V.F.8 A Total Cost of Ownership Model for Design and Manufacturing Optimization of Fuel Cells in Stationary and Emerging Market Applications

Max Wei (Primary Contact), Roberto Scataglini, Hanna Breunig
Lawrence Berkeley National Laboratory (LBNL)
1 Cyclotron Road, MS 90R-4000
Berkeley, CA 94706
Phone: (510) 486-5220
Email: mwei@lbl.gov

DOE Manager: Donna Ho
Phone: (202) 586-8000
Email: Donna.Ho@ee.doe.gov

Subcontractors:
University of California, Berkeley, CA
Strategic Analysis, Arlington, VA

Project Start Date: October 1, 2011
Project End Date: September 30, 2016

Overall Objectives

- Develop total-cost-of-ownership (TCO) modeling tool for design and manufacturing of fuel cell systems in emerging markets (e.g., co-generation and back-up power systems) for low temperature (LT) polymer electrolyte membrane (PEM), high temperature (HT) PEM, and solid oxide fuel cell (SOFC) technologies.
- Expand cost modeling framework to include life-cycle analysis and possible ancillary financial benefits, including carbon credits, health and environmental externalities, end-of-life recycling, and reduced costs for building operation.
- Perform sensitivity analysis to key cost assumptions, externality valuation, and policy incentive structures.

Fiscal Year (FY) 2016 Objectives

- Update direct manufacturing cost model for SOFC fuel cell systems in combined heat and power and stationary power applications
- Revise total cost of ownership model for LT PEM combined heat and power (CHP) systems.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section (3.4) and the Manufacturing R&D section (3.5) of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

Fuel Cells

(B) Cost: Expansion of cost envelope to total cost of ownership including full life cycle costs and externalities

Manufacturing R&D

(A) Lack of High-Volume Membrane Electrode Assembly Processes

(B) Lack of High-Speed Bipolar Plate Manufacturing Processes

Technical Targets

This project is conducting cost of ownership studies of LT PEM, HT PEM, and SOFC fuel cell systems in non-automotive applications. Insights gained from these studies can be applied toward the development of lower-cost, higher-volume manufacturing processes that can meet the DOE combined heat and power system equipment cost targets (Table 1).

- PEM: For reference, the LT PEM and HT PEM costs from earlier work are shown.

TABLE 1. DOE Combined Heat and Power System Equipment Cost Targets

System	Units/yr (Annual Volume in MW)	2015 DOE equipment cost target with markup	2020 DOE equipment cost target with markup	This Work		
				LT PEM equipment cost with 50% markup	HT PEM equipment cost with 50% markup	SOFC direct equipment cost with 50% markup
10 kW CHP System	50,000 (500 MW)	$1,900/kW	$1,700/kW	$2,585/kW	$2,925/kW	$1,650/kW
100 kW CHP System	1,000 (100 MW)	$2,300/kW	$1,000/kW	$1,800/kW	$2,235/kW	$1,140/kW

- SOFC: Updated estimated costs are shown for SOFC CHP system direct equipment cost with a 50% markup in price. At the annual production volumes shown, the SOFC cost per unit kW is estimated to be about 35% lower than LT PEM systems.
- The 10-kW SOFC CHP system cost of $1,650/kW at an annual production volume of 50,000 units per year meets the 2020 DOE target under the assumptions made in this work, e.g., automated stack production processes and high process yields at high production volumes.
- The 100-kW SOFC CHP system cost of $1,140/kW at an annual production volume of 1,000 units per year exceeds the 2020 DOE equipment cost target by 14% under the assumptions made in this work, e.g., automated stack production processes and high process yields at high production volumes.

FY 2016 Accomplishments

- Updated direct manufacturing cost model for SOFC CHP applications.
- Revised total cost of ownership model for LT PEM CHP systems.

