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Recipient: Battelle

Final Report
Stationary and Emerging Market Fuel Cell System Cost Assessment

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Executive Summary

The U.S. Department of Energy (DOE) is focused on providing a portfolio of technology solutions to meet energy security challenges of the future. Fuel cells are a part of this portfolio of technology offerings. To help meet these challenges and supplement the understanding of the current research, Battelle has executed a five-year program that evaluated the total system costs and total ownership costs of two technologies: (1) an ~80 °C polymer electrolyte membrane fuel cell (PEMFC) technology and (2) a solid oxide fuel cell (SOFC) technology, operating with hydrogen or reformate for different applications.

Previous research conducted by Battelle, and more recently by other research institutes, suggests that fuel cells can offer customers significant fuel and emission savings along with other benefits compared to incumbent alternatives. For this project, Battelle has applied a proven cost assessment approach to assist the DOE Fuel Cell Technologies Program in making decisions regarding research and development, scale-up, and deployment of fuel cell technology.

The cost studies and subsequent reports provide accurate projections of current system costs and the cost impact of state-of-the-art technologies in manufacturing, increases in production volume, and changes to system design on system cost and life cycle cost for several near-term and emerging fuel cell markets. The studies also provide information on types of manufacturing processes that must be developed to commercialize fuel cells and also provide insights into the optimization needed for use of off-the-shelf components in fuel cell systems. Battelle's analysis is intended to help DOE prioritize investments in research and development of components to reduce the costs of fuel cell systems while considering systems optimization.

Project Goals/Objectives and Accomplishments

The following applications and power levels for fuel cell systems were evaluated over the five-year program with associated reports delivered to DOE and published under the same contract number:

- primary power and combined heat and power (CHP) applications at power levels of 1, 5, 10, 25, 100, and 250 kilowatts (kW);
- auxiliary power unit (APU) applications at power levels of 1 and 5 kW;
- material handling equipment (MHE) applications at power levels of 1, 5, 10, and 25 kW; and
- backup power applications at power levels of 5 and 10 kW.

The analyses also considered variable rates of production; 100, 1,000, 10,000, and 50,000 units per year were considered. Attractive value propositions were found for the MHE and primary power and CHP applications, while the APU and backup power applications value propositions were less clear. For all applications, BOP was found to be the dominant cost driver.

The program was broken out into 12 specific tasks; Table 1 shows the goals / objectives and lists the major accomplishments associated with each task.

Table 1. Project goals / objectives and significant accomplishments by task.

Task	Goal / Objective	Significant Accomplishments
1 - Program Management and Quality Control	Use standard project management principles to guide the project and ensure that project work and deliverables are of highest quality.	• Performed program management, quality management, and administration activities (weekly internal team meetings, biweekly to monthly meetings with DOE, participation in the DOE peer review, communication of results to DOE and industry stakeholders, budget tracking, and quarterly reporting). • Prepared annual project plans identifying schedule, key tasks, milestones, and deliverables; presentation and publication for the DOE peer review; quarterly reports; midpoint review presentation and final review presentation with DOE; and final report at the end of each budget period. • Conducted quality management to produce project work and deliverables of the highest quality. Applied certified quality control (QC) processes. Identified all assumptions and documented the basis for each assumption. • Periodically performed independent reviews to maintain quality during the Design for Manufacture and Assembly (DFMA®) modeling process, bill of materials (BOM) development, and cost estimation process. • Internally reviewed all project deliverables (e.g., engineering diagrams, reports, cost models, cost estimates) to ensure that each deliverable was accurate and technically sound and met or exceeded client expectations.
2 - Establish Application Requirements	Define the basis for fuel cell system design.	• Identified operation and performance requirements for various applications and markets by reviewing and augmenting previous analysis based on discussions with end users. • Gathered information on durability, cycling, lifetime, and operating conditions required for lift truck operation in Year 1 to support the basis for system design; performed similar analysis each year.

