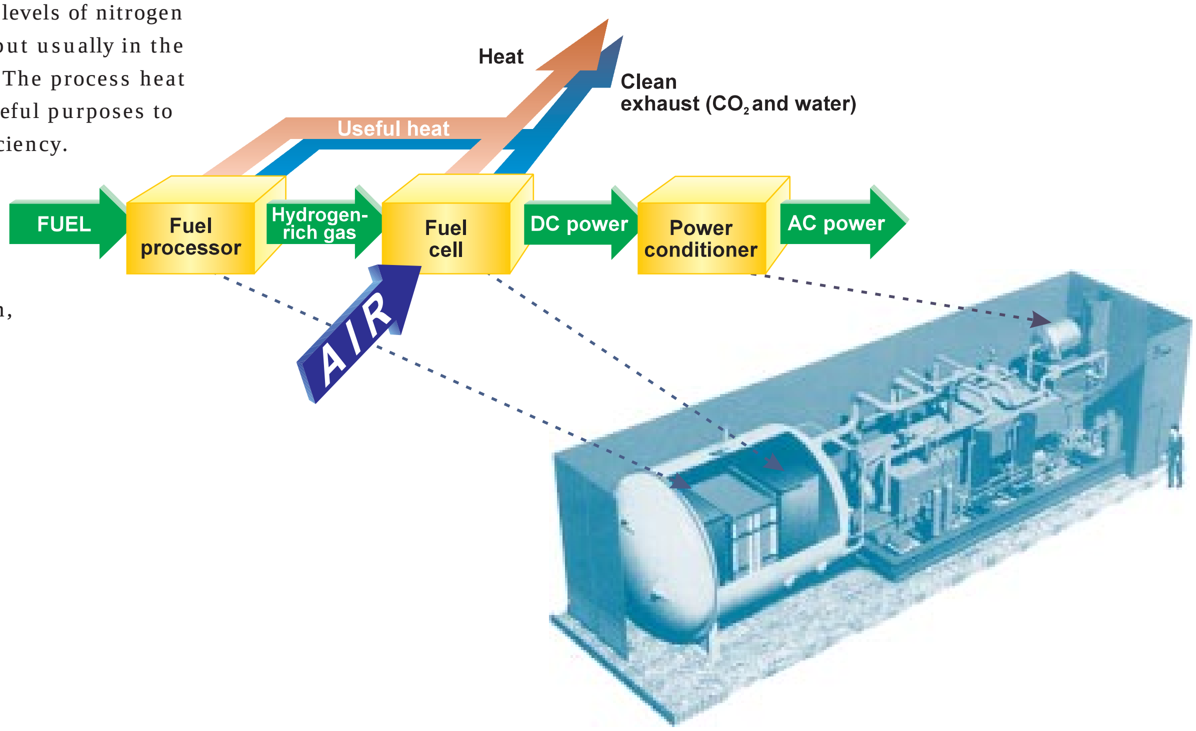
Fuel cells have tremendous feedstock flexibility. Any hydrocarbon material can be used, whether gas, liquid, or solid. These materials must, however, undergo "reforming" to free the hydrogen from the carbon bonds.



Natural gas, the most common fuel used with fuel cells, is reformed by subjecting it to steam and high temperatures. In order to use coal, biomass, or a range of hydrocarbon wastes, a similar process is applied, called gasification. But these more complex fuels require a clean-up step to remove pollutants that could otherwise poison the fuel cell elements.

Fuel cell systems also require a power conditioner to convert direct current from the fuel cell to the more commonly used alternating current.

A single cell typically produces 0.5 to 0.9 volts. These cells are stacked together and electrically connected in series to build up voltage and power delivery capability. Plants can be built to a customer's specific requirements from one to hundreds of kilowatts now, and eventually hundreds of megawatts. Fuel cells convert a remarkably high proportion of the chemical energy in fuel to electricity, making them very efficient. The electrochemical conversion also makes fuel cell efficiency largely insensitive to the size of the unit or the amount of load applied.



Fuel Cells—The Right Technology . . .

The emergence of fuel cells comes at an opportune time. An unprecedented expansion in electricity need is forecasted, retail electricity deregulation (utility restructuring) is underway, and public environmental policy is placing a premium on efficiency and environmental performance.