◆ ◆ ◆ ◆ ◆

INTRODUCTION

The DOE has supported cost analysis studies for fuel cell systems for both automotive [1,2] and non-automotive [3,4] systems over the last decade. These studies have primarily focused on the manufacturing costs associated with fuel cell system production. This project expands the scope and modeling capability from existing direct manufacturing cost modeling in order to quantify more fully the benefits of fuel cell systems by taking into account life cycle assessment, air pollutant impacts and policy incentives. TCO modeling becomes important in a carbon-constrained economy and in a context where health and environmental impacts are increasingly valued. TCO is also critical as an input to industry and governments decisions on funding research, development and deployment as well as an input to organizations and individuals who make long-term investment decisions.

Three components of the TCO model are (1) direct manufacturing costs, (2) life-cycle or use- phase costs, such as cost of operations and fuel, and (3) life-cycle impact assessment (LCIA) costs, such as health and environmental impacts. FY 2016 has been focused on updating the direct manufacturing cost model for SOFC systems for application in CHP and stationary power and updating the LCIA model for LT PEM CHP systems.

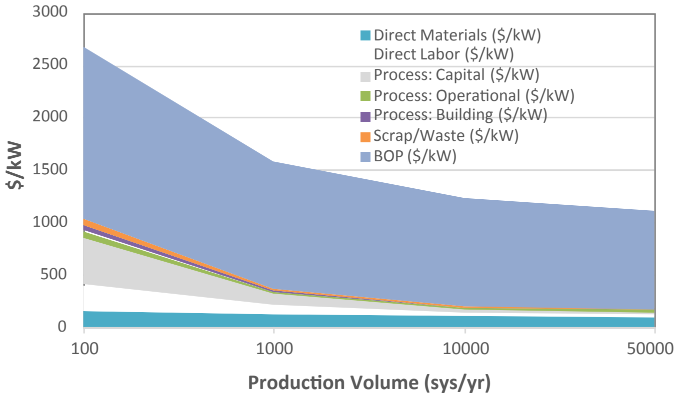
APPROACH

Data for system designs and component costing is derived from (1) existing cost studies where applicable, (2) literature and patent sources, and (3) industry and national laboratory advisors. Vertically integrated manufacturing is assumed for stack components with high-speed roll-to-roll processes for gas diffusion layer, gas diffusion electrode, and catalyst coated membrane components and largely purchased components for balance of plant. Life cycle or use-phase costing utilizes existing LBNL tools [5], a National Renewable Energy Laboratory database of commercial building electricity and heating demand profiles by building type and geographical region [6], and earlier CHP modeling work by one of the authors [7].

LCIA is focused on use-phase impacts from energy use, carbon emissions, and pollutant emissions [8], specifically on particulate matter emissions since particulate matter is the dominant contributor to life-cycle impacts [9]. The health impact from particulate matter is disaggregated by geographical region using existing LBNL health impact models [10] and an estimation of the amount of displaced grid-based electricity and heating fuel for a fuel cell CHP system in that building type and geographical region.

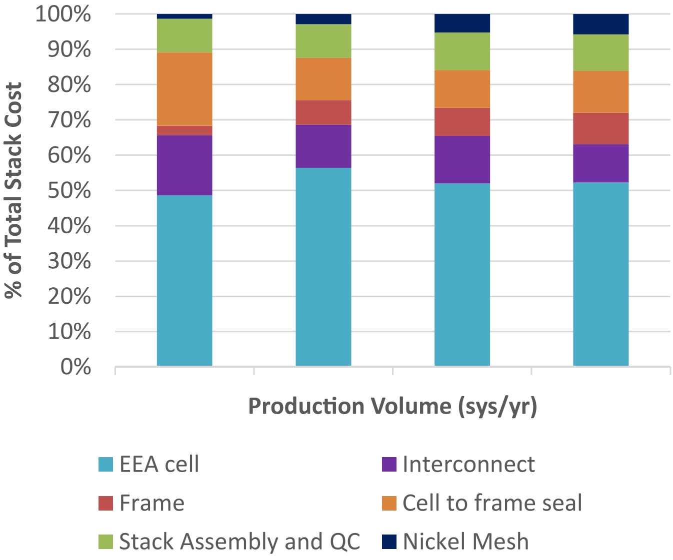
RESULTS

Direct cost modeling of SOFC stack has been revised to more accurately model labor requirements, factory costs, and the electrode/electrolyte assembly (EEA) sintering process, based on review of our assumptions with several manufacturing equipment vendors. Updated system costs are shown in Figures 1 and 2. Direct costs for SOFC CHP 10-kW systems are found to be $2,650/kW at annual production volumes of 100 systems per year and $1,100/kW at 50,000 systems per year (Figure 1). Balance of plant costs make up 60–80% of overall direct costs while Figure 2 shows



