V.A.3 Stationary Fuel Cell System Cost Analysis

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Fiscal Year (FY) 2012 Objectives

- Perform Design for Manufacturing and Assembly (DFMA®) cost analysis for low-temperature (LT) proton exchange membrane (PEM), high-temperature (HT) PEM, and solid oxide fuel cell (SOFC) systems at manufacturing rates of 100, 1,000, 10,000, and 50,000 systems per year for 1-kilowatt-electric (kWe), 5-kWe, 25-kWe, and 100-kWe systems.
- Explore sensitivity of DFMA® cost to design parameters.
- Validate cost results and sensitivities against industry partner costs.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

(B) System Cost
    - Realistic, process-based system costs
    - Need for realistic values for current and future cost targets
    - Demonstrates impact of technical targets and barriers on system cost:
        - Balance of plant
        - Materials of construction
        - System size and capacity (weight and volume)

(H) Balance-of-Plant (BOP) Components

Technical Targets

This project conducts cost modeling to attain realistic, process-based system costs for a variety of stationary fuel cell systems. These values can help inform future technical targets for stationary fuel cell system cost.

FY 2012 Accomplishments

- Completed preliminary DFMA® cost analysis for LT PEM, HT PEM, and SOFC systems at manufacturing rates of 100, 1,000, 10,000, and 50,000 systems per year for 1-kWe, 5-kWe, 25-kWe, and 100-kWe systems.
- Identified primary capital cost drivers for all systems, with roughly ~40% of capital costs stemming from the fuel processing sub-system and ~40% of capital costs from the fuel cell sub-system, depending on the production rate, system size, and fuel cell type.
- Quantified the marginal increase in capital cost for grid-independent operation (5% to 10% of total capital costs) and for combined heat and power (CHP) operation (2% to 5% of total capital costs).
- Calculated the decrease in fuel cell system (FCS) capital cost with increased FCS size (for example, 100-kWe SOFC systems are 18% of the cost of 1-kWe systems at a global installed capacity of 10,000 kWe in one year; 5-kWe SOFC systems are 43% of the cost of 1-kWe systems for a 50,000 kWe global installed capacity in one year.)

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Introduction

To better assess the potential usefulness and market-worthiness of stationary FCSs, this work describes a DFMA®-style [1] analysis of the cost to manufacture a series of stationary FCSs. The manufacturing costs of stationary FCSs based on three different fuel cell technologies are studied: LT PEM, HT PEM, and SOFC. The FCS's fuel processing subsystem includes a steam reforming reactor external to the fuel cell stack that converts natural gas into a hydrogen-rich gas for the fuel cells. Systems are cost-modeled with peak electrical capacities of 1 kWe, 5 kWe, 25 kWe, and 100 kWe across annual production rates of 100, 1,000, 10,000, and 50,000 systems per year. In addition, this analysis assesses the marginal cost increase from enhancing an electricity-only FCS (base design) to one that can serve CHP applications [2] and/or grid-independent conditions.

This work focuses primarily on efforts to design and cost-model LT PEM, HT PEM, and SOFC stationary systems. Each system's stack, fuel processor, and BOP design and performance parameters are discussed and the methods of cost-modeling are explained. Cost trends are evaluated in terms of the capital costs per unit ($/kWe) as a function of system installed capacity, system annual production rate, and individual system capacity for the same global installed capacity. Finally, LT PEM, HT PEM, and SOFC system costs are compared.

Approach

The cost model relies upon a DFMA®-style methodology to determine the cost to manufacture several stationary system designs at varied rates of production. The methodology consists of three major steps: (1) System Conceptual Design, (2) System Physical Design, and (3) Cost Modeling.

