IX.2 Fuel Cell Combined Heat and Power Commercial Demonstration

Kriston Brooks (Primary Contact), Siva Pilli
Pacific Northwest National Laboratory
P.O. Box 999
Richland, WA 99352
Phone: (509) 372-4343
Email: kriston.brooks@pnnl.gov

DOE Manager
Peter Devlin
Phone: (202) 586-4905
Email: Peter.Devlin@ee.doe.gov

Subcontractor:
ClearEdge Power, Hillsboro, OR

Project Start Date: August 2010
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- Deploy and monitor combined heat and power fuel cell systems (CHP FCSs) in the range of 5-50 kWe in commercial applications.
- Evaluate the engineering, economics, and environmental impact to provide end-users with an independent assessment of the technology.
- Monitor the long-term performance of the systems. As funding allows, we have a contract in place to monitor the systems for five years.
- Demonstrate the viability of the technology to potential customers by developing a business case.

Fiscal Year (FY) 2013 Objectives

- Monitor fuel cell performance and share the results at conferences and in other forums.
- Demonstrate the impact of updated balance of plant (BOP) on the micro-CHP FCS availability.
- Prepare business case for micro-CHP FCSs and incorporate comments from an industrial review.

Technical Barriers

This project addresses the following technical barriers from the Market Transformation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

(F) Inadequate user experience for many hydrogen and fuel cell applications

(H) Utility and other key industry stakeholders lack awareness of potential renewable hydrogen storage application

(I) Lack of cross cutting information on how to use hydrogen and fuel cell systems in combination with energy efficiency and renewable energy technologies with existing projects

Technical Targets

Applicable DOE 2015 Technical Targets for 1-10 kWe CHP FCSs operating on natural gas:

- Electrical efficiency at rated power = 38.4% (higher heating value)
- System equipment cost, 5 kW = $1,700/kW
- Degradation with cycling = 0.5%/1,000 hrs
- Operating Lifetime = 40,000 hrs
- System Availability = 98%

FY 2013 Accomplishments

- Analyzed 11,255 hours (average hours per system as of July 1, 2013), for 15 micro-CHP FCSs in terms of net electrical and thermal power and system efficiency and availability.
- Recommended changes in the fuel cell operation that resulted in improved fuel cell stability.
- Developed an approach to compare the economics of the micro-CHP FCS to conventional technologies.
- Prepared a draft micro-CHP FCS business case describing the anticipated growth of the FCS market, applications where CHP FCSs would be beneficial and economic conditions that favor their use.

✧ ✧ ✧ ✧ ✧

INTRODUCTION

PNNL provides support to the Market Transformation sub-program with the objective to aid in the development of the fuel cell and associated hydrogen markets. The strategy is to identify near term niche markets where fuel cells have potential, work with the DOE and stakeholders to develop activities in those areas, analyze the business case, and present the results to the community.

APPROACH

The objective of this project is to demonstrate micro-CHP FCSs and assess their performance to help determine and document market viability. PNNL has worked with a vendor to provide micro-CHP FCS at several small industrial buildings. The purpose of these installations is to gather performance data over the course of 1-5 years. The gathered information is being analyzed, to provide "real-world" data from units "in the customer's hands" to validate performance, durability, and reliability; installation, operations, and maintenance costs; and identify advantages to their commercialization.

This project also is developing a business case that could be provided to industry to estimate the size of the market and its growth potential, identify possible niche markets, and compare the micro-CHP FCS with its alternatives in terms of economics, engineering and environmental impact. It has also utilized techno-economic-environmental optimization models to analyze the business case for micro-CHP FCSs. Model results can elucidate competitive strengths of this technology by building type, load curve, and climate. Analyses under this effort incorporate market characteristics that will strengthen the business case such as spark spread and environmental regulations. It also addresses the FCS characteristics such as capital cost, payback period, and reliability. The micro-CHP fuel cell systems being monitored under this project are being used as a case study within the business case.

