X.2 Fuel Cell Combined Heat and Power Industrial Demonstration

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

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

Contract Number: DE-AC05-76RL01830

Subcontractor:
ClearEdge Power, Portland, OR

Project Start Date: May 2010
Project End Date: September 2012

Fiscal Year (FY) 2012 Objectives

The overall objective of this project is to:

- Demonstrate combined heat and power (CHP) fuel cell systems (FCS) in small commercial buildings.
- Analyze engineering, economic, and environmental performance data from the demonstration systems to reveal barriers to commercialization that should be emphasized - identify where industry needs to spend the greatest effort to achieve high market penetration and reveal issues that may expedite its commercialization.
- In the longer term, document market viability (a business case) of this class of fuel cells for small commercial buildings.

Technical Barriers

This project addresses technical and economic issues preventing the full commercialization of CHP FCSs. This includes the lack of long-term validated performance data for 5 kilowatt-electric (kWe) to 100 kWe FCSs such as:

- Energy production performance, durability, and reliability.
- Installation, operations, and maintenance costs.

Technical Targets

No specific technical targets have been set.

FY 2012 Accomplishments

- Established baseline models to evaluate the cost and technical performance of FCSs.
- ClearEdge Power provided 15 CHP FCSs that were installed at four different deployment sites (refer to the results section for location list).
- Have been remotely monitoring several parameters (see Approach for the list) at one-second intervals for all 15 operating units.
- Established several new performance definitions and characterized baseline system performance for ongoing data analysis.
- Engaged and informed stakeholders in different industry venues:
  - Presented initial data analysis results to more than 13 conferences and trade groups.
  - Submitted three peer-reviewed journal articles (two accepted, one in review) for publication.

✧ ✧ ✧ ✧ ✧

Introduction

The objective of this project is to demonstrate CHP FCSs in small commercial facilities and assess their performance to help determine and document market viability. This information is important for the DOE, the fuel cell community, and most importantly for small commercial facilities that have operational power and heat requirements. The FCSs for this demonstration were acquired through an open competition in which ClearEdge Power won the award. Between September 2011 and March 2012, ClearEdge Power installed 15 of their CHP FCSs for application and demonstration at four small industrial facilities. Pacific Northwest National Laboratory (PNNL) began obtaining performance data of these systems as they were commissioned, and will continue with this objective over the course of the next few years. This project provides "real-world" data from units "in the customer's hands" to validate performance, durability, and reliability; installation, operations, and maintenance costs; and identifies remaining barriers to widespread commercialization.

Approach

First, we established a baseline method for cost and technical performance of the FCSs to assure a common basis in which to evaluate the systems that were eventually to be deployed. Next we set out to acquire the FCSs for demonstration. The acquisition process was described in detail in the previous year's progress report [1]. ClearEdge Power was selected as the fuel cell manufacturer, and four different industrial partners, including retail, education, food provision, and recreation/community buildings, were selected for these deployments. Deployments occurred between September 2011 and March 2012. We are currently remotely monitoring several parameters at one-second intervals for these 15 operating units: (1) natural gas mass inlet flow rate to burner; (2) natural gas mass inlet flow rate to reactor; (3) current exported from FCS to the building's electrical grid; (4) grid voltage measured by FCS inverter; (5) estimated FCS heat generated; (6) net electrical power generated; (7) system electrical power setpoint; and (8) temperature of heat delivered by FCS to site. We began to analyze and document the performance data collected over the last few months of each FCS deployed. We will continue to analyze the performance data collected over at least a two-year period for each FCS deployed and document the overall market viability of this class of FCSs for small commercial buildings. These ongoing analyses will include overall technical, economic, and environmental performance.

FIGURE 1. Two FCS units tested for this study in Portland, Oregon

Results

ClearEdge Power provided 15 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. The analysis data presented here is for five FCS units that were commissioned early in the deployment. Analysis of the other units is in progress.