(1) System Conceptual Design

A main purpose of the system conceptual design phase is to develop a conceptual model of a fully functional FCS with defined thermodynamic performance. In this phase, design requirements are identified and performance parameters are determined. Design requirements include considerations such as system technology (LT PEM, HT PEM, SOFC), system-rated electrical output (1, 5, 25, and 100 kWe for each technology), whether to allow for CHP operation or grid-independent operation, input fuel composition, water neutrality, and so forth. Once these design requirements are identified, a conceptual system can be laid out which satisfies the requirements. Detailed designs are developed for the four main fuel cell subsystems: the fuel cell subsystem, the fuel processing subsystem, the electrical management subsystem, and the thermal management subsystem. The entire FCS is modeled within Aspen HYSYS® process modeling software to determine performance parameters such as net system electrical efficiency, flow rates, temperatures, and pressures. Table 1 indicates several of the key design assumptions made for the SOFC system. Reference to existing FCSs is made to assure the performance parameters are consistent with expected values for systems with similar performance and operational goals. The system conceptual design also facilitates the next stage, system physical design, by identifying all required system components and their physical constraints, for example mass flow quantities, operating temperatures, and heat exchanger area.

TABLE 1. SOFC System Design Assumptions

Assumption	Value
Design Stack Power Density	291 mW/cm^2 (0.8 volts/cell at 364 mA/cm^2)
Stack Geometry	Planar SOFC geometry
Electrolyte Manufacturing Method	Tape casting
System Net Electrical Efficiency	49% (Net Alternating Current Electrical Out/Natural Gas Higher Heating Value Input)
Operating Pressure	1 atm
Reactants	Fuel: reformate gas from the stream reformer, oxidant: air
Electrode Material	Yttria-Stabilized Zirconia (YSZ)
Cathode Catalyst Material and Application Method	Lanthanum strontium cobalt ferrite, screen-printing
Anode Catalyst Material and Application Method	Nickel cobalt, spray deposition

(2) System Physical Design

A main purpose of the system physical design phase is to develop detailed bills of materials for each major system and subsystem component. The system physical design is based on the system conceptual design. For standardized components such as compressors, blowers, sensors, heat exchangers, piping, etc. (common in the BOP), it is sufficient to use the required performance parameters to obtain an appropriate price quote for each piece of equipment. For integral components for which a full DFMA®-style analysis will be performed, the system physical design step involves determining the full physical embodiment of the system, including materials, geometry, and manufacturing methods. Design for this step is supplemented by assistance from industry partners and previous design work. For example, the fuel processor subsystem design is based upon an integrated reactor designed by Tokyo Gas [3,4]. For the LT and HT PEM FCSs, fuel cell subsystem designs are based upon prior work on automotive PEM subsystems, adapted for the new requirements identified in the previous step [5,6]. The physical design for the SOFC stack was based upon the FlexCell SOFC system by NexTech [7].

(3) Cost Modeling

Once the physical embodiment has been determined, costs can be modeled. There are two levels of detail in cost modeling: (A) detailed DFMA®-style cost modeling of the core system components, and (B) less detailed quote-based cost estimates of standardized components common in the system BOP. For (A), a full physical, manufacturing process train is specified. For (B), mass-produced cost estimates are obtained for all subcomponents via industry quotes.

Iteration

To reduce costs and optimize system performance, changes at all stages of the modeling and design process are constantly considered as the system conceptual design, system physical design, and manufacturing cost models are developed. Additionally, feedback from industry is continuously incorporated into this work. Thus, the three-step methodology is constantly iterated upon. New design approaches and physical system embodiments are continually examined, and the cost model refined, with the primary aim of identifying the design and manufacturing processes that result in the lowest system cost.

Results

The cost analysis yields preliminary results detailing the final estimated capital cost of the entire stationary FCS, at different annual manufacturing rates and installed capacities. As shown in Figure 1, the capital cost per unit of electric output ($/kWe) is seen to decrease dramatically both with increasing system size and increasing system annual production rate. Example results shown are for SOFC systems.

Results also indicate the proportion of capital cost attributable to each subsystem and subsystem component. Figure 2 (for an SOFC system) shows that the marginal increase in cost between producing a basic system which is not capable of CHP or grid-independent operation and producing a more advanced FCS that is capable of both CHP and grid-independent operation is in fact relatively small, with grid-independent operation capital costs representing 5% to 10% and CHP operation capital costs representing only 2% to 5% of the overall capital cost of such a system.