RESULTS

The micro-CHP FCS subcontractor provided 15 micro-CHP FCSs that were installed at four different deployment sites: two sites in Northern California, one site in Southern California, one site in Oregon (for a sample deployment see Figure 1). Independent evaluation of manufacturer-stated economic, engineering, and environmental performance of the CHP FCSs was performed.

Economic Performance

Cost analyses of micro-CHP FCS installations were performed to quantify their current and expected future profitability. Cost data gathered from the manufacturer include the FCS capital cost, additional equipment cost, installation, sales tax, and decommissioning costs, and the total cost of fuel over the lifetime of the project. All costs are recorded in present day dollars. The total project cost along with the DOE cost share for each site is shown in Table 1. The DOE cost share varied from 36 to 44 percent depending on the location. The differences in cost per unit/DOE cost share arise from the differences in additional equipment costs (vary depending on the infrastructure at a given site), variable sales tax, and fuel costs. On average, the cost of one unit is approximately $83,500. Figure 2 shows the average cost distribution among the micro-CHP FCSs in the deployed

FIGURE 1. Two Micro-CHP FCS Units Tested for this Study in Portland, Oregon

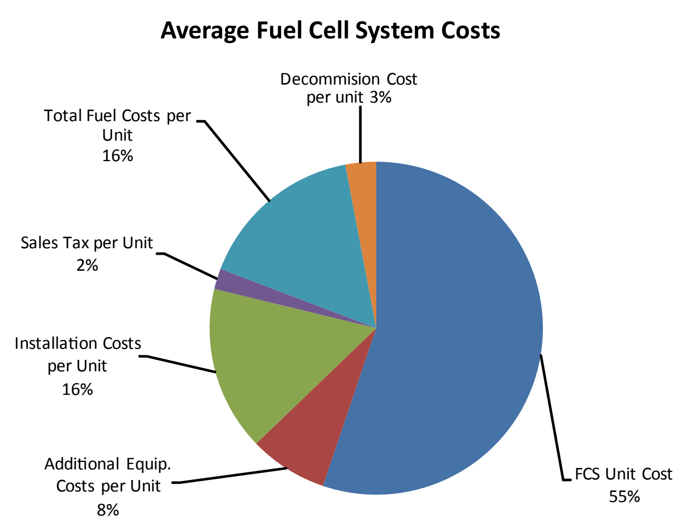

FIGURE 2. Cost Distribution for an Average Micro-CHP FCS in the Deployed Fleet

TABLE 1. Total Project Costs and Cost Share Information for Individual Sites

Partner/Site	Location	Number of FCSs	Total Project Cost [$]	DOE Cost Share		Payback (Years)	
				$	%	Without Incentives	With Incentives
College	Portland, OR	2	$188K	$82K	44%	8.66	N/A
Nursery	Corona Del Mar, CA	3	$228K	$83K	36%	4.95	3.75
Recreation	Oakland, CA	5	$409K	$150K	37%	5.32	4.06
Grocery	San Francisco, CA	5	$427K	$158K	37%	5.43	3.99
Total		**15**	**$1252K**	**$473K**	**38%**	**6.09**	**5.12**

fleet. Capital costs include an estimate for operation and maintenance costs for replacement of the stack and BOP components.

Two different payback analyses (one including incentives in the life cycle cost [LCC] analysis and the other excluding incentives from the LCC analysis) were performed to calculate the payback time (see Table 1). The payback period varied from 4.95 years to 8.66 years when incentives were excluded from the LCC analysis. The payback period varied from 3.75 years to 4.06 years when incentives were included from the LCC analysis. Note that "college" is not eligible for incentives because of the financial nature and location of this organization.

Figure 3 shows the average payback period based on current and projected (next five years) sales of micro-CHP FCS units. The projected costs are based on an estimated production of 4,000 systems/year and represent a 25% cost decrease. Assuming no incentives, the average payback periods for the current and projected costs are 6.09 and 4.71 years, respectively. The cost reduction with increased production is consistent with a previous study that predicted that the cost of 5-kW stationary proton exchange membrane fuel cells would decrease by 32% by increasing the production of systems from 100/year to 10,000/year [1].