Meeting Electricity Needs

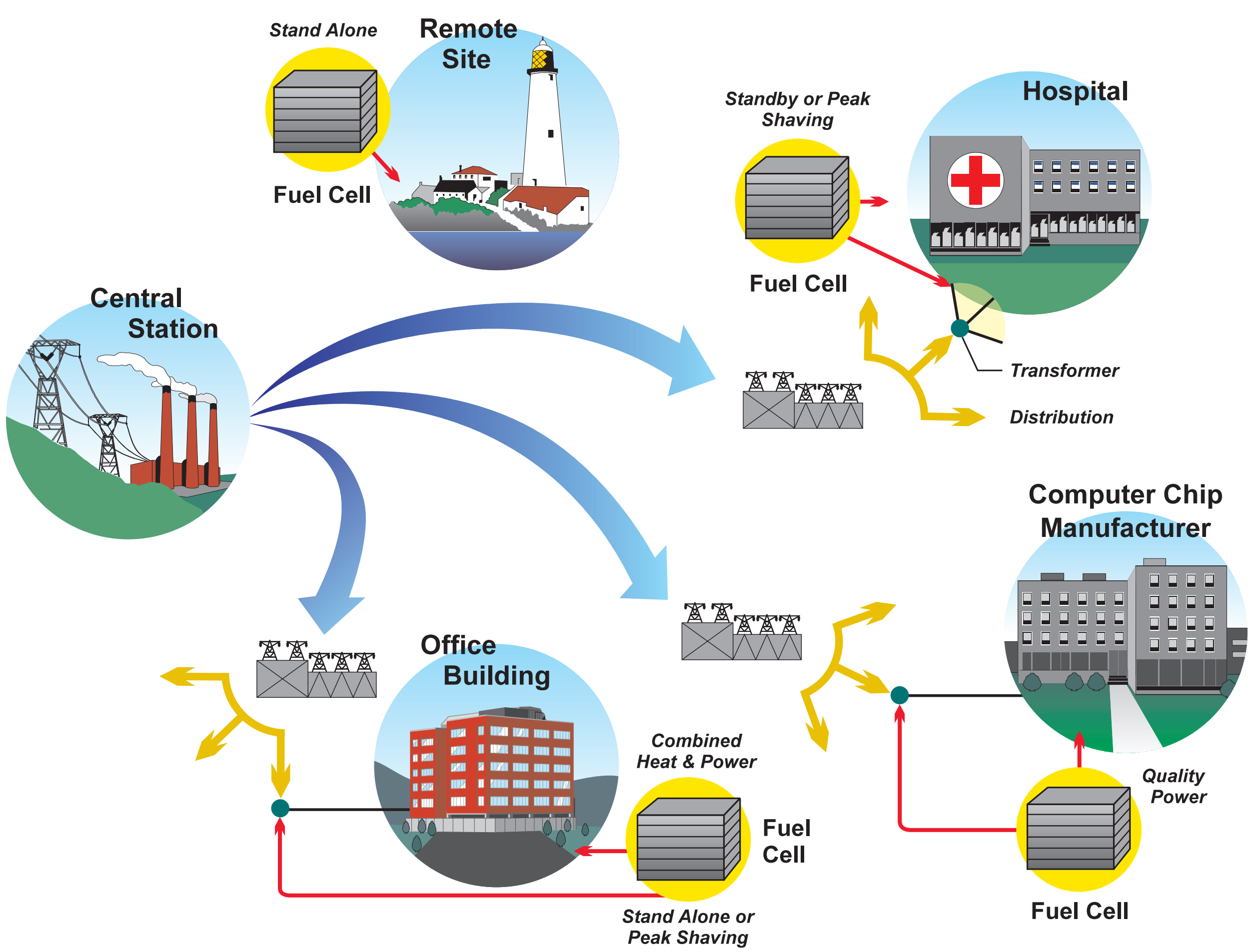
Domestically, there is a projected need for as much as 1.7 trillion kilowatt-hours of additional electric power over the next two decades, almost twice that of the past 20 years. The magnitude of this growth will severely strain many existing transmission and distribution (T&D) systems, precipitating capacity constraints. Upgrading T&D systems is extremely costly and time consuming.

Fuel cells are ideally suited to relieve T&D pressures by placing power at or near customer sites, which is called distributed generation. Power can be located near a substation to relieve transmission, or at user sites to relieve distribution.

Efficiency can be significantly enhanced in on-site applications by using fuel cell process heat to: (1) heat facilities (combined heat and power), (2) generate steam for industrial processes (cogeneration), or (3) generate steam for electricity generation.

On-site applications include: (1) relying solely on on-site power with no grid connection—stand-alone; or (2) using on-site power during periods of peak grid load and providing power back to the grid during off-peak periods—peak shaving. Siting fuel cells is relatively easy with their small footprint, low noise levels, and lack of emissions.

Fuel Cell Applications



Alleviating Risk

Utility restructuring shifts the burden of financing energy ventures from consumers to power suppliers, favoring less capital-intensive projects and projects requiring less time for permitting and construction.

The modular nature of fuel cells enables energy suppliers to match capacity with specific load requirements, avoiding the high costs of large new plants and the potential for underutilized capacity. The absence of emissions significantly reduces permitting time, usually a major time requirement in scheduling electricity generating operations. In addition, shop fabrication on a mass-assembly basis shortens installation time.

Providing Reliable Quality Power

Uncertainties associated with utility restructuring have exacerbated concerns over the reliability and quality of electric power delivery. Reserve margins are shrinking as energy suppliers increase capacity factors on existing plants rather than install new capacity to meet growing demand. This increases the probability of forced outages and reduced power quality.

On-site fuel cell installation ensures reliable service, eliminates the voltage spikes and harmonic distortion typical of grid power, and tailors the power delivery for the most sensitive electronic equipment.