BOP - Balance of plant

FIGURE 1. 10 kW SOFC CHP direct costs vs. production volume



QC – Quality control

FIGURE 2. Break-down of total stack cost by module for 10 kW SOFC CHP system as a function of annual manufacturing volume

that stack costs are dominated by the EEA cell across all production volumes.

Detailed revisions were made to the LCIA (or externality valuation) models for LT PEM CHP systems and are summarized in Figure 3. First, monetary benefit estimates for displaced criteria pollutants (e.g., SO_2 and NO_x) in dollars per ton of emissions were updated from the Air Pollution Emission Experiments and Policy (APEEP) analysis model to revised values from AP2 [11]. These displaced criteria pollutant monetary benefits effectively increase the benefits by a factor three to five times over values from APEEP, but bring benefit estimates to the same range as estimates quoted by the Environmental Protection Agency in the Clean Power Plan (CPP) Regulatory Impact Assessment from October 2015 [12]. Second, marginal emission factors were revised from large-area North American Electric Reliability Corporation (NERC) regions from Siler-Evans et al. (2012) [13] to sub-regional emission factors from the Emissions & Generation Resource Integrated Database (eGRID) [14]. This provides greater regional specificity of pollutant emission factors (tons/kWh). The net of these changes is that total externality benefits (CO_2, health, environmental) are up to 5X greater than previously reported values. We find values for displaced grid-electricity emissions that are comparable to earlier reported data by Siler-Evans et al. (2013) [15], i.e., up to $0.10/kWh in the Midwest and upper Midwest.

The second extension to the LCIA model is that we have explored the reduction in externality benefits for fuel cell CHP from 2016–2030 assuming that the CPP is implemented as proposed. The CPP would reduce average CO_2 emissions by an estimated 13% from current levels and SO_2 and NO_x would be reduced an average of 80% and 50%, respectively across all NERC regions. Thus, the expected benefits of fuel cell CHP from displaced CO_2, NO_x, and SO_2, and other criteria pollutants would be reduced over time. Even with this clean-up of the electricity system, we find that the installation of LT PEM fuel cell CHP still has net positive societal benefits from 2016–2030 in regions which currently have high grid-electricity emissions (e.g., the upper Midwest). A notional or "societal" cash flow from 2016–2030 for a 50 kW LT PEM CHP system including total cost of ownership savings for a small hotel in Chicago is shown in Figure 4.