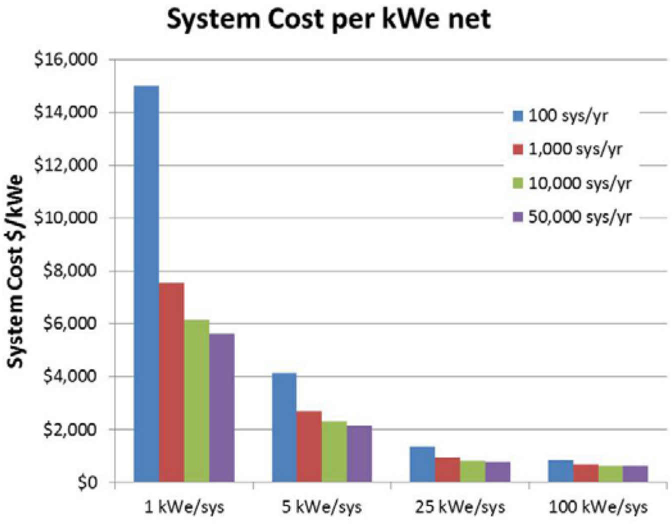

FIGURE 1. Total SOFC system cost results across all system sizes and production rates

Figure 3 breaks down total system capital costs for the baseline 5-kWe SOFC system (i.e. no CHP or grid independent operation) into six different categories. These categories are exhaust gas heat exchanger/condenser, housing and final assembly, power electronics subsystem, cost margin, fuel processing subsystem, and fuel cell stack subsystem. As evident from the figure, the greatest contributors to the capital cost are the fuel processing subsystem and the fuel cell subsystem, together representing 2/3^{rds} to 3/4^{ths} of the total system capital cost. Model results also tabulate the capital cost breakdowns for the fuel

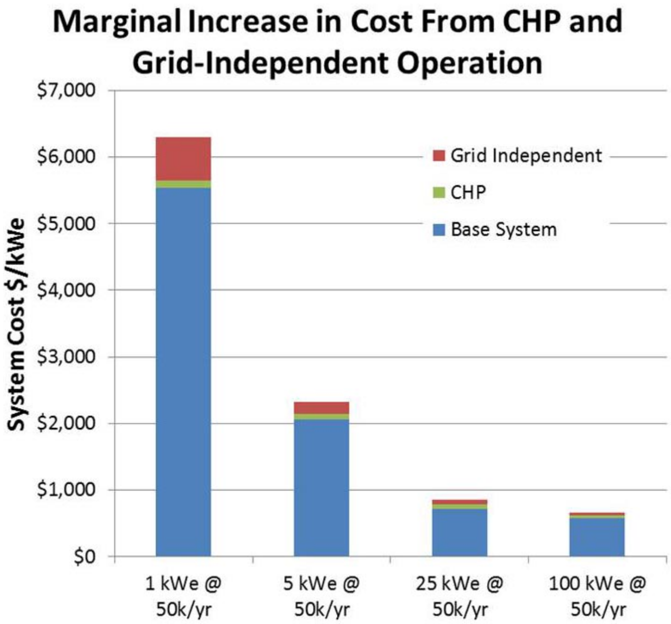

FIGURE2. Marginal increase in cost with CHP and with grid-independent operation

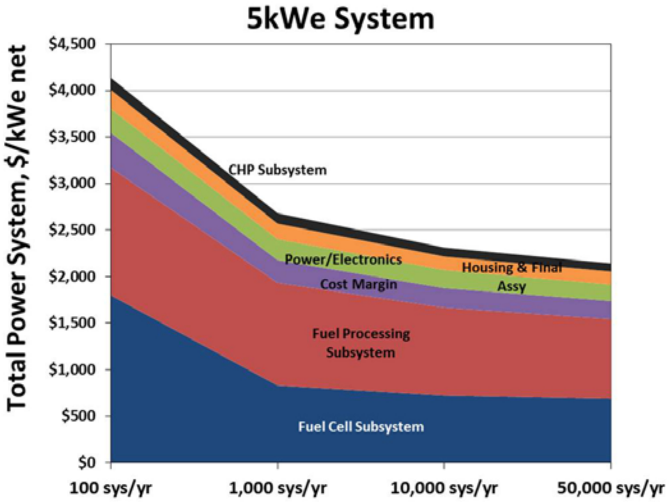

FIGURE 3. SOFC subsystem cost breakdown for a 5-kWe system

processing subsystem's BOP. For example, within the fuel processor BOP of the 5-kWe SOFC system, the natural gas compressor and the condenser are identified as large cost contributors and thus are prime candidates for cost reduction efforts.