Addressing Environmental Concerns

U.S. source emission standards are tightening for sulfur dioxide (SO_2), oxides of nitrogen (NO_x), and particulate emissions. More importantly, ambient air quality standards impose requirements that translate to near-zero tolerance for additional emissions as most regions of the country strive to come into compliance with existing capacity. Public policy, reflecting concern over global climate change, is providing incentives for capacity additions that offer high efficiency and use of renewable resources.

Fuel cell emissions are negligible, and as a result, systems have been installed in some of the most environmentally sensitive areas without ramifications. Blanket environmental permitting exemptions have been issued in California and Massachusetts. In addition, their high efficiency has resulted in fuel cells being adopted by a presidential Climate Change Action Plan. As part of the plan, the resultant U.S. Climate Change Fuel Cell Program provides rebates to accelerate fuel cell commercialization.

Leveraging the Global Market

Worldwide forecasts show electricity consumption nearly doubling over the next two decades, largely due to growth in developing countries without nationwide power grids. Public dissatisfaction in urban population centers of these developing countries is beginning to precipitate environmental standards, but this will only become an economic driving force in the long-term. There are, however, an estimated 2-billion people in rural areas without access to a power grid who are demanding electricity. Industrialized countries like the United States face the same pressures to lower pollutant emissions and stabilize carbon emissions as energy requirements increase to support economic growth.

Fuel Cells— The Technology of Choice

- Negligible emissions
- High efficiency
- Cogeneration options
- Modularity
- Distributed and centralized configurations
- Uninterruptible power
- Fuel flexibility
- Public acceptance
- Incremental power additions
- Low noise/small footprint
- Useful heat
- Siting flexibility
- Premium power quality

In the urban sector of developing countries, fuel cells have near-term sales potential in the rapidly growing industrial sector and critical public service applications where a premium is placed on reliable, quality power delivery. The fuel flexibility afforded by fuel cells opens up the possibility of lowering project costs through use of fuels derived from municipal, agricultural, forestry, or refinery wastes (opportunity fuels). For rural regions currently without access to commercial power, fuel cells are an attractive option, particularly where opportunity fuels exist, such as landfill gas, anaerobic digestor gas, and other waste gas. Fuel cells have tremendous potential in industrialized countries outside of the United States for the same reasons outlined for domestic use.

Domestic Opportunities

Domestically, an estimated 363 gigawatts of capacity will be required by 2020 to meet new demand and to replace lost capacity from plant retirements. Under utility restructuring, distributed generation is expected to capture a considerable portion of the market. This projected market capture is the result of energy suppliers shouldering the financial risk of capacity additions, customers concerned about reliability and power quality, and increased T&D traffic. One assessment indicates a requirement of 5-6 gigawatts per year over the next decade. Fuel cells are ideal for distributed generation given their ability to match demand, operate efficiently, produce near-zero pollutant emissions, and facilitate permitting and installation.

On-site markets are targeted for early entry as a proving ground for natural gas-fueled plants of 200 kW to 20 MW. Fuel cell attributes can be leveraged in these markets to support higher prices. Commercial building applications can support the highest fuel cell price and represent important long-term potential for fuel cells, particularly with the emergence of energy management service companies.

As fuel cell costs decrease, industrial applications will represent a major market. With the increased use of sensitive electronic components, the need for reliable, high-quality power supplies is paramount for most industries. The cost of power outages, or poor quality power, can be ruinous to industries with continuous processing and pinpoint-quality specifications. Studies indicate that power fluctuations cause annual losses of $12-26 billion nationwide. Fuel cells can provide reliable, high quality electric power and high energy heat for industrial processes.

Lastly, as a fuel cell industry emerges and manufacturing capacity and techniques bring down costs, a broader spectrum of applications will emerge, including central power generation. The chart below summarizes fuel cell market opportunities along with competing options.

Fuel Cell Markets and Competition

Market segment	Typical capacity (MW)	Market size (MW/yr.)	Competing options
High-value commercial building	0.2-2	10-125	Power marketer* Reciprocating engine
Broader commercial self-generation and cogeneration	0.2-2	125-250	Power marketer* Reciprocating engine
Distributed power	5-20	300-600	Gas turbine combined cycle Recuperated gas turbine
Public power, self-generation	50-500	800-900	Reciprocating engine
Industrial cogeneration	5-200	100-200	Gas turbine Power marketer*
Central station	100-500	1000-2000	Pulverized coal Circulating fluidized-bed combustion Gas turbine combined cycle