Task	Goal / Objective	Significant Accomplishments
3 - Develop Baseline System Design and Improvements	Develop a baseline stack and system design and define near-term improvements. Determine whether some designs are more suitable for a specific application. Select specific system designs as the focus of analysis in a given budget period.	• Gathered information from published literature, Battelle's engineering experience, and input from external stakeholders. • Vetted the fundamental design, detailed design, and potential improvements with DOE, component suppliers, system integrators, and stack manufacturers to further improve the baseline design. • Defined a final baseline design and improvements to the baseline design with increasing production volumes and advancements in technology. • Generated a BOM and a table of system specifications and operational parameters.
4 - Identify Manufacturing Processes	Update and define additional manufacturing processes for fuel cell-specific and non-commercial off-the-shelf components identified in the system design.	• Reviewed the literature and discussed processes with component suppliers, equipment manufacturers, and tooling companies. • Defined manufacturing processes and updated the BOM, noting which items would be manufactured and which would be procured externally.
5 - Gather Vendor Quotes	Define the basis for estimating costs in the DFMA® and system cost analysis.	• Identified potential vendors through Battelle's existing network of manufacturing vendors, through literature, and through industry stakeholders. • Gathered vendor quotes for capital equipment required for production, materials to be used in production, commercially available balance of plant (BOP) components, and other outsourced activities. • Documented vendor quotes and incorporated vendor quotes into the DFMA® analysis and BOM.
6 - Conduct DFMA® Analysis	Use DFMA® software and methodology to systematically estimate the total manufacturing cost of various system components and of the system at various production volumes. Conduct a comparative cost analysis so as to redesign a system for lowest cost.	• Defined and parametrically modeled custom manufacturing process models based on knowledge of the machine, energy, and labor requirements for individual process steps. • Developed and analyzed the sequence of actions required to assemble the components and test the final fuel cell system for cost reduction opportunities through component consolidation and process optimization. • Used component costs calculated from both custom and library manufacturing processes in the assembly and test sequence models to determine the final cost of producing the fuel cell systems. • Used the output of the DFMA® models to calculate production line utilization to determine the number of individual process lines required to support various product demand levels, which were used as input to the manufacturing capital cost model.

Task	Goal / Objective	Significant Accomplishments
7 - Develop Total System Costs	Determine total system cost by totaling the applicable component costs (both procured and manufactured), system assembly costs, and capital costs.	• Integrated outsourced component costs obtained through vendor quotes with DFMA® manufacturing costs to determine the total cost of system components. • Using the DFMA® production models, determined system assembly, test, and conditioning costs. • Amortized capital expenditures for production and equipment over a 20-year period and distributed the annual amortized cost over the production volume for that year.
8 - Solicit Feedback from Stakeholders	Obtain stakeholder feedback to the preliminary stack and system cost estimate.	• Presented the methodology, design, assumptions, manufacturing process details, and stack and system costs to DOE, fuel cell component makers, system integrators, and stack manufacturers. • Hosted a teleconference for all interested stakeholders. • Documented comments received and shared them with DOE.
9 - Update System Costs	Prepare and publish final stack and system costs.	• Considered comments received from stakeholders and incorporated appropriate improvements in cooperation with DOE. • Reran cost models. • Prepared and submitted final stack and system costs.
10 - Conduct Sensitivity Analysis	Consider sensitivity of total system costs to changes in system design parameters, costs of materials, and application requirements.	• Discussed sensitivity factors to be considered with DOE and incorporated recommendations into the analysis. • Provided sensitivity plots in the final report for each application analyzed.
11 - Conduct Life Cycle Cost Analysis	Estimate the life cycle costs for owning and operating the fuel cell systems based on the defined application requirements.	• Used Battelle's modified Hydrogen Analysis (H2A) model to estimate life cycle costs and updated costs as required. Assumptions used were consistent with the current H2A model developed by DOE. • Provided estimates of the total costs of ownership and sensitivity of application requirements, system costs, and performance parameters on total costs of ownership.
12 - Publish Findings	Prepare and publish a comprehensive final report for the budget period.	• Documented the methodology, assumptions, findings of the manufacturing and life cycle cost assessment, findings of the sensitivity analysis, and feasible pathways forward to reduce stack, total system cost, and total ownership costs. • Provided a draft report to DOE for comment and a final report after comments on the draft report were received.

Summary of Project Activities

Primary Power and Combined Heat and Power Applications

For these applications, fuel cell power systems may be beneficially used to offset all or a portion of grid-purchased electrical power and supplement on-site heating requirements. The fuel of choice will usually be pipeline natural gas or on-site propane storage. These fuel sources generally have much higher reliability than utility electric power as they are less subject to damage-related outages. Therefore, they can provide some continued operation in the event of grid outage, performing both primary power and backup power functions. Battelle evaluated low-temperature polymer electrolyte membrane (LTPEM) and solid oxide fuel cell (SOFC) systems for use as a continuous power supplement (primary power) and to provide auxiliary heating in combined heat and power (CHP) configurations.

1- to 25-kW Fuel Cell Systems

The power levels considered for this portion of the project were 1, 5, 10, and 25 kilowatts (kW). A primary-power/CHP commercial market has not yet developed in the 1- to 25-kW range; however, our analysis suggests an attractive business opportunity under the right conditions.

In the absence of a developed market and commercially available systems for analysis, Battelle defined and evaluated representative systems that could serve a hypothetical market such as restaurants. The representative system concepts were subjected to detailed cost evaluation based on industry feedback and the application of standard design for manufacturing and assembly analysis methods, including the application of the Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA®) software for specific hardware and assembly evaluation. A sensitivity analysis was performed to evaluate the influence of specific high-cost items and components with a high degree of cost uncertainty.