Economic Performance: This analysis is based on the rated performance data (5 kWe and 5.5 kilowatt-thermal [kWt]) provided by the manufacturer (i.e., not independently measured data). The average electrical and thermal demand values were calculated using all the 10 deployment sites, which includes the four sites mentioned above, that were initially down selected (see Figure 2). Using both a standard and a management accounting approach, an economic analysis was performed to calculate (1) the average per-unit cost of the CHP FCSs per unit of power (electricity only); and (2) the average per-unit cost of the CHP FCSs per unit of energy. The average per-unit cost of electrical power for these systems ranged from \$15,000–19,000/kWe (depending on site-specific installation, fuel, and other costs), while the average per-unit cost of combined electrical and heat recovery power ranged from \$7,000–\$9,000/kW. From the energy perspective, the average per-unit cost of electrical energy was estimated to range from \$0.38 to \$0.46/kilowatt-hour-electric (kWhe), while the average per-unit cost per unit of electrical and heat recovery energy varied from \$0.18 to \$0.23/kWh (Figure 2). The breakdown of the total cost per unit of installed electrical and heat recovery energy capacity is also illustrated in Figure 2 (DOE shows the portion that is provided/paid by the project, Partner shows the portion that is paid by the installation partner, and Federal/State shows the portion paid by federal and state incentives). In addition, Figure 2 compares the CHP FCSs' costs with the average electricity and heating prices for California and Oregon [2,3,4]. The combination of federal and state incentives reduces CHP FCS costs in several cases to be within ~25% of being economically competitive with existing average commercial electricity prices in California. When federal and state incentives are accounted for, the CHP FCS price drops to within a range of \$0.14/kWh to \$0.23/kWh with an average of \$0.17/kWh. Tax incentives help CHP FCSs compete more closely with statewide average commercial electricity and heating prices in California and Oregon.

Engineering Performance: Engineering performance parameters are independently evaluated. Based on an

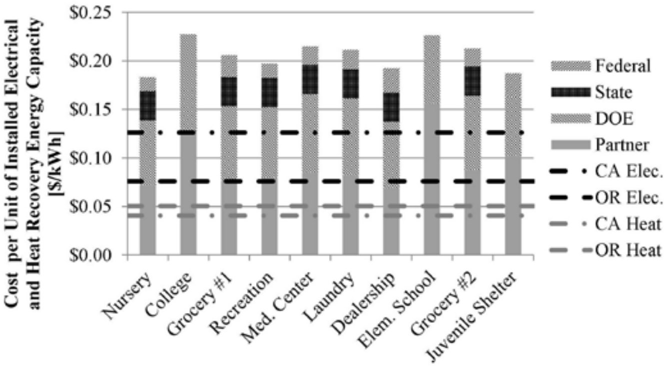

FIGURE 2. Breakdown of cost per unit of electrical and heat recovery energy capacity [2,3,4]

analysis of the first few months (October 2011 to April 2012) of measured operating data of the five FCS units, FCS performance is consistent with manufacturer-stated performance. Initial data indicate that the FCSs have relatively stable performance and a long-term average production of about 4.57 kWe of power. This value is consistent with, but slightly below, the manufacturer's stated rated electric power output of 5 kWe. The measured system net electric efficiency has averaged 33.7%, based on the higher heating value of natural gas fuel. This value also is consistent with, but slightly below, the manufacturer's stated rated electric efficiency of 36%. The FCSs provide low-grade hot water to the building at a measured average temperature of about 48.4°C, lower than the manufacturer's stated maximum hot water delivery temperature of 65°C. A summary of the results for five CHP FCSs is shown in Table 1. The uptime of the systems is also evaluated. System availability (A_0) can be defined as the quotient of total operating time compared to time since commissioning. The average values for system availability vary between 96.1% and 97.3%, depending on the FCS evaluated in the field.

For FCS Unit 130, a maximum decline in electric power output of approximately 18% was observed over a 500-hour period in January 2012, as shown in Figure 3.