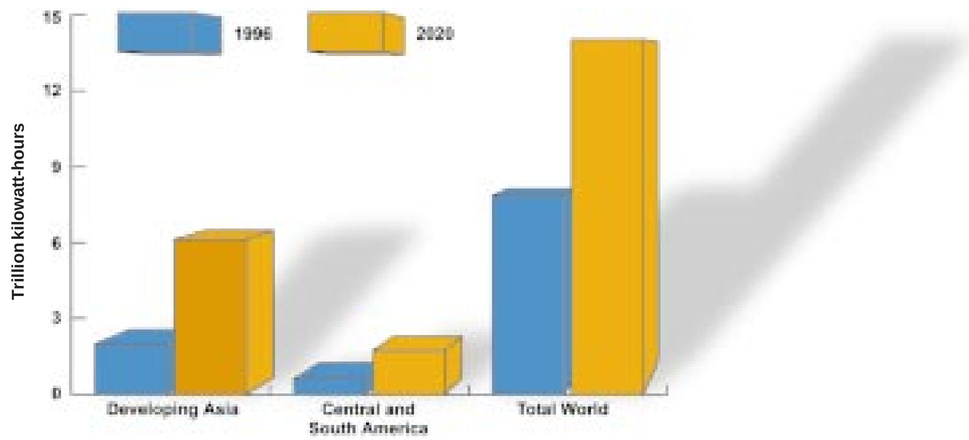
* competed retail grid price

GLOBAL OPPORTUNITIES

In future years, electricity will continue to be the most rapidly growing form of energy consumption. Forecasts show total worldwide electricity consumption rising from 12 trillion kilowatt-hours in 1996 to almost 22 trillion kilowatt-hours in 2020. The strongest growth is expected in developing Asia at an average annual rate of nearly five percent, followed by Central and South America at an average annual rate of over four percent. And by 2020, developing nations are expected to account for 43 percent of the world's total energy consumption, compared with only 28 percent in 1996.

In meeting worldwide power needs, fuel cells are applicable to both central powerplant generation and distributed generation scenarios. Their greatest potential, at least in the near term, lies in distributed generation.

World Electricity Consumption by Region, 1996 and 2020



Source: Energy Information Administration, *International Energy Outlook 1999*

The first commercial fuel cell on the market, the phosphoric acid fuel cell (PAFC), proved that early entry markets exist to sustain their relatively high initial costs of $3,000-4,000/kW. These niche markets include premium power applications, such as use in hospitals and computer centers, and opportunity fuel applications where gas from waste materials can be generated in quantity. Regions exceeding ambient air quality standards for pollutants (non-attainment areas) also represent prime market areas. The premium power market in the United States alone is conservatively estimated at $1 billion per year. The U.S. Environmental Protection Agency estimates that the current global market for opportunity fuels is 40-50 gigawatts.

Ultimately, for fuel cells to realize their full potential, costs must be competitive with other distributed generation technologies such as gas turbines and reciprocating engines. The incentive to bring costs down is reflected in the size of the global market. The U.S. and European growth and replacement market for distributed generation is expected to approach 10 gigawatts per year for the next decade. Globally, it is expected to be 20 gigawatts per year.

PAFC being installed at New York City's Times Square

The Program

Goals

FETC, in partnership with the power industry, is carrying out a fuel cell research and development program targeting the stationary power generation sector. Industry participation in the program is extensive, with over 40 percent cost-sharing. Intended applications include distributed generation in the near- to mid-term and central power in the longer-term. The goals are:

- To enable the power industry to take advantage of the superior efficiency, reliability, and environmental performance characteristic of fuel cells by reducing cost and further enhancing performance; and
- To strengthen the economy by developing U.S. leadership in the manufacture of fuel cells.