The evaluation showed that the highest cost category for these systems was the balance of plant (BOP) hardware. Within the overall BOP, the hardware directly related to connecting to the grid and providing heat to an on-site process (e.g., water heating) represents a major portion of the cost for both PEM and SOFC systems. This hardware includes the power electronics (direct current/direct current [DC/DC] converter and direct current/alternating current [DC/AC] inverter), energy storage to enable grid-outage operation, and the appropriate hardware for continuous connection to a utility electric grid. For PEM systems, the fuel processing costs were comparable to the grid/CHP hardware costs. For SOFC systems, the fuel processing costs were significantly lower due to the ability of the SOFC stack to accept partially reformed fuel and benefit from internal reforming. Stack costs were less than 30% of the overall system cost for all technologies and system sizes once production volumes reached 1,000 units/year—and less than 10% in several cases. PEM stack costs were lower than SOFC stack costs for all sizes and production volumes, though the difference becomes negligible at larger sizes and higher production volumes.

A life cycle cost analysis was performed for restaurants in two U.S. locations: San Diego, California, and Honolulu, Hawaii. Both locations showed attractive return on investment (ROI) through operational savings without taking any credit for avoided losses that would occur in the case of a grid outage without backup power. Both sites had high electricity costs, which helped to offset the initial cost of the CHP system. Payback was estimated as under three years for all cases analyzed at these two locations, and internal rate of return was on the order of 28% or greater for the projected five-year life of a system. Future cost reduction opportunities identified can make the systems attractive in a wider range of locations with lower spark spreads, and improvements in reliability will extend the projected life, resulting in higher rates of return. Site-specific assessment of grid outage impact (loss of refrigerated food, loss of ongoing business, loss of data) without backup power will provide additional incentive to install these systems. Key assumptions to enable this value proposition include electrical and system efficiencies of the systems and the lifetime (durability) of the systems in the field.

100- and 250-kW Fuel Cell Systems

The power levels considered for this portion of the project were 100 kW and 250 kW. A significant primary-power/CHP commercial market has not yet developed in this size range; however, our analysis suggests an attractive business opportunity under the right conditions. Indeed, FuelCell Energy, Bloom, and Doosan are approaching the primary power market with three different fuel cell technologies (molten carbonate, solid oxide, and phosphoric acid, respectively) and are achieving some market penetration. Based on the installed applications from these companies, we believe that fuel cell systems of this size will primarily serve medium to large commercial buildings, data centers, product distribution centers, and light industrial fabrication/manufacturing sites. We also suggest that utility operators and municipality-operated power companies may find these systems attractive for distributed generation and electric power islanding support.

In the absence of a developed market and publicly available system configuration information, Battelle's evaluation included the definition of representative systems that could serve this market. The representative system concepts were subjected to detailed cost evaluation based on industry feedback and the application of standard design for manufacturing and assembly analysis methods, including the application of the BDI DFMA® software for specific hardware and assembly evaluation. A sensitivity analysis was performed to evaluate the influence of high-cost/custom subassemblies and components with a high degree of cost uncertainty. Commercially available components and commodity materials generally have a low level of variability and do not significantly impact the overall economics. Because some of the commercially available BOP hardware for systems in this range is commonly configured for different operating conditions (typically higher pressure), some assumptions were required regarding customization of hardware such as heat exchangers.

The evaluation shows that the highest cost category for these systems is the BOP hardware directly related to connecting to the grid—the inverter. For this evaluation, we selected recently developed hybrid inverters which incorporate a separate DC input/output (I/O) port for connection to batteries. These inverters, while initially more expensive than a more conventional inverter, eliminate the need for a DC/DC converter to match battery voltage, as we have used in other system analyses. Eliminating the DC/DC converter saves significant cost, though the power electronics still represent the highest-cost system component. Hybrid inverters are relatively new technology developed primarily for solar applications, and their costs (particularly for higher volumes) are not well defined. Therefore, while the selection of the hybrid inverter does represent some uncertainty, the benefit is so clear for both fuel cell and solar installations that we believe some version of hybrid inverter will be available for fuel cell systems.

Heat exchangers, particularly high-temperature heat exchangers, also represent a major portion of the BOP. For the PEM system, the most expensive heat exchanger was the steam superheater/reformate cooler. Our cost for this heat exchanger was based on a commercially available heat exchanger that is overdesigned for the application and is hence probably more expensive than necessary. A designed-to-purpose heat exchanger, not evaluated in this study, may offer notable savings.