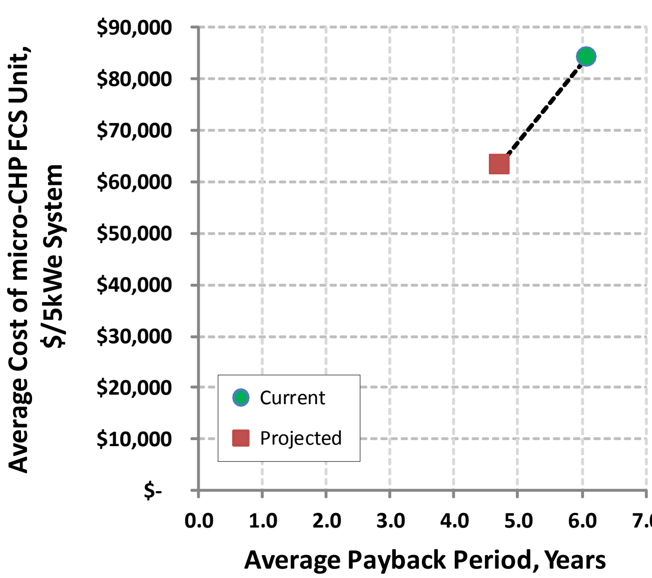

FIGURE 3. Average Payback Period versus Average Cost of the Micro-CHP FCS Unit

Engineering Performance

Engineering performance parameters identified and used in the economic analysis, were independently monitored and analyzed by PNNL. This analysis led to several recommendations which resulted in system improvements and system upgrades. The analysis is presented in Table 2 to document all the improvements and upgrades to date.

- Data analysis of as-installed FCS units: A total of 10 systems were installed between September and December 2011. Initial data indicated that the FCSs have a long-term average production of about 4.5 kWe of power. This was slightly below the manufacturer's stated rated electric power output of 5 kWe. Furthermore, the power output declined for all units over this time period. The rate of decline averaged over the fuel cells evaluated is near 3.2% per 1,000 hours. This decline was primarily the result of high-temperature polybenzimidazole fuel cell stack degradation.
- Data analysis after set-point changes: Based on PNNLs recommendation, the micro-CHP FCS set points were changed from 5 kWe to 4 kWe for the short term. Between March 2012 and June 2012, data analysis indicated that the FCSs have relatively stable performance and a long-term average production of about 4 kWe of power, consistent with the new set-point. However, there were some reliability issues, which are reflected in a decreased availability (88.9%). This availability reduction was attributed to the BOP system failures. Based on this analysis, the project team started to make BOP upgrades in late-June/early-July 2012.
- Data analysis after BOP upgrades: BOP upgrades for eight systems were done during June 2012 and July 2012. The project team is currently working on system upgrades for the rest of the systems/units. Data analysis of the systems with BOP upgrades indicated that the FCSs continue to have relatively stable power performance but now

TABLE 2. Micro-CHP FCS Performance Summary

	Unit	Stated Value	Initial Data	After Set-Point Changes	After BOP Upgrades
Period of Operation	--	--	Oct. 2011 to Feb. 2012	Mar. 2012 to June 2012	July 2012 to July 2013
Number of Operating Units Measured	--	--	10	15	8
Average Net Electric Power Output	kWe	5.0[c]	4.5±0.3	4.0 ± 0.2	4.0 ± 0.2
Average Net Heat Recovery[b]	kWth	5.5[c]	5.1 ± 0.4	4.6 ± 0.3	4.5 ± 0.2
Temperature to Site	°C	Up to 65	56.3 ± 3.8	49.6 ± 3.9	48.3 ± 5.1
Average Net System Electric Efficiency[a]	%	36	33.0 ± 2.1	33.5 ± 2.5	33.3 ± 2.4
Average Net Heat Recovery Efficiency[a]	%	40	37.4 ± 2.3	38.0 ± 2.8	37.8 ± 2.8
Overall Net System Efficiency[a]	%	76	70.4 ± 4.4	71.6 ± 5.4	71.1 ± 5.2
Availability, A_o	%	--	95.7 ± 2.8	88.9 ± 7.4	96.5 ± 1.3

(a) Efficiencies are based on higher heating value.
(b) The average heat recovery values are calculated by the manufacturer, and do not represent a measured value.
(c) The 5.0 kWe and 5.5 kWth set-points were changed to 4.0 kWe and 4.5 kWth during March/April of 2012.

also have increased system reliability as reflected in an increased availability (96.5%).

Environmental Performance

The environmental impacts of CHP FCSs are quantified by applying a life cycle assessment methodology [2-5]. In brief, this methodology quantifies the environmental impact of both GHG emissions and air pollution emissions.

- Greenhouse Gas (GHG) Emissions: The CHP FCS was compared to a conventional coal-fired power plant, an average gas-fired plant, and an advanced cogeneration plant. A CHP FCS can produce as little as one-third the emissions of a conventional energy system composed of a coal power plant and a coal-fired boiler, producing the same quantity of electricity and heat. A CHP FCS can emit just one-half the GHG emissions of an average gas-fired system. Table 3 shows the GHG mitigation cost comparison for all cases using the 2010 annual total electricity consumption in the United States [6]. Values of $20/metric tonne of CO_2 equivalent emissions and $100/metric tonne of CO_2 equivalent emissions, based on United Nations Intergovernmental Panel on Climate Change estimates [7-9], are considered here to provide both low and high estimates for GHG mitigation cost. These are proportional to the changes in the GHG gas emissions for the systems shown.
- Human Health Effects: The exhaust gas composition from a CHP FCS was analyzed to quantify the change in air pollution emissions. Based on the methodology presented by Colella [5], the human health costs associated with air pollution emissions from a CHP FCS were compared with the same conventional, average, and advanced systems described above assuming all the electricity in the U.S. is being generated from that single source. This comparison is also shown in Table 3. The human health costs decrease significantly when switching from a conventional coal-powered system to a CHP FCS. For example, the total human health costs stemming from air pollution from electricity production in the United States based on the use of a conventional coal-powered system is estimated to be approximately $505 billion per year. By contrast, the same human health costs using CHP FCSs instead for electricity generation are estimated to be only $0.57 billion per year. The costs between Case 1 and Case 4 differ by a factor of approximately 1,000.

Micro-CHP FCS Business Case

A business case was also developed for a micro-CHP FCS. In this business case, parameters that determine their competitive advantage were identified. Places with high electricity prices and low natural gas prices are ideal

TABLE 3. GHG Mitigation Cost and Human Health Cost Comparison of CHP FCS and Other Energy Generators

	CO_2 Equivalent (g/kWhr)	CO_2 Equivalent for Total Energy (Billion tonnes/kWhr)	GHG Mitigation Cost (in Billion $)		Total Human Health Costs due to Air Pollution (in Billion $/year)
			Low Estimate ($20/ metric tonne)	High Estimate ($100/ metric tonne)	
Case 1: Conventional System	1,696	6.49	$132	$659	$505
Case 2: Average System	1,188	4.54	$92	$462	$485
Case 3: Advanced System	602	2.52	$47	$234	$146
Case 4: Micro-CHP FCS	528	2.05	$41	$205	$0.57

locations for using these systems. These conditions make a high "spark spread" and are generally in the northeastern area of the United States and California where government incentives are already in place to offset the current high cost of these FCSs. Fuel cell systems differentiate themselves from other CHP generating technologies by being more efficient and having fewer environmental impacts. Although micro-turbines and reciprocating engines are less expensive, they are not as efficient as fuel cells, thus their fuel costs are higher. Forecasts suggest that the micro-CHP fuel cell market will grow at a compound annual growth rate of over 30% over the next five years.

CONCLUSIONS AND FUTURE DIRECTIONS

The real-time monitoring of FCSs installations over a 20-month period (September 2011 – June 2013) has provided a variety of insights about the system performance.