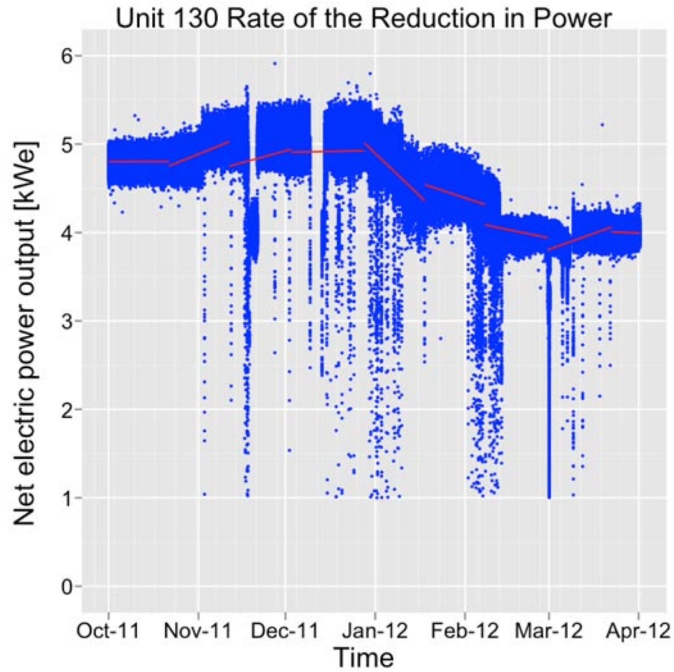

FIGURE 3. Decline in Power Output (Unit 130). A maximum decline in electric power output of approximately 18% over 500 hours was observed.

Power output declined from approximately 5 kWe to 4.3 kWe over this time period due in part to ClearEdge Power reducing the system setpoint (from 5 KWe to 4 KWe). The rate of change was calculated by fitting a simple linear regression (red solid lines) of the power output data. Power output data below 1 kW was not included in the regression analysis. Although 1,000-hour periods are more standard in industry, the system downtime for some of the units made it difficult to calculate 1,000-hour rates, so periods of 500 hours were considered in this work and the rates have been converted to the more standard unit. Table 2 indicates that the rate of decline averaged over the fuel cells evaluated is near 0.16 kW per 1,000 hours. The decline represents a maximum degradation rate during the observation period. This decline could be partly a result of high-temperature

TABLE 1. FCS Performance Summary. Downtime events (power output less than 1 kWe) and startup were not included in the calculated averages. The average heat recovery values are calculated by the manufacturer, and do not represent a measured value.

Unit	Average Net Electric Power Output (kWe)	Average Net Heat Recovery for External Heating (kWth)	Average Temp of Water Sent to Site (°C)	Average Net System Electrical Efficiency (%)	Average Net Heat Recovery Efficiency (%)	A_o (%)
129	4.58±0.5	5.19±0.5	46.1±3	33.5	38	96.3
130	4.53±0.5	5.14±0.5	45.7±3	32.8	37.2	96.2
131	4.58±0.4	5.19±0.5	51.5±6	33.7	38.2	96.1
132	4.64±0.4	5.26±0.4	50±6	33.5	37.9	96.7
133	4.50±0.4	5.1±0.5	48.7±7	34.8	39.4	97.3
All Units	**4.57**	**5.18**	**48.4**	**33.7**	**38.1**	**96.5**

proton exchange membrane degradation and/or fuel cell stack degradation. Other units show a similar downward trend prior to maintenance performed in March, which may include a partial stack replacement or regeneration. It is also possible that a portion of the decline in power output may be attributable to changes in setpoint that are unrelated to degradation. The rate of decline when corrected for the system setpoint is an order of magnitude lower (right hand column of Table 2). The degradation rate most likely lies somewhere between these values.

TABLE 2. Decline in Power Output. Maximum power output rate of decline based on the power output and the normalized power output ΔW_E (difference between the control setpoint and the power output).

Unit	Power Output Maximum Rate of Decline (kW per 1,000 hrs)	Normalized Power Output Maximum Rate of Decline from ΔW_E (kW per 1,000 hrs)
129	-0.24	-0.007
130	-0.18	-0.014
131	-0.08	-0.004
132	-0.05	-0.004
133	-0.25	-0.004
All Units	**-0.16**	**-0.007**

Environmental Performance: Preliminary environmental analyses (not reported at this time, analysis is underway) were shown to decrease the greenhouse gas (GHG) emissions by one-third by shifting from a conventional energy system to a CHP FCS system. The GHG mitigation costs also were proportional to the changes in the GHG gas emissions. Human health costs were estimated to decrease significantly with a switch from a conventional system to a CHP FCS system.

Conclusions and Future Directions

The real-time monitoring of five FCSs over a five-month period has provided a variety of insights about the system performance.