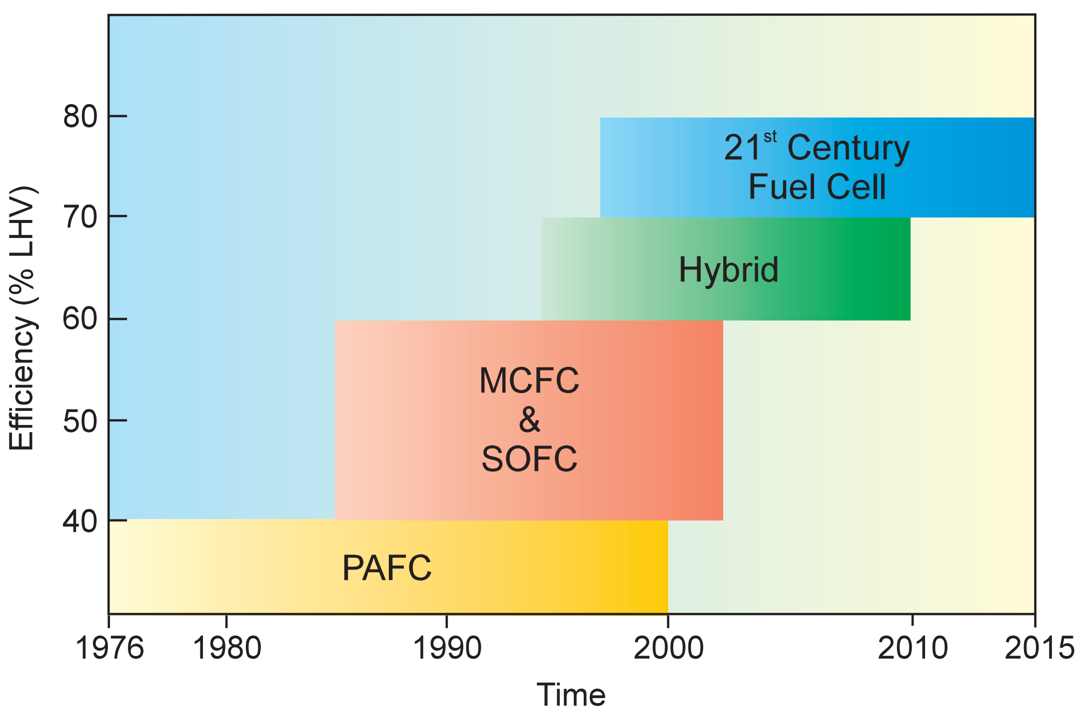
Objectives

- By 2003, commercially introduce high-temperature natural gas-fueled molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) at \$1,000–1,500/kW capable of 60 percent efficiency, ultra-low emissions, and 40,000 hour stack life.
- By 2010, commercially introduce early fuel cell/gas turbine hybrids capable of 70 percent efficiency.
- By 2015, achieve market entry for a 21st Century Fuel Cell using solid state composition and advanced fabrication techniques to achieve 80 percent efficiency, near-zero emissions, 40,000 hour stack life, and capital costs of \$400/kW (<\$90/kW stack).
- By 2015, increase market penetration and efficiency of fuel cell/gas turbine hybrids by introducing Vision 21 hybrids with advanced materials and manufacturing, and combustion techniques and expanded fuel flexibility.

Strategy

FETC relies on its long history of working with industry to forge partnerships that allow the public interests to be protected, innovation to be encouraged, and technical progress to proceed rapidly. The effectiveness of these partnerships is reflected in the commercial success of the first generation PAFC technology. This success resulted from a close working relationship between International Fuel Cells (IFC) Corporation and FETC. ONSI Corporation of South Windsor, Connecticut, the marketing subsidiary of IFC, is now manufacturing commercial 200-kW units using advanced robotics and automated assembly techniques. Turnkey 200-kW PAFC plants have been installed at more than 165 sites around the world. Similar partnerships are in place to introduce the next generations of fuel cells.

Fuel Cells for the Future



EMERGING FUEL CELLS

A Fuel Cell Energy (formerly Energy Research Corp) molten carbonate fuel cell

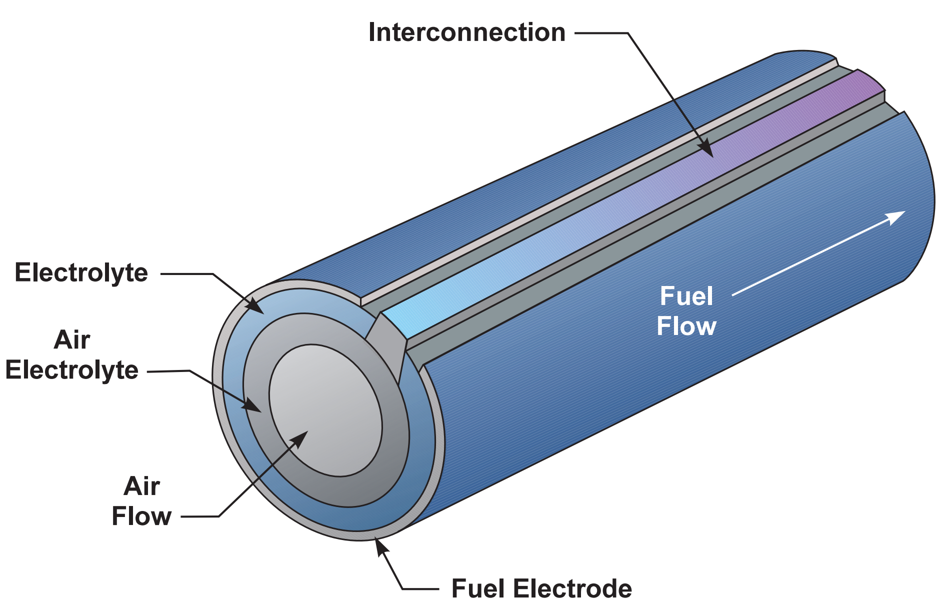
First generation PAFC systems currently being commercialized operate at about 200 °C (400 °F), which is sufficient for providing hot water and space heating. Electrical efficiencies for PAFCs range from 40–45 percent on a lower heating value (LHV) basis, and overall thermal efficiency can reach 80 percent LHV in applications that use the process heat.

Emerging second generation fuel cells are designed to operate at higher temperatures to enhance both fuel-to-electricity and thermal efficiencies. The higher temperatures contribute to improved fuel-to-electricity efficiencies and enable increased thermal efficiency through generation of steam for cogeneration, combined-cycle applications, and reforming of fuels. Moreover, these units either tolerate or use reformed fuel constituents such as carbon monoxide, which represents a poison to PAFCs.

One of two high temperature fuel cells currently under development is the molten carbonate fuel cell (MCFC). MCFC technology has the potential to reach fuel-to-electricity efficiencies of 60 percent LHV. Operating temperatures for MCFCs are around 650 °C (1,200 °F), which allows total system thermal efficiencies up to 85 percent LHV in combined-cycle applications.

The other high temperature fuel cell under development is the solid oxide fuel cell (SOFC). SOFCs operate at temperatures up to 1,000 °C (1,800 °F), which further enhances combined-cycle performance. The solid-state ceramic construction permits the high temperatures, allows more flexibility in fuel choice, and contributes to stability and reliability. As with MCFCs, SOFCs are capable of fuel-to-electricity efficiencies of 60 percent LHV and total system thermal efficiencies up to 85 percent LHV in combined-cycle applications.

Siemens Westinghouse Solid Oxide Fuel Cell Tube



ACHIEVING MARKET ENTRY

Second generation fuel cell devel opment is proceeding efficiently. FETC is working with Fuel Cell Energy (FCE) and M-C Power to bring two versions of the MCFC to commercial fruition, and is working with Siemens Westinghouse Power Corporation (SWPC) to commercialize the SOFC.

These second generation systems are currently being demonstrated, with market entry for natural gas-based systems planned for 2003. Objectives include achieving 40,000 hours of stack life and reducing capital costs to $1,000–1,500/kW. Subsequent to market entry, capital costs are expected to decline as manufacturing capacity and capability increase.

By 2003, natural gas-fueled MCFCs and SOFCs will be commercially available in sizes ranging from 500 kW to 3 MW. As market acceptance and manufacturing capacity increases, natural gas-fueled plants in the 20–100-MW range will become available. Follow-on testing will address expanding the fuel options by testing other reformed fuels and associated cleanup systems. By 2010, a transition to coal-gas-powered fuel cells will occur as gasification and gas cleanup costs are reduced through commercial plant replications.

M-C Power's 250-kW MCFC demonstration unit at the Miramar Marine Corps Air Station, San Diego, California

100-kW SOFC cogeneration system operating in The Netherlands, built by Siemens Westinghouse *(photo courtesy of Siemens Westinghouse)*

System Integration Yields Synergy

Efforts also are underway to develop a system that integrates a fuel cell with a gas turbine. Hybrid fuel cell/gas turbine technology for stationary power generation offers the potential to achieve efficiencies in excess of 80 percent, nitrogen oxides and carbon monoxide emissions less than 2 parts per million (ppm), and costs 25 percent below a comparably sized fuel cell.

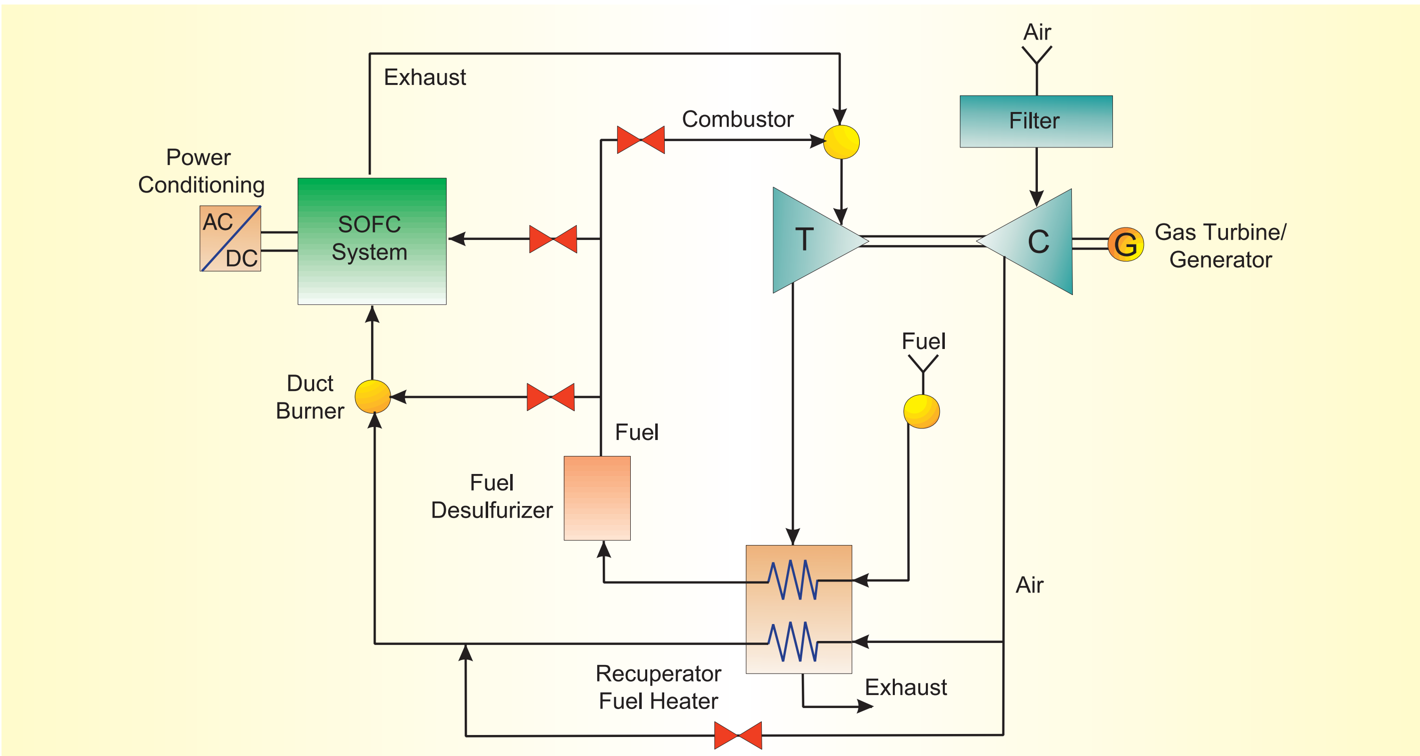
The synergy realized by fuel cell/turbine hybrids derives primarily from using the rejected thermal energy and residual fuel from a fuel cell to drive the gas turbine. This leveraging of thermal energy makes the high-temperature MCFCs and SOFCs ideal candidates for hybrid systems. Use of a recuperator contributes to thermal efficiency by transferring heat from the gas turbine exhaust to the fuel and air used in the system.

FETC is engaged in exploratory research on fuel cell/turbine hybrids in partnership with the National Fuel Cell Research Center at the University of California at Irvine. The experimental work involves evaluation of a 75-kW turbine at FETC operating in combination with a simulated fuel cell. The particular focus is on dynamic operating conditions (start-up, shutdown, load following, and upsets) and the associated controls. The objective is to establish: key operating parameters and their interrelationships, a range of safe operating conditions, and a database and dynamic modeling tools to support further development.

FETC also supports hybrid system development in its Low-Btu Combustion Studies Facility. Fuel cell anode gases can be simulated for combustor design studies. The fully instrumented facility is made available for cooperative research between FETC and industry under Cooperative Research and Development Agreements (CRADAs), which are designed to protect industrial participants' intellectual property.

In an attempt to develop an early entry hybrid system, FETC engaged five teams of fuel cell and turbine manufacturers, who conducted conceptual feasibility studies on fuel cell/turbine systems. The teams were predominately composed of the high-temperature MCFC and SOFC fuel cell manufacturers and the turbine manufacturers participating in the Department of Energy's industrial scale Advanced Turbine Systems Program. The goal is to develop hybrid systems with efficiencies greater than 70 percent for market entry by 2010. More advanced hybrid configurations with 21st Century Fuel Cells could offer 80 percent efficiency by 2015.