- Assuming no incentives, the average payback periods of micro-CHP FCSs for the current and projected costs are 6.1 and 4.7 years respectively.
- Analyzed 11,255 hours (average hours per system as of July 1, 2013) for 15 micro-CHP FCSs in terms of net electrical and thermal power and system efficiency and availability which led to several recommendations resulting in system improvements and system upgrades.
  - Recommended changes in the fuel cell operation that resulted in improved fuel cell stability.
- Prepared a draft micro-CHP FCS business case describing the anticipated growth of the FCS market, applications where CHP FCS would be beneficial and economic conditions that favor their use.

Future Directions

- Continue monitoring and analyzing engineering and economic performance data from all the demonstration systems. Heat and electricity usage is also monitored at two installations.
- Share the results at conferences and in other forums.
- Demonstrate the impact of updated BOP on the micro-CHP FCS availability.
- Incorporate comments from the industrial review and finalize business case for micro-CHP FCSs.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. Received Best Poster Award at the Fuel Cell Seminar & Exposition, November 2012.

FY 2013 PUBLICATIONS/PRESENTATIONS

1. Kriston Brooks, et.al; "Business Case for a 5 kW Combined Heat and Power Fuel Cell System" - For Industry Review, June 2013.

2. Holladay, Jamie, "Independent Analysis of Real-Time Performance Data from Co-Generative Fuel Cell Systems Installed in Commercial Buildings," Invited speaker to the U.S. DOE CHP R&D Meeting, February 13, 2013.

3. Pilli, Siva, "Thermo-Economic & Real-Time Measured Performance Analysis of Micro Combined Heat & Power Fuel Cell Systems," Fuel Cell Seminar & Exposition, November 7, 2012.

REFERENCES

1. James BD. 2012. "Fuel Cell Transportation Cost Analysis, Preliminary Results." 2012 DOE Annual Merit Review Meeting, May 17, 2012, Washington, D.C. Retrieved from: http://www.hydrogen.energy.gov/pdfs/review12/fc018_james_2012_o.pdf.

2. O'Hayre R, SW Cha, W Colella, and FB Prinz. 2009. "Fuel Cell Fundamentals." Second Edition, ISBN 978-0-470-25843-9, John Wiley & Sons, Inc., Hoboken, New Jersey, pp. 451–482.

3. Jacobson MZ, WG Colella, and DM Golden. 2005. "Air pollution and health effects of switching to hydrogen fuel cell and hybrid vehicles." Science 308:1901.

4. Colella WG, MZ Jacobson, and DM Golden. 2005. "Switching to a U.S. Hydrogen Fuel Cell Vehicle Fleet: The Resultant Change in Energy Use, Emissions, and Global Warming Gases." Journal of Power Sources 150:150–181.

5. Colella WG. 2010. "Designing Energy Supply Chains Based on Hydrogen." Chapter 45 in Climate Change Science and Policy, 2nd edition, SH Schneider, A Rosencranz, and MD Mastrandrea (eds.), Island Press, Washington, D.C., pp. 456–466.

6. U.S. Energy Information Administration, Table 7.2. Retail Sales and Direct Use of Electricity to Ultimate Customers by Sector. Available at: http://www.eia.gov/electricity/annual/pdf/table7.2.pdf.

7. Working Group III Intergovernmental Panel on Climate Change (IPCC). 2007. Working Group III Contribution to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, Climate Change 2007: Mitigation of Climate Change, Summary for Policy Makers, Bangkok, Thailand, 20 April – 4 May, 2007, Table SPM1, Table SPM2, p. 12; Figure SPM 5B, p. 13. Available at: http://www.mnp.nl/ipcc/docs/FAR/ApprovedSPM0405rev4b.pdf.

8. Intergovernmental Panel on Climate Change (IPCC). 2001. "Climate Change 2001: The Scientific Basis." Cambridge University Press, Cambridge, United Kingdom.

9. Levine, M, D Ürge-Vorsatz, K Blok, L Geng, D Harvey, S Lang, G Levermore, A Mongameli Mehlwana, S Mirasgedis, A Novikova, J Rilling, and H Yoshino. 2007. "Residential and Commercial Buildings." In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, B Metz, OR Davidson, PR Bosch, R Dave, and LA Meyer (eds.), Cambridge University Press, Cambridge, United Kingdom and New York.