- CHP FCS costs in several cases are found to be within ~25% of being economically competitive with existing average commercial electricity prices. Federal and/or state incentives further improve this competitiveness.
- FCS engineering performance is consistent with manufacturer-stated performance, but slightly below the manufacturer's stated rated electric power.
- The rate of decline in electric power output averaged over the five fuel cells evaluated is near 0.16 kW per 1,000 hours.

Future directions:

- Continue analyzing engineering, economic, and environmental performance data from all the demonstration systems.
- In the next FY, develop a business case documenting the market viability of this class of fuel cells for small buildings. This business case will include estimates of the projected costs would be at various production levels and the process of power that would make the system cost competitive both with and without government incentives.

Special Recognitions & Awards/Patents Issued

1. Whitney G. Colella, Siva P. Pilli, "Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings," ASME 2012 10th Fuel Cell Science, Engineering & Technology Conference, San Diego, CA, July 23rd–26th, 2012. *Nominated for the Best Paper Award.*

FY 2012 Publications/Presentations

Peer-Reviewed Journal Articles and Conference Proceedings

1. Whitney G. Colella, Siva Pilli, "Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings," ASME 2012 10th Fuel Cell Science, Engineering & Technology Conference, San Diego, CA, July. 23rd-26th, 2012.

2. Whitney G. Colella, Heather E. Dillon, "Independent Evaluation of Real-Time Measured Performance Data From Micro-Combined Heat and Power Fuel Cell Systems Installed in the Field," ASME 2012 10th Fuel Cell Science, Engineering & Technology Conference, San Diego, CA, July. 23rd-26th, 2012.

3. Whitney G. Colella, Viraj Srivatsava, "System Integration of Combined Heat and Power Fuel Cells within Commercial Buildings Using Advanced Computer Models," ASME 2012 10th Fuel Cell Science, Engineering & Technology Conference, San Diego, CA, July. 23rd–26th, 2012.

4. Whitney G. Colella, Siva Pilli, "Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings,," Accepted to Journal of Fuel Cell Science & Technology.

5. Whitney G. Colella, Heather E. Dillon, "Independent Evaluation of Real-Time Measured Performance Data From Micro-Combined Heat and Power Fuel Cell Systems Installed in the Field," Accepted to Journal of Fuel Cell Science & Technology.

6. Whitney G. Colella, Viraj Srivatsava, "System Integration of Combined Heat and Power Fuel Cells within Commercial Buildings Using Advanced Computer Models," Submitted to Journal of Fuel Cell Science & Technology.

7. W.G. Colella, "Initial Deployment and Independent Testing of Micro-Combined Heat and Power Fuel Cell Systems in Light Commercial Buildings," EFC11178, Proceedings of the European Fuel Cell - Piero Lunghi Conference & Exhibition (EFC2011), Rome, Italy, Dec. 14–16th, 2011 (in press).

Oral Conference Presentations

1. W.G. Colella, H Dillon, S Pilli, V Srivastava, 2011, "Fuel Cell Combined Heat and Power Industrial Demonstration," U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, May 16th, 2012.

2. Thomas Benjamin, Dimitrios Papageorgopoulos, "DOE Efforts for Development and Deployment of Small-Scale Systems for Stationary Power," 1st International Expert Workshop - High Temperature Fuel Cells, March 27-28, 2012, Duisburg, Germany (PNNL contribution: Slides 15 to 19).

3. Colella, W.G., Advances in Distributed, Grid-Connected Energy Generation and Storage, Korea Institute of Energy Research Seminar, Korea Institute of Energy Research, Daejeon, Republic of Korea, Feb. 17th, 2012.

4. Colella, W.G. "The Next Generation, Low Carbon Electricity Grid," The International Workshop on Energy, Environment, Water and Sustainability (EEWS) at the Korea Advanced Institute of Science and Technology (KAIST), Seoul, Republic of Korea, Feb. 16th, 2012.

5. Colella, W.G. "Addressing Increased Variability on the U.S. Electric Grid from Higher Renewables Penetration using Generation and Storage in the Balancing Market," Korea Advanced Institute of Science and Technology (KAIST), Seoul, Republic of Korea, Feb. 16th, 2012.

6. Colella, W.G. "Independent Analysis of Real-Time Performance Data from Multiple Co-Generative Fuel Cell Systems Installed in Buildings," Korea Advanced Institute of Science and Technology (KAIST), Seoul, Republic of Korea, Feb. 16th, 2012.

7. Colella, W.G., Innovative Power Generation, Storage, and Control, Seoul National University Seminar, Seoul National University (SNU), Seoul, Republic of Korea, Feb. 15th, 2012.

8. Colella, W.G., Independent Analysis of High Temperature Proton Exchange Membrane Combined Heat and Power Fuel Cell Systems Deployed in Light Commercial Buildings, Korea Institute of Science and Technology (KIST) Seminar, Fuel Cell Research Center, KIST, Seoul, Korea, Feb. 14th, 2012.

9. Colella, W.G. Stationary Cogenerative and Polygenerative Fuel Cells, Korea Institute of Science and Technology (KIST), Seoul, Republic of Korea, Feb 14th, 2012.

10. Colella, W.G., Advanced Distributed Generation for Buildings using Co-generative and Poly-generative Fuel Cells. Green Manufacturing Research Center (GMRC) at Korea University, Seoul, Republic of Korea, Feb. 13th, 2012.

11. Colella, W.G., Next Generation Building Energy Technologies: Independent Testing of Micro Co-generative Fuel Cell Systems for Light Commercial Buildings, Pacific Northwest National Laboratory (PNNL) Building Energy Systems and Technologies (BEST) Seminar, Richland, WA, Jan. 25th, 2012.

12. Colella, W.G., Cutting-Edge Electricity Generation and Storage for Future Electricity Grids, Pacific Northwest National Laboratory (PNNL) Seminar, PNNL-Seattle Office, Seattle, WA, Jan. 5th, 2012.

13. Colella, W.G., Dillon, H. "Initial Deployment and Independent Testing of Micro-Combined Heat and Power Fuel Cell Systems in Light Commercial Buildings," American Society of Mechanical Engineers (ASME) Journal of Fuel Cell Science and Technology -- Proceedings of the European Fuel Cell - Piero Lunghi Conference & Exhibition (EFC2011), Rome, Italy, Dec. 14–16th, 2011 (delivered remotely by video file).

14. Colella, W.G., Dillon, H. "Independent Analysis of the Engineering, Economic, and Environmental Performance of Micro Combined Heat and Power High Temperature Proton Exchange Membrane Fuel Cell Systems in Buildings," Zing Conference -- 1st Annual International Hydrogen & Fuel Cells Conference: Hydrogen production, storage, and utilisation, Xcaret, Mexico, Dec. 1st–5th, 2011 (delivered remotely by video file).

15. Colella, W.G., "Independent Evaluation of Measured Performance Data from Stationary Combined Heat and Power (CHP) Fuel Cell Systems (FCSs) Installed in Light Commercial Buildings," Fuel Cell Seminar, Orlando, FL, Nov. 2nd, 2011.

17. Colella, W.G., Advanced On-Site Power Generation, Storage, and Control for Residential and Commercial Buildings, Pacific Northwest National Laboratory (PNNL) Seminar, PNNL-Portland Office, Portland, OR, Dec. 16th, 2011.

18. Colella, W.G., Independent Analysis of High Temperature Proton Exchange Membrane Fuel Cells for Micro-CHP, International Energy Agency (IEA) Advanced Fuel Cells Bi-Annual Meeting, Orlando, FL, Oct. 31st, 2011.

References

1. Rinker MW, Colella WG, and Timme RJ; "Fuel Cell Combined Heat and Power Industrial Demonstration" FY 2011 Annual Progress Report, DOE Hydrogen and Fuel Cells Program.

2. U.S. Energy Information Administration, 2011, "Electrical Power Monthly, April 2011," DOE/EIA-0226 (2011/04), Washington, DC, USA.

3. U.S. Energy Information Administration, 2011, "Electric Power Annual, 2009," DOE/EIA-0348 (2009), Washington, DC, USA.

4. U.S. Energy Information Administration, 2011, "Natural Gas Monthly, April 2011," DOE/EIA-0130 (2011/04), Washington, DC, USA.