PEM stack costs were less than 18% of overall system cost for all sizes and production volumes considered, averaging 14% at the higher production volumes. SOFC stacks, however, represented a notably larger fraction of overall costs, ranging from 25% to 35% for all sizes and production volumes considered as a result of a much simpler BOP.

A sensitivity analysis of some of the major cost contributors shows the potential for further cost reductions through design-to-purpose engineering for some high-cost items, especially for heat exchangers. Unlike other studies, we found the price of platinum to have a minor overall impact on the PEM system cost. This outcome primarily results from the relatively small overall contribution of the stack-to-system costs at this size. As noted above, a significant cost benefit at the system level was achieved by using a hybrid converter in place of a DC/DC converter and separate DC/AC inverter. Although not specifically considered in the sensitivity analysis, we outlined a possible method of directly connecting batteries in parallel with the fuel cell that may be satisfactory for some applications, providing another path to cost reduction.

A life cycle cost analysis was performed for a nominal commercial installation requiring electrical power and additional heating or cooling energy input. With or without a supplemental heat requirement, the analysis showed a significant positive ROI with greater than 50% internal rate of return (IRR) for locations where electricity prices are high and natural gas prices are low. For example, in California, the spark spread is approximately $0.145. For applications with a need for supplemental space or process heating, the number of attractive geographic installation sites increases since lower spark spreads can still yield positive ROI. The analysis considered the utility costs for specific states, finding several to be attractive for fuel cell installations. However, when the overall gas and electricity cost averages for the Unites States in 2015 were considered, the ROI was not good until high production volumes, greater than 10,00 units per year, were reached and heat recovery was needed, suggesting that additional capital cost reduction is needed to achieve widespread acceptance.

Our analysis showed that the stack costs, while a significant portion of the overall system costs, may not be the most critical area in need of development for achieving attractive initial costs. Instead, engineering activities focused on addressing cost reductions for power electronics (all systems) and heat exchangers (primarily PEM systems) are appropriate. SOFC systems were found to have better ROI than PEM systems based on initial costs and overall efficiency; however, the lifetime for SOFC stacks has not yet been demonstrated to the necessary level under deployed operating conditions.

Material Handling Applications: 1-, 5-, 10-, and 25-kW PEM Fuel Cell Systems

Manufacturing costs of fuel cells using appropriate manufacturing processes at annual production volumes of 100, 1,000, 10,000, and 50,000 units were identified. A conceptual system design was defined by Battelle based on literature review and system integration experience. The conceptual design was refined through discussion with industry partners. Our approach considered the design of the system and primary design assumptions, manufacturing processes modeled using the BDI DFMA® software, and BOP component costs obtained via quotes and industry consultation. The main cost drivers were identified and a sensitivity analysis was conducted to analyze opportunities for cost reduction. The life cycle system costs and benefits were compared to potential material handling applications where the primary incumbent technologies are lead-acid battery and propane-powered equipment.

For all system capacities and at all volumes considered, the costs were dominated by BOP costs. Further, the BOP costs did not scale significantly with power output: the BOP for a 5-kW system at 10,000 units per year was only 25% more than the 1-kW system at an equivalent production volume and the BOP for a 25-kW system was only 100% more than the 1-kW system. This characteristic resulted from threshold costs for many of the components (e.g., the cost of having a specific component in a system regardless of system capacity). Since a system included only one instance of most BOP components, the threshold costs dominated at these small sizes. Within the BOP costs, the three highest-cost items were the DC/DC converter, batteries and fuel storage. For fuel storage in the BOP, the use of steel tanks, which are 75% cheaper than higher-cost composite tanks did provide a significant cost reduction when compared to previous studies. Stack costs (characteristically between 12% and 30% of costs for all systems) were dominated by the cost of the membrane electrode assembly (MEA) (due to catalyst and membrane cost) and bipolar plates (due to plate machine processing time). As system capacity increased, the contribution of the stack cost to the total cost also increased because the BOP cost did not rise as steeply as stack cost.

A life cycle cost analysis was performed for manufacturing volumes of 1,000 units/year and 10,000 units/year for the 10-kW systems. Both small (75 trucks) and large fleets (300 trucks) were considered for two and three shifts. In the individual cases considered, conversion to vehicles powered by fuel cells showed value with payback periods greater than one year and less than three years. A sensitivity analysis was also performed to understand the main cost drivers using tornado charts and a Monte Carlo analysis. The cost analysis was particularly sensitive to the assumptions made regarding labor rate, number of shifts per day, the cost of hydrogen (H_2), and the cost of battery exchange or recharge. The Monte Carlo results indicated that the payback period is around one year on average, though the payback can be less than a year under favorable conditions (inexpensive H_2 fuel and labor coupled with high electricity costs) and as high as four years under less ideal conditions (expensive H_2 and labor coupled with low electricity costs).

Backup Power Applications: 5- and 10-kW PