Status and Promise of Fuel Cell Technology

Mark C. Williams*

United States Department of Energy, National Energy Technology Laboratory,
Morgantown, WV26507-0880, and Pittsburgh, PA 15236-0940, U.S.A

Received 29 January 2001; received in revised form 30 May 2001

Abstract

The niche or early entry market penetration by ONSI and its phosphoric acid fuel cell technology has proven that fuel cells are reliable and suitable for premium power and other opportunity fuel niche market applications. Now, new fuel cell technologies – solid oxide fuel cells, molten carbonate fuel cells, and polymer electrolyte fuel cells – are being developed for near-term distributed generation 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. Market estimates indicate that 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 (kW) promises deeper and wider market penetration in a range of applications including a residential, auxiliary power, and the mature distributed generation markets. The Solid State Energy Conversion Alliance (SECA) with its vision for fuel cells in 2010 was recently formed to commercialize solid state fuel cells and realize the full potential of the fuel cell technology. Ultimately, the SECA concept could lead to megawatt-size fuel-cell systems for commercial and industrial applications and Vision 21 fuel cell turbine hybrid energy plants in 2015.

Niche or Early Opportunity Markets

Market penetration of fuel cells is determined to a large extent by product costs. Increasing manufacturing volumes lowers product cost, leading to increased market penetration. Through an Interagency Agreement between NETL and the U.S. Department of Defense (DOD), DOD has provided funds for the Climate Change Fuel Cell Program. For several years, this program has supported the market penetration of fuel cells by a rebate of \$1,000/kW or one-third of the total project costs, whichever is lower, to those organizations installing a fuel cell manufactured in the U.S. Priority has been given to powerplants placed at DOD installations.

In 1996, the Climate Change Fuel Cell Program was managed by NETL and resulted in 33 awards for the installation of 42 ONSI PC25, 200 kW phosphoric acid fuel cell (PAFC) powerplants. ONSI Corporation, a subsidiary of International Fuel Cells, located in South Windsor, Connecticut, has been actively involved in the development and marketing of on-site PAFC systems and has a 40 megawatt (MW)/year manufacturing facility.

In 1997, DOD again provided funds to reduce the costs of fuel cells by providing the same rebate opportunity. This program was managed by DOD's Advanced Research and Development Engineering Center in Picatinny, New Jersey. Fifty-three awards for ONSI PC25 installations were made in the program in 1997.

In 1998, DOD provided funds (\$5 million) to NETL to manage the Climate Change Fuel Cell Program. The DOD program management was provided through the Construction Engineering Research Laboratories (CERL). Awards were made twice in 1999 as a result of this funding from 1998. The first set of awards were for sixteen ONSI powerplants. Following the first set of awards, the qualification criteria were modified to lower the minimum fuel cell size from 100 kW to 3 kW. The second set of awards were for ninety 7-kW proton exchange membrane (PEM) fuel cells manufactured by PlugPower, sixteen 3-kW PEM units from American Power, and one 300 kW SOFC unit from SWPC.

[*] Corresponding author, mark.williams@netl.doe.gov

NETL awarded seven grants in 2000. In addition, Bonneville Power Administration will be given a Letter of Authorization in lieu of a grant. The awards totaled \$ 29.6 million including \$ 2.3 million of federal funding. The awards encompassed a variety of fuel cell types and sizes (8–200 kilowatt Phosphoric Acid; 10–3 kW and 23–7 kW Proton Exchange; 1–250 kW Solid Oxide; and 1–250 kW Carbonate). The successful proposers under this solicitation were: Bonneville Power Administration, Bill Martin (Moose River), Omaha Public Power District, NJR Power Services, Idaho State University, Bell Atlantic, Ontario Power, and Los Angeles Department of Water and Power. These proposers will demonstrate, through their applications, a commitment to purchase, install, operate, and maintain fuel cell power plant(s). These projects will culminate with a summary report after one year of power plant operation. The proposers used a mix of fuel cell types including proton exchange membrane, phosphoric acid, carbonate, and solid oxide and vendors including: Northwest Power Systems, Plug Power, ONSI, Fuel Cell Energy, and Siemens Westinghouse. Additional awards will also be made in 2001 under the program.

Near-Term Distributed Generation Market

The near-term market includes premium power applications: computer centers, hospitals, and other facilities that must have a reliable supply of high-quality electricity and are willing to pay for it. Distributed generation technologies must have low introductory and installation costs, and they must be reliable. The current DOE program, now in the last phase of development, has two parts: development of molten carbonate fuel cell (MCFC) systems, by Fuel Cell Energy (FCE), and development of tubular solid oxide fuel cell systems, by Siemens Westinghouse (SWPC). The program's goals are commercialization of solid oxide fuel cell (SOFC) and molten carbonate fuel cell power plants in the 200-kW to 3-MW range by 2003 at costs of \$1,000 to \$1,500 per kilowatt, efficiencies of 50 to 60%. Its objective is also to have at least 50 MW per year of U.S. molten carbonate fuel cell manufacturing capacity, and to have at least 30 MW per year of U.S. solid oxide fuel cell manufacturing capacity by 2003.

FCE is developing an externally manifolded, internally reformed MCFC and has constructed a 50-MW/year MCFC manufacturing plant. FCE has constructed a 400 kW test facility in Danbury, Connecticut, and has scaled up to a 8-square foot (0.74 square meter) area stack.

Commercial size stack tests at the Danbury facility evolved from the Santa Clara experience and have been extremely successful. Tall stack testing in integrated test facilities at FCE, that simulated final product operating conditions, was successfully completed. Two 250 kW tall stacks have been 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 is currently operating in a grid-connected mode and has operated some 9,000 hours.

Fig. 1 Fuel Cell Energy Megawatt-class power plant

Performance and stack cost goals are being met through cell area scaleup 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 design of FCE's market-entry, 3-MW direct fuel cell powerplant has been completed. A conceptual installation of this system is shown in Figure 1 above. In response to market interest, FCE will also offer a 1-MW design. Further cross licensing arrangements with MTU of Germany has given FCE access to MTU's 250 kW product in the United States. Therefore, FCE will be able to offer products ranging in size from 250 kW to 3-MW. Performance characteristics and early production units (EPU's) have been identified. Projected capital costs are under \$1,300/kW.

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 cell is now supported by the air electrode. SWPC completed 114 thermal cycles on 2 Air Electrode Supported (AES) cells which were 50-centimeter (cm) active length and used 2 Electrochemical Vapor Deposition (EVD) steps.

The Kansai Electric Company (Japan) tested a four-cell article and accumulated 10,529 hours of operation at high current densities and completed 101 thermal cycles. These cells were 150-cm active length and used 2 EVD steps. In addition, the cells experienced only minor voltage degradation. 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 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 has accumulated over 3,200 hours after the unit was restarted

Fig. 2 SWPC 100-kilowatt ELSAM Power Plant

(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 (Figure 2 above, courtesy of the Dutch Umbrella Association EnergieNed on behalf of the Energy Distribution Companies in the Netherlands) was completed in December 1997 and has completed over 11,000 hours of operation.

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 Southern California Edison combined cycle unit in March 1998. 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, SWPC 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 MW in a combined-cycle configuration.

The U.S. and European growth and replacement market for near-term distributed generation is expected to approach 10 GW per year over the next decade. Globally it is expected to be 20 GW per year by 2010. The near-term developers, Fuel Cell Energy and Siemens Westinghouse, have had impressive test performance, and each plans multiple demonstrations within the next few years. Collectively, they could be capturing 1 to 2 GW per year of the global market by the end of the decade.

SECA and the Mature Distributed Generation Market

The first SECA Kickoff Meeting and National Roadmapping Workshop was held in Baltimore, MD, June 1–2, 2000. Two national laboratories, NETL and Pacific Northwest National Laboratory (PNNL), the driving forces behind SECA, are providing the leadership, focus and integration needed to bring solid state fuel cell technology into the mature distributed generation and auxiliary power markets. In order to obtain national input, these laboratories held an initial kickoff meeting at which there were almost 200 participants with broad representation from industry, national labs, academia, and defense. SECA is a mechanism to build and integrate the industry base for low-cost fuel cells to penetrate the mature distributed generation market. SECA will build an alliance of government agencies, commercial developers, universities, and national laboratories to develop solid oxide fuel cells with the capability for immediate commercial success. The alliance will provide a focal point, an “organizational center” for the development of distributed generation and larger stationary power applications, auxiliary power units for military applications, and auxiliary power units for transportation applications. All three applications will benefit from the free flow of leveraged fuel cell technology development. The first industry teams under the alliance are expected in late 2001.

Long-term cost goals for military and transportation applications for the commodity and transportation propulsion market are \$50 to \$200 per kilowatt. Efficiencies for all applications will be greatly improved over current state-of-the art. The results of this program will provide early low-cost power systems for mature distributed generation market applications, and will feed directly into the Vision 21 Fuel Cells Program.

SECA Vision: Fuel Cells in 2010

The vision for solid-state fuel cell systems in 2010 is:

- These systems will be low cost: \$400 per kilowatt in the multi-kilowatt size range, a remarkable accomplishment

Fig. 3 Fuel Cell Market Projections

in this small size range. The price trajectory will be downward, such that a system for transportation applications is on the horizon.

- Fuel-to-end-use efficiencies will be high: nearly twice as high as today's conventional technologies, again a remarkable accomplishment in the multi-kilowatt size range. These high efficiencies translate to reduced greenhouse gas emissions.
- Given a fuel, there will be a fuel-cell system that can operate on it. Fuel cells will be able to operate on natural gas, gasoline, diesel fuel, landfill gas, hydrogen, and defense logistics fuels.

By 2010 it is hoped that industry teams will have commercialized them as auxiliary power units for the nation's cars and trucks, distributed generation units for homes, and field power units for military operations. The core of this vision is a 5-kilowatt, low-cost, high power-density, solid-state fuel-cell stack. The core module measures approximately 4 by 4 by 12 inches. It can be mass produced because it can be used in multiple end-use markets. Because it is a standard core module, the cost to customize it for multiple markets is cheap. This concept of mass customization of common modules eliminates the Catch-22 of commercialization, that is, high-volume production is needed to reduce costs, but low costs are needed to create a large market. The 5-kilowatt core modules can be combined (like batteries) for applications with larger power needs. This building block approach enables low-cost customization. This is the Gateway or Dell computer concept applied to fuel cells. Gateway and Dell keep personal computer costs low and meet the exact needs of their customers by applying using the concept of mass customization. Ultimately, the SECA concept could lead to megawatt-size fuel-cell systems for commercial and industrial applications and Vision 21 energy plants. This vision is achievable, but it will take a new approach to technology development.

Fig. 4 Applications for the SECA 5-kilowatt Module

Vision 21: Fuel Cells in 2015

Fossil fuels currently provide 85% of global and U.S. energy supply. Even under a climate change scenario, we will need to use fossil energy well into the future. But we need to use it smarter. The goal of Vision 21 is to wring every possible bit of useful energy out of carbon-based feedstocks to produce energy products. The Vision 21 fuel cells segment will develop advanced fuel cell modules that would be integrated with other Vision 21 advanced technology modules, and would be tailored to meet specific market needs. Fuels cells are needed to obtain the 60% efficient coal-fueled Vision 21 power plants of the future. To reach these high efficiency targets, a hybridized, high-efficiency fuel cell is required. Getting the cost of the fuel cell power module to \$400 per kW is a key factor in deploying Vision 21 systems by 2015. If this can be done, fuel cell/turbine hybrids could replace turbines as the power block in integrated gasification combined-cycle applications. These highly efficient combined systems, in multi-megawatt sizes, would have no environmental impact outside their own footprint. The goal is to make these modules ready for use in integrated systems by 2015. This program segment will accept additional technology input from the SECA program segments as solid state fuel cells become available. Fuel cells also have an advantage in Vision 21 sequestration applications. Fuel cells have inherently high efficiency and can also be configured to produce concentrated CO₂ streams. Under the recent DOE Fossil Energy Vision 21 solicitation, Siemens Westinghouse received an award to reconfigure their tubular solid oxide fuel cell to produce a concentrated CO₂ stream for use in enhanced oil recovery and other applications.

Fig. 5 Longterm Fuel Cell Power Plant Concept for Vision 21 Systems

Bibliography

- [1] M. C. Williams, "Fuel Cell Power Plants", Wiley Encyclopedia of Electrical and Electronics Engineering, Volume 8, pp. 2–11, 1999.
- [2] M. Williams, A. Layne, S. Samuelson, and P. Hoffman, 'Hybrid Status', in Proceedings IGTI, 1999.
- [3] M. Williams, "Status of SOFC Development and Commercialization in the US", 6th International SOFC Symposium, in Proceedings, pp. 3–9 (1999).
- [4] M. Williams, "Fuel Cells: the Evolving Market", New Orleans, in Proceedings PowerGen 1999, December, 1999.
- [5] M. Williams, "Deregulation and Distributed Generation", in Proceedings Frontiers of Power Conference, Stillwater, OK, October, 26–27, 1999.
- [6] M. Williams, "Status of MCFC Development and Commercialization in the US", Keynote Speaker, 5th International CFC Symposium, in Proceedings, pp. 40–46 (1999).
- [7] M. C. Williams, "Fuel Cells – Realizing the Potential", Fuel Cell Seminar, Portland, November 1, 2000, in Proceedings Fuel Cell Seminar, (2000).
- [8] M. Williams, "Energy Futures: Advanced Fuel cell Power Systems", Brookings Institute Seminar, "Science and Technology Policy: Current and Emerging Issues", June 14, 2000.
- [9] A. Layne, S. Samuelson, P. Hoffman, and Mark Williams, "Hybrid Systems Development", in Proceedings IGTI, 2000.
- [10] M. Williams and D. Gyorke, "DOE/FEs fuel cell program: status and future plans", Proceedings of 16th US/Korean Workshop, September, pp. 18–22, 1999.
- [11] Williams, M., "Overview of US Stationary Fuel Cell Program, R&D and Markets", Proceedings, DOE-Russian Academy of Sciences Workshop on the Science behind Fuel Cell Technology, Moscow, Russia, October 12–14, 1999.
- [12] M. Williams and Marvin Singer, "Status of Fuel Cells for DG in the US", in Proceedings IFC, Kyoto, Japan, 1999.
- [13] M. Williams, "Status of Fuel Cells for DG in the US", in Proceedings AIST/DOE Meeting, Portland, Oregon, 2000.
- [14] M. Williams, "Fuel Cells in the US: Federal Initiatives", in Proceedings PowerGen, Orlando, FL, 2000.
- [15] M. Williams, "Distributed Generation/Fuel Cells", in Cogeneration and Competitive Power Journal, vol. 15, no. 3, pp. 70–79 (2000).
- [16] M. Williams and S. Singhal, "Mass-produced ceramic fuel cells for low-cost power", in Fuel Cell Bulletin, no. 24, pp. 8–11 (September 2000).
- [17] B. Washom, et. al, "Market Prospects and Attendant Intervention Strategies to Accelerate the Deployment of Fuel Cells in Distributed Power Generation for Developing Countries", prepared for World Bank, May 2001.
- [18] W. Miller, "Delphi Automotive System", in SECA Workshop Proceedings, pp. 53–60, June 1, 2000.
- [19] S. Samuelson, "Environmentally Preferred Technologies", in Proceedings ICEPAG, pp. 1–24, April 1999.
- [20] European Fuel Cell Projects 1995–2000, European Commission, EUR 19368, 2000.