Model results indicate that, at the same cumulative global installed capacity, higher power FCSs are expected to have lower per unit capital costs ($/kWe) than lower power FCSs. For the same cumulative global installed capacity in a given year, FCSs with a higher electrical power output are several times more economical per kilowatt of electric power than systems with a lower power output. For example, for a 10,000 kWe global installed capacity in one year, 100-kWe SOFC systems are 13% of the cost of 1-kWe systems ($836/kWe vs. $6,157/kWe). For a 50,000 kWe global installed capacity in one year, 5-kWe SOFC systems are 41% of the cost of 1-kWe systems ($2,312/kWe vs. $5,651/kWe). For a 250,000 kWe global installed capacity in one year, 25-kWe SOFC systems are 39% of the cost of 5-kWe systems ($828/kWe vs. $2,142/kWe). This analysis implicitly assumes that the FCS electricity and heat will be used with 100% utilization in the buildings that they serve, regardless of system size. In practice, lower power FCSs may experience higher utilizations than higher power systems [8,9]. Also, the total market volume for lower power FCSs may be larger, allowing for higher production rates.

Additional results include the comparison of fuel cell stack cost to fuel cell subsystem BOP at different system sizes. Results indicate that for a 1-kWe SOFCs, at the highest production rates evaluated (50,000 units/year), the BOP is the largest contributor to fuel cell subsystem capital costs. At this fuel cell size and production rate, BOP costs are higher than stack costs. By contrast, for higher power SOFCs, stack costs dominate subsystem costs. Results further indicate that, in the larger 5-kWe SOFC systems, the stack costs are the largest contributor to the fuel cell subsystem capital costs. For comparison, at the same 5-kWe level, fuel processor BOP costs dominate fuel processing subsystem capital costs. The fuel processing reactor itself did not contribute greatly to the cost. Model results indicate that fuel processor BOP costs are the largest contributor to fuel processing subsystem capital costs for all SOFC sizes and production rates.

Model results indicate that LT PEM stacks are less expensive than SOFC and HT PEM stacks. Based on a series of parallel analyses conducted for HT PEM [10] and LT PEM FCSs [11], for a 100-kWe stack at a production volume of 10,000 units per year, stack costs are $129/kWe for LT PEM, $352/kWe for HT PEM, and $318/kWe for SOFC. (Stack power densities assumed in these analyses are 408 mW/cm^2, 240 mW/cm^2, and 291 mW/cm^2, respectively.) According to these data, SOFC stack capital costs are about 10% lower than HT PEM stack capital costs but 2.5 times higher than LT PEM stack capital costs. These results are preliminary and analysis is still underway. Further, the PEM cost models used in this comparison have been fine-tuned over the past 15 years [12,13] whereas the SOFC models have only been recently developed. Consequently, the cost estimates may shift as the analysis is refined. Computation of the total system costs for LT PEM, HT PEM, and SOFC are not yet complete, thus preventing a total system cost comparison at this time.

It is further noted that the cost comparisons between fuel cell technologies in this analysis apply only to initial capital cost rather than to life-cycle cost. The projected net system electrical efficiency based on higher heating value of natural gas of the SOFC FCS (49%) is substantially higher than that of LT PEM (32%) or HT PEM (27%). While a life-cycle analysis has not been conducted, it is expected that the higher net electrical efficiency of the SOFC system could substantially off-set the higher initial stack capital cost.