Example of Fuel Cell/Turbine Hybrid System



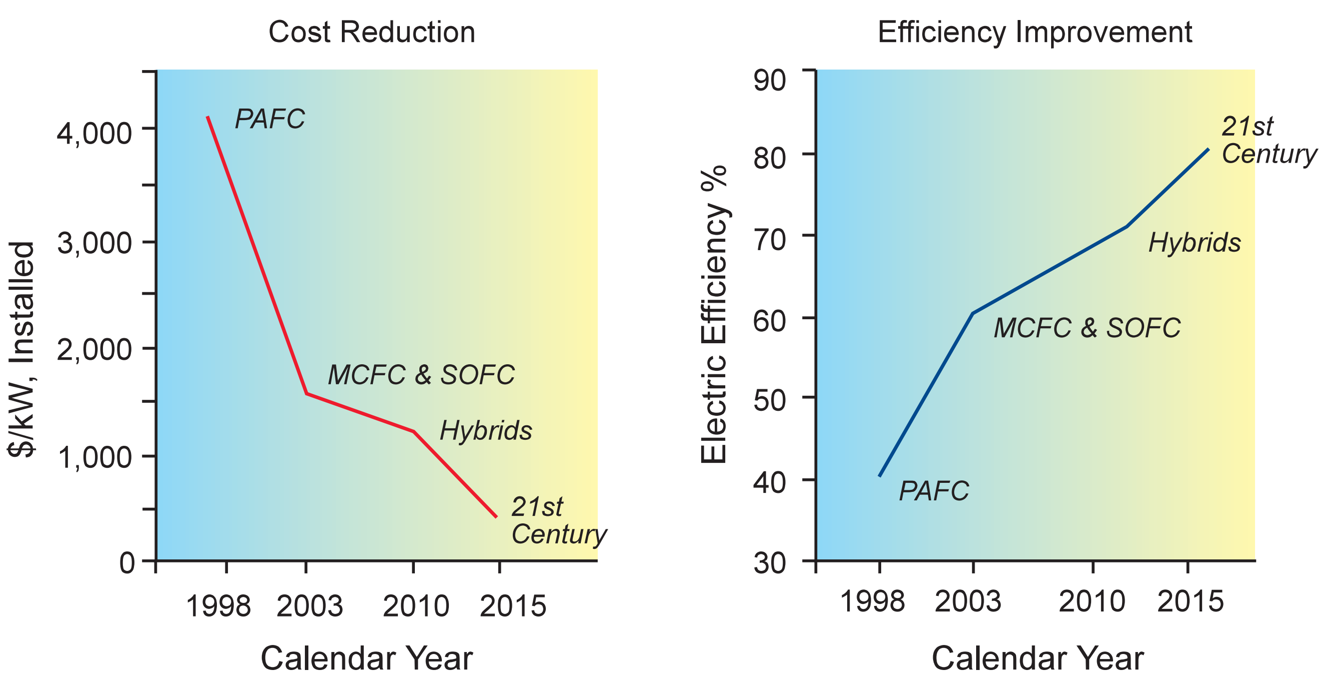
courtesy of Siemens Westinghouse

21^ST^ CENTURY FUEL CELLS

Research and development into new ceramic materials and manufacturing techniques is ongoing. In the near-term, R&D supports cost and performance improvements in MCFCs, SOFCs, and hybrid systems. The long-term goal is to develop a new solid state fuel cell that provides quantum leaps in cost and performance—a 21st Century Fuel Cell. Integration of design, high-speed manufacturing, and materials selection from the start is deemed critical to meeting the goal. Long-term materials development is anticipated to realize the full potential of the 21st Century Fuel Cell.

A set of cost and performance targets has been established that will provide wider and deeper penetration into a full range of market applications. These targets include achieving stack fabrication and assembly costs of $100/kW, system costs of $400/kW, efficiencies of 80 percent or more, near-zero emissions, and compatibility with carbon sequestration. These targets represent order-of-magnitude improvements in power density and cost, and a factor of two improvement in efficiency.

Fuel Cell Program Future



Developing the Potential

Building the Foundation

In fiscal year 1995, fuel cells became an integral part of the federal government's strategy to address global climate change concerns. Through a Defense Department appropriations bill, Congress authorized the Climate Change Fuel Cell Program to accelerate commercialization of fuel cells—a joint effort of the U.S. Departments of Defense and Energy. FETC is responsible for implementing the program, which is managed by the Department of Defense Construction Engineering Research Laboratory.

The program is a key element of the Federal Administration's Climate Change Action Plan, designed to curb greenhouse gas emissions through expedited deployment of highly efficient, clean technologies. Defense Department goals were addressed as well by helping to create a fuel cell manufacturing capability critical to the Department's energy security and readiness needs. The Climate Change Fuel Cell Program has resulted in over 165 ONSI 200-kW PC25TM fuel cells being sold worldwide. Many of these installations are at military bases.

To explore expanded applications for fuel cells, FETC has established a test and evaluation facility to simulate operating cycles typical of military and other specialty applications for fuel cells in the 20–5,000 watt range. The objective is to explore, through joint government-industry-academia partnerships, new ways to leverage the unique performance characteristics of fuel cells. The facility provides the fuel, thermal management, humidification, load simulation, and performance measurement instrumentation necessary to fully evaluate fuel cell systems.

The impetus exists to fully develop the potential of fuel cells. They offer the hope of satisfying energy needs without adverse impact on the environment, and providing a means of ushering in a hydrogen-based energy infrastructure. Establishing a strong U.S. fuel cell technology position and manufacturing capability strengthens the economy, creates quality jobs, enhances the environment, and provides energy security.

FETC fuel cell test and evaluation facility

SUMMARY OF BENEFITS

Customer Benefits

- Ensures reliability of energy supply, increasingly critical to business and industry in general, and essential to some where interruption of service is unacceptable economically or where health and safety is impacted;
- Provides the right energy solution at the right location;
- Provides the power quality needed in many industrial applications dependent upon sensitive electronic instrumentation and controls;
- Offers efficiency gains for on-site applications by avoiding line losses, and using both electricity and the heat produced in power generation for processes or heating and air conditioning;
- Enables savings on electricity rates by self-generating during high-cost peak power periods and adopting relatively low-cost interruptible power rates;
- Provides a stand-alone power option for areas where transmission and distribution infrastructure does not exist or is too expensive to build;
- Allows power to be delivered in environmentally sensitive and pristine areas by having characteristically high efficiency and near-zero pollutant emissions;
- Affords customers a choice in satisfying their particular energy needs; and
- Provides siting flexibility by virtue of the small size, superior environmental performance, and fuel flexibility.

Supplier Benefits

- Limits capital exposure and risk because of the size, siting flexibility, and rapid installation time afforded by the small, modularly constructed, environmentally friendly, and fuel flexible systems;
- Avoids unnecessary capital expenditure by closely matching capacity increases to growth in demand;
- Avoids major investments in transmission and distribution system upgrades by siting new generation near the customer;
- Offers a relatively low-cost entry point into a competitive market; and
- Opens markets in remote areas without transmission and distribution systems, and areas that have no power because of environmental concerns.

National Benefits

- Reduces greenhouse gas emissions through efficiency gains and potential renewable resource use;
- Responds to increasing energy demands and pollutant emission concerns while providing low-cost, reliable energy essential to maintaining competitiveness in the world market;
- Positions the United States to export distributed generation in a rapidly growing world energy market, the largest portion of which is devoid of a transmission and distribution grid;
- Establishes a new industry worth billions of dollars in sales and hundreds of thousands of jobs; and
- Enhances productivity through improved reliability and quality of power delivered, valued at billions of dollars per year.

For more information, contact:

Mark C. Williams, Product Manager
Fuel Cells
mwilli@fetc.doe.gov
(304) 285-4747

U.S. Department of Energy
Federal Energy Technology Center
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

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