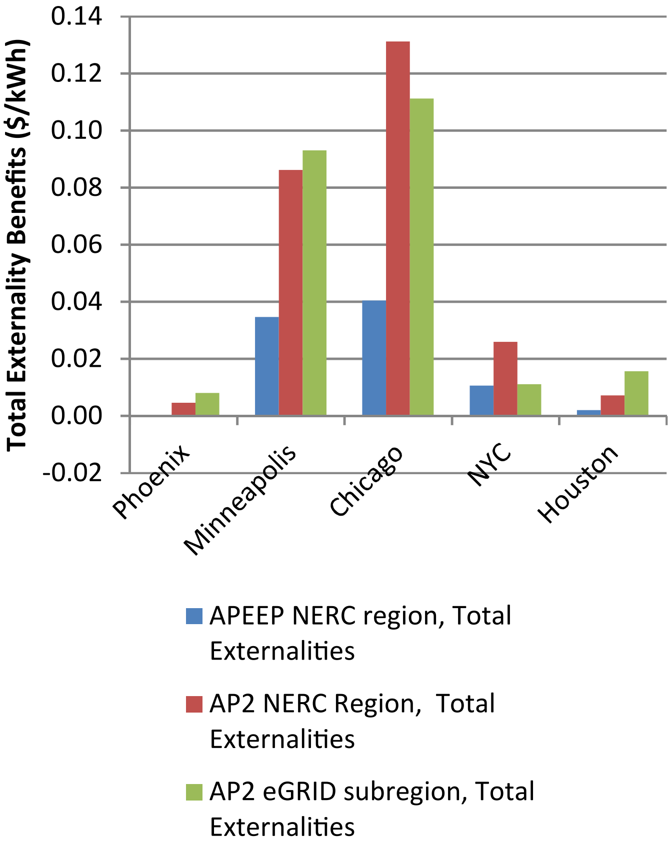
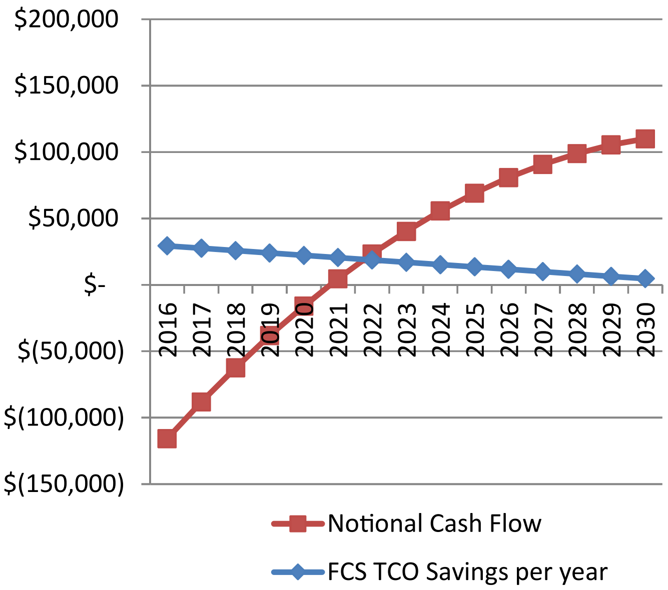


FIGURE 3. Updated externality savings per unit of displaced grid electricity for a 50 kW LT PEM CHP system in small hotels. The first bar for each city represents values used in the project's earlier modeling while the third bar represents values incorporating (1) updated AP2 externality valuation factors and (2) updated eGRID emission factors by subregion.

CONCLUSIONS AND FUTURE DIRECTIONS

- Direct costs for SOFC CHP 10-kW systems are found to be $2,650/kW at annual production volumes of 100 systems per year and $1,100/kW at 50,000 systems per year (Figure 3). Adding a 50% markup gives a direct equipment cost of $3,975/kW at 100 systems per year and $1,650/kW at 50,000 systems per year.



FCS – Fuel cell systems

FIGURE 4. Notional cash flow for a 50 kW LT PEM CHP system in small hotel in Chicago from 2016–2030 including total cost of ownership savings. Reductions in grid emissions factors for CO_2 and NO_x/SO_2 to 2030 are estimated from the CPP.

- Non-stack costs (balance of plant and fuel processor) are generally found to be the largest component of CHP system costs for LT PEM, HT PEM systems, and SOFC systems. For example, the BOP is estimated to be 60% of system cost at low volumes (100 systems per year) and 80% at high volumes (50,000 systems per year) for 10-kW SOFC CHP systems.
- Scenario modeling has been done for fuel cell system lifetime costs vs. the no-fuel cell case of grid electricity and conventional heating as a function of fuel and electricity costs, and the carbon intensity of grid electricity using goals from the CPP. Even with the CPP's proposed clean-up of the electricity system, we find that the installation of fuel cell CHP still has net positive societal benefits from 2016–2030 in regions which currently have high grid-electricity emissions (e.g., the upper Midwest).
- The research team plans to release an updated LT PEM total cost of ownership report in the final quarter of FY 2016.

FY 2016 PUBLICATIONS/PRESENTATIONS

1. Max Wei, Tim Lipman, Roberto Scataglini, Ahmad Mayyas, Shuk-Han Chan, Hanna Breunig, Tom McKone. "Total Cost of Ownership Model for SOFC CHP systems," Fuel Cell Seminar Conference, Los Angeles, CA. November 2015.

2. Roberto Scataglini, Ahmad Mayyas, Max Wei, Shuk Han Chan, Timothy Lipman, David Gosselin, Anna D'Alessio, Hanna Breunig, Whitney G. Colella, and Brian D. James. "A Total Cost of Ownership Model for Solid Oxide Fuel Cells in Combined Heat and Power and Power-Only Applications." Lawrence Berkeley Lab Report LBNL-1005725. December 2015.

REFERENCES

1. James, Brian, Kalinoski, J., and K. Baum. Mass-Production Cost Estimation for Automotive Fuel Cell Systems. 2010 Annual Merit Review Proceedings, Department of Energy, Hydrogen and Fuel Cells Program. Washington, D.C., June 2010.

2. Sinha, Jayanti and Y. Yang. *Direct Hydrogen PEMFC Manufacturing Cost Estimation* for Automotive Applications. 2010 Annual Merit Review Proceedings, Department of Energy, Hydrogen and Fuel Cells Program. Washington, D.C., June 2010.

3. Mahadevan, Kathya , V. Contini, M. Goshe, J. Price, F. Eubanks, and F. Griesemer. Economic Analysis of Stationary PEM Fuel Cell Systems. 2010 Annual Merit Review Proceedings, Department of Energy, Hydrogen and Fuel Cells Program. Washington, D.C., June 2010.

4. James, B., Spisak, A., Colella, W. *Manufacturing Cost Analysis of Stationary Fuel Cell Systems*, Strategic Analysis Inc. Arlington VA, September 2012.

5. Stadler, Michael, Marnay, C., Gonçalo Cardoso, G. et al. *The Carbon Dioxide Abatement Potential of California's Mid-Sized Commercial Buildings*. California Energy Commission, PIER Program. CEC-500-2010-050 (2011).

6. Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, B., Halverson, M., Winiarski, D., Rosenberg, M., Yazdanian, M., Huang, J., Crawley, D. (2011). *Reference Building Models of the National Building Stock*. NREL Technical Report NREL/TP-5500-46861.

7. Lipman, Timothy E., Jennifer L. Edwards, and Daniel M. Kammen, *Fuel Cell System Economics: Comparing the Costs of Generating Power with Stationary and Motor Vehicle PEM Fuel Cell Systems*, Energy Policy 32(1): 101–125 (2004).

8. Van Rooijen, Jaap. *A Life Cycle Assessment of the PureCell™ Stationary Fuel Cell System: Providing a Guide for Environmental Improvement, Center for Sustainable Systems*, Report No. CSS06-09 University of Michigan, Ann Arbor, MI, June 30, 2006.

9. National Research Council. *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*. The National Academies Press: Washington, D.C., 2010.

10. Muller, N.Z., and R.O. Mendelsohn, *The Air Pollution Emission Experiments and Policy Analysis Model (APEEP)*: Technical Appendix [online]. Yale University, New Haven, CT. December 2006. Available at: https://segueuserles.middlebury.edu/nmuller/APEEP_Tech_Appendix.pdf

11. AP2 Model, https://sites.google.com/site/nickmullershomepage/home/ap2-apeep-model-2, Accessed February 15, 2016.

12. Environmental Protection Agency 2015. *Regulatory Impact Analysis for the Clean Power Plan Final Rule*. October 23, 2015. Available at https://www.epa.gov/sites/production/files/2015-08/documents/cpp-final-rule-ria.pdf

13. Siler-Evans, K.; Lima Azevedo, I.; Morgan, M.G. *Marginal Emissions Factors for the U.S. Electricity System*. Environ. Sci. Technol. 2012. *46*, 4742–4748.

14. Environmental Protection Agency 2015. eGRID database, https://www.epa.gov/energy/egrid, Accessed February 15, 2016.

15. Kyle Siler-Evans, Inês Lima Azevedo, M. Granger Morgan, and Jay Apt, *Regional variations in the health, environmental, and climate benefits of wind and solar generation*, PNAS 2013 110 (29) 11768–11773.