Conclusions and Future Directions

The primary findings of this analysis of stationary LT PEM, HT PEM, and SOFC systems relate to the key cost drivers across the range of analysis, from the low power (1-kWe) FCSs to the large (100-kWe) FCSs and from low production (100 systems/year) to higher production rates (50,000 systems/year). Based on the analysis presented here, it was found that for a given cumulative global installed quantity, FCS capital costs are lower if manufacturers produce fewer very large systems as compared to a large number of lower power systems. Thus, while both production quantity and system size drove cost down, capital cost was found to be more sensitive to system size than to production rate. At the same time, this analysis does not consider other important economic factors, including life-cycle costs, market accessibility, and FCS in-use heat recovery and electrical efficiency within buildings. Additional results quantify the relative cost contribution of various subsystems. The greatest contributors to the FCS capital cost are the fuel processing subsystem and the fuel cell subsystem, together representing 2/3$^{\text{rds}}$ to 3/4$^{\text{ths}}$ of the total system capital cost. Furthermore, model results indicate that the addition of CHP and grid-independent operation adds only about 10% to total system capital costs, compared with the base case design involving no CHP or grid-independent operation. Finally, model results indicate that SOFC stack capital costs are about 10% lower than HT PEM stack capital costs, and SOFC stack capital costs are about 2.5 times higher than LT PEM stack capital costs

FY 2012 Publications/Presentations

1. James, Brian D., Spisak, Andrew, Colella, Whitney G. "Combined heat and power (CHP) and Grid-Independent Stationary Fuel Cell Systems (FCSs) -- Conceptual and Physical Design and Capital Cost Estimates," American Society of Mechanical

Engineers (ASME) 2012 International Mechanical Engineering Congress and Exposition, Houston, Texas, November 9th-15th, 2012.

2. James, Brian D., Spisak, Andrew, Colella, Whitney G. "Design for Manufacturing and Assembly (DFMA) Cost Estimates of Stationary Fuel Cell Systems," Fuel Cell Seminar, November 5th–8th, 2012.

3. James, Brian., "Fuel Cell Transportation Cost Analysis, Preliminary Results," *Department of Energy (DOE) Fuel Cell Technology (FCT) Program Annual Merit Review*, Washington, D.C., May 14–18th, 2012.

4. James, Brian D., Perez, Julie., Baum, Kevin N., Spisak, Andrew, Sanders, Matt. "Low Temperature PEM Stationary Fuel Cell System Cost Analysis," *2011 Fuel Cell Seminar*, Orlando, Florida, 1 November 2011.

6. James, B., "Fuel Cell Transportation Cost Analysis, Preliminary Results," *United States (U.S.) Department of Energy (DOE) Fuel Cell Technology (FCT) Program Annual Merit Review*, Washington, D.C., May 17th, 2012.

7. NexTech Materials, Ltd., *Validation of Novel Planar Cell Design for MW-Scale SOFC Power Systems: Final Technical Report*, December 31, 2011.

8. Colella, W.G. and Srivastava, V., 2012, "Examining the Integration of Fuel Cell Systems Into Buildings Through Simulation," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23–26, 2012, San Diego, CA, USA. ESFuelCell2012-91474. PNNL-SA-87066.

9. Colella, W.G. and Pilli, S.P., 2012, "Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23–26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709.

10. James, B., Perez, J., Baum, K., Spisak, A., Sanders, M., *High Temperature PEM Stationary Fuel Cell System Cost Analysis*, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies (FCT) Program, Forrestal Building, Washington, D.C., Nov. 11th, 2011.

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12. James, B., Lomax, F., Thomas, S. and Colella, W.G., *PEM Fuel Cell Power System Cost Estimates: Sulfur-Free Gasoline Partial Oxidation and Compressed Direct Hydrogen*, report for the U.S. Department of Energy, 1997.

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2. Colella, W.G., Niemoth, C., Lim, C., Hein, A. "Evaluation of the Financial and Environmental Feasibility of a Network of Distributed 200 kWe Cogenerative Fuel Cell Systems on the Stanford University Campus," *Fuel Cells – From Fundamentals to Systems*, 1, 148-166, Feb. 2005.

3. Komiya, J., et al., "Single-Pipe Cylinder-Type Reformer." US Patent 7,037,472, issued May 2, 2006.

4. Miura, T., et al., "Cylindrical Steam Reforming Unit." US Patent 7,182,921, issued February 27, 2007.

5. James, B., J. Kalinoski, and K. Baum, "Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications: 2010 Update," September 30, 2010.