Distributed Generation/Fuel Cells

DOE Helps Expand Both Technologies and Markets

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The early entry market penetration by ONSI and its phosphoric acid fuel cell (PAFC) technology has proven that fuel cells are reliable and suitable for premium power and other opportunity fuel niche applications. Now, new fuel cell technologies—solid oxide fuel cells, molten carbonate fuel cells, and polymer electrolyte fuel cells—are being developed for early market entry shortly after 2003. Some of the evolving fuel cell systems are incorporating gas turbines in hybrid configurations. The combination of the gas turbine with the fuel cell promises to lower system costs and increase efficiency to enhance market penetration.

Significant early entry markets exist to sustain the initially high cost of some distributed generation technologies. However, distributed generation technologies must have low introductory first cost, low installation cost, and high system reliability to be viable options in competitive commercial and industrial markets. In the long-term, solid state fuel cell technology with stack costs under $100/kilowatt promises deeper and wider market penetration in a range of applications including a mature distributed generation market.

FUEL CELL TECHNOLOGY

Fuel cell power plants offer the potential for ultra-high-efficiency energy conversion and the enhancement of the quality of the environment, Concerns for the global environment are driving future power generation systems toward technologies that produce extremely low environmental emissions. Because of their high efficiencies, fuel cell power plants will help in reducing carbon dioxide emissions. Since combustion is not utilized in the process, fuel cells generate very low amounts of NO_x. Fuel cell power plants have been exempt from air permitting requirements in California and Massachusetts.

The fuel cell is attractive for both urban and remote applications. It is ideal as a distributed generator, that is, it can be sited at or near the electricity user—for example, at electrical substations, at shopping centers or apartment complexes, or in remote villages—minimizing long-distance transmission lines.

In the United States, the Department of Energy (DOE)/Fossil Energy's Fuel Cell Program is a cost-shared, market-driven program. As implemented by DOE/National Energy Technology Laboratory (NETL), the Program emphasizes natural gas-powered stationary applications and currently supports fuel cell designs being developed by three U.S. firms. The future of the Fuel Cell Program will incorporate higher efficiencies, lower cost, and performance improvements through the use of fuel cell/gas turbine hybrids and 21st Century Fuel Cells.

Fuel cells will also be a key enabling technology of Fossil Energy's "**Vision 21 Program**." As the Vision 21 power plant matures, fuel cells will eventually be operated on coal gas.

FUEL CELL TECHNOLOGY STATUS

Molten Carbonate Fuel Cells

Over the past several years, the primary focus of the Fuel Cell Program has been on the development of advanced high-temperature fuel cells. These include molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs) that have the potential for efficiencies in the range of 50-70 percent and are suitable for integration with a gas turbine in a hybrid configuration or a coal gasifier for Vision 21.

The MCFC developer is Fuel Cell Energy (FCE, formerly Energy Research Corporation). FCE is developing an externally manifolded, internally reformed MCFC and has constructed a 17-MW/year MCFC manufacturing plant. FCE has constructed a 400 kW test facility in Danbury, Connecticut, and has scaled up to an 8-square-foot (0.74 square meter) area stack. FCE operated the largest fuel cell power plant in the United States when it conducted its 2 MW test at Santa Clara in 1996,

Commercial size stack tests at the Danbury facility evolved from the Santa Clara experience and have been extremely successful. Two 250 kW tall stacks have been recently tested. The first 250 kW stack was tested for over 2,500 hours with three thermocycles and no noticeable deterioration of performance. The other 250 kW stack (shown in Figure 1) is currently operating in a grid-connected mode and providing power to the Danbury facility. Performance and stack cost goals are being met through cell area scale-up and testing, efficient packaging, and component cost reduction through design manufacturing improvements. Stack module and balance-of-plant (BOP) improvements will be verified at a 300 kW scale.

The preliminary designs of FCE's market-entry, 1-MW and 3-MW direct fuel cell power plants have been completed. Further cross licensing arrangements with MTU of Germany has given FCE access to MTU's 300 kW product in the United States. In 2000, FCE plans to deliver 300 kW units for field tests to be conducted in the United States and Germany in 2001. Capital costs of FCE's products are projected to be under $1,300/kW.

Solid Oxide Fuel Cells

Siemens Westinghouse Power Corporation (SWPC) is the acknowledged world leader in tubular SOFC technology. SWPC is developing a tubular configuration that has been validated to a far greater extent than any other SOFC technology. Two thin-wall porous support tube cells have been on test for over 7 years (>69,000 hours). The tubes have been scaled up to a nominal 2 meters in length. The porous air support tube has been eliminated; the air electrode now supports the cell.

SWPC completed 114 thermal cycles on 2 Air Electrode Supported (AES) cells, which were 50-centimeters (cm) active length and used 2 Electrochemical Vapor Deposition (EVD) steps. Ontario Hydro has accumulated more than 1,725 hours of operation on a single 150-cm AES cell manufactured with two EVD steps. More than 1,475 of the 1,725 hours were operated at a pressure of 5 atmospheres. This type of cell is typical of the cells that SWPC has used in the 100 kW demonstration unit in late 1997 and will be used in their commercial offerings. Southern California Edison has operated a 25 kW unit at their High Grove Generating Station in Terrace, California.

This unit was moved to the University of California and was restarted after two years of being stored in a warehouse. It accumulated over 3,200 hours after the unit was restarted (8,800 hours total). SWPC completed testing of a 25 kW unit for the Joint Gas Utilities (JGU) at their Science and Technology Center at Pittsburgh, Pennsylvania, after completing over 13,000 hours of operation and surviving 10 thermal cycles. The 100 kW EDB/ELSAM unit was completed in December 1997, and has completed 6,000 hours of operation and two thermal cycles.

SWPC has brought on line a 45,000-square-foot Pilot Manufacturing Facility with a production capacity of 4 MW/year per shift. This facility completed cell production for a 250 kW fuel cell turbine hybrid

Figure 1: FCE's 250 kW MCFC Test Stack at Danbury, CT (Energy Research Corporation is now Fuel Cell Energy: FCE)

that will be tested at the National Fuel Cell Research Center in Irvine, California, in 2000. SWPC appears to have eliminated two of the three EVD steps in manufacturing. They are currently working on the elimination of the last EVD step (for the electrolyte).

To further reduce costs, SWC is increasing the cell output by cell redesign and pressurized operation, testing low-cost air electrode material, and investigating low-cost air electrode manufacturing. Current cell life is estimated to be 10 years, with 7 years already demonstrated. SWPC believes cell life for commercial cells will be 10 to 20 years. Commercial product size will range from 1 to greater than 50 WM in a combined-cycle configuration.

FUEL CELL TECHNOLOGY EVOLUTION

The Fuel Cell Program expects to increase efficiency and improve performance through the development of fuel cell/gas turbine hybrids and 21st Century Fuel Cells. One of the most promising developments in fuel cell power plants is the conceptual development of very high efficiency fuel cell/gas turbine power plants. The hybrid, fuel cell-turbine power plant can configure the high- or intermediate-temperature fuel cell with a low-pressure-ratio gas turbine. Electrical conversion efficiencies from 70 to over 80 percent are calculated for this type of system. Even higher efficiencies may be possible as the fuel cells are networked or staged and other refinements or advances are incorporated.

Fuel Cell/Gas Turbine Hybrids and *Vision 21*

Because of the synergistic effects leading to the higher efficiencies and lower emissions achieved by combining a fuel cell and a gas turbine into a power generation system, many potential system configurations have been developed. These systems are the logical extension of the DOE-funded fuel cell and gas turbine development and represent the most promising fossil energy power plants ever conceived.

The typical hybrid system size is 3 to 20 MW. By allowing the fuel cell in the power plant to serve as the combustor for the gas turbine, and the gas turbine to serve as the balance of plant for the fuel cells, the combined efficiency is raised to the 60 percent range. Even at sizes of less than 3 to 10 MW, NO_x emissions are essentially eliminated.

Larger fuel cell/gas turbine hybrids will become enabling technologies for Vision 21 plants at sizes of 30 MW and greater. The Vision 21 program aims to combine fossil fuel technologies for electric power generation and fuels/chemicals production to enable the design of plants that achieve substantially improved performance, i.e., higher efficiency and lower emissions, at lower costs than are possible by applying any single technology. These highly efficient combined systems (above 60% with coal and above 75% with natural gas) in multi-megawatt sizes would have no environmental impact outside their own small footprint. The goal is to make these modules ready for use in integrated systems by 2015.

21st Century Fuel Cells

21st Century Fuel Cells are a new generation of fuel cells with high efficiency and lower costs to meet the increasing demand for electrical energy with the challenge of improved environmental performance. The fuel cell products of the 21st Century promise to provide the following benefits:

- Stack costs approaching $100/kW and system costs approaching $400/kW.
- Efficiency as high as or exceeding 80 percent (combined cycle).
- Compatible with carbon sequestration and near-zero emissions of other pollutants.
- Wide range of applications: stationary and mobile, large and small scale, central and distributed generation.
- Fuel flexibility with multiple future energy options, including hydrogen as an energy carrier.

With 21st Century Fuel Cells, an order of magnitude improvements in power density and cost and a factor of two improvement in efficiency appear possible.

THE EVOLVING GLOBAL MARKET

The electric power industry is undergoing profound change during deregulation. Open access and competition is expected to increase the opportunities for the fuel cell technology within the coming decade as the DG market opportunities evolve.

Today, market estimates indicate that significant early entry markets exist to sustain the initially high cost of some DG fuel cell technologies. The early entry market penetration by ONSI with its phosphoric acid fuel cell technology at $3,000-$4,250/kW has proven that fuel cells are reliable and suitable for premium power (computer centers, hospitals, etc.) and other opportunity fuel niche applications (landfill gas, anaerobic digestor gas, waste gas).

Nonattainment areas are of particular interest. The premium power market is estimated to be conservatively a $1 billion annual market in the U.S. EPA estimates that globally there exist some 40-50 GW of market for opportunity fields. These niche markets can support the higher $3,000-4,000/kW fuel cell capital costs.

While market estimates indicate that significant early entry or niche markets exist today to sustain the initial high cost of some DG technologies, DG technologies must have ultimately low introductory first cost, low installation cost, and be reliable. If this is possible, they will be viable options in more competitive commercial and industrial markets.

The U.S. and European growth and replacement market for distributed generation (all sizes, non-central station, including residential) is expected to approach 10 GW/year for the next decade. Globally it is expected to be 20 GW/year (see Table 1). Sales of power plants 250-kW to 10-MW today are approaching 10 GW/year globally.

Credible market studies, with logical market penetration scenarios, including the impact of competing technologies and penetration curves, indicate that by 2010 the SOFC and two MCFC developers could be selling commercial products at around $1000/kW-$1500/kW. This could capture some 10-20 percent of the emerging European and U.S. distributed generation market.

Some of the evolving fuel cell technologies are fuel cell gas turbine hybrids. The combination of the gas turbine with the fuel cell promises to lower systems costs more quickly thus enhancing market penetration. Cost estimates reveal that hybridization of fuel cells can result in as high as a 25 percent reduction in cost and 25 percent increase in efficiency for the same size system.

In the long term, 21st Century Fuel Cell technology, such as solid state fuel cell technology, with potential stack costs under $100/kilowatt and system costs of $400/kW, promise deeper and wider market penetration in a wide range of applications. This includes mature,

Table 1: DG Market Projections (*Courtesy of FCE*)

MARKET AND SALES VOLUME PROJECTIONS

US MARKET	2001	2002	2003	2004	2008
Installed Capacity (GW) —Growth Rate 1.3%, Replacement .7%	832	843	854	865	911
Total Generation Market (GW)	16.6	16.9	17.1	17.3	18.2
Dist. Gen. Market (MW) —Percent to Total	2,662 16%	3,034 18%	3,415 20%	4,151 24%	6,738 37%
EURO. MARKET	2001	2002	2003	2004	2008
Installed Capacity (GW) —Growth Rate 1.3%, Replacement 1.2%	790	800	810	821	865
Total Generation Market (GW)	19.7	20.0	20.3	20.5	21.6
Dist. Gen. Market (MW) —Percent to Total	2,764 14%	3,000 15%	3,242 16%	3,489 17%	4,323 20%

highly competitive distributed generation, transportation, DOD and Vision 21 (bulk power) markets.

Technology transfer to the DOD is an important part of fuel cell commercialization strategy and part of the DOE strategy. Broad DOD fuel cell use is possible in a wide range of applications including: battery replacement, shipboard power, propulsion, remote sites, instrumentation and control sites, premium power, and portable power. For mobile power generators (3-kW to multi-megawatt) alone there are 500,000 units in the U.S, military inventory and 5 million in inventory in NATO and allied countries which the U.S. supplies.

Major new programs are interested in investing in new, competitive technology. Fuel cell technologies of interest to DOD include hybrids and 21st Century Fuel Cells. The global maritime market for both propulsion and shipboard power, including private and DOD, is estimated at 800 GW.

The 50 million vehicle per year global and 15 million vehicle per year U.S. transportation sector is a vast energy market. Ford Motor Company estimates that high-speed manufacturing will be required to lower the fuel cell stack cost to $35/kW required in the mature, competitive automobile industry. Without the hydrogen infrastructure, for non-fleet vehicles, the costly and bulky reforming technology required makes other fuel cells less attractive and less efficient than the potential 21st Century Fuel Cells. 70 miles per gallon is possible with the 70-80 percent (LHV) 21st Century Fuel Cells and their ease of reforming conventional, available fuels makes them a potential option in the transportation industry. Early entry is anticipated for heavy-vehicle ancillary power applications.

The Vision 21 market is the long-term fuel cell market. The Vision 21 concept is based on integration of emerging technology concepts for high-efficiency power generation and pollution control into a new class of fuel-flexible electricity generation facilities.

The goals of Vision 21 are to be clean, cost-effective and highly efficient in order to meet our nations growing energy needs. The Department has focused on two possible activities planned to address the Vision 21 goals: Fuel Cell/Gas Turbine Hybrids, and 21st Century Fuel Cells. As the Vision 21 concept progresses, it will incorporate the latest fuel cell designs, first from the Hybrid Program and later from the 21st Century Fuel Cell Program.

CONCLUSION

The fuel cell technology and fuel cell markets are evolving. Fuel cell technology has immense, revolutionary technological potential with much lower costs and higher efficiencies than alternative technologies, making it suitable for widespread market applications. The DOE is prepared with a vision for the near-term as well as for the future. For very competitive and mature distributed generation markets, hybrids and 21st Century Fuel Cells could lead to wider application and deeper market penetrations, ultimately including Vision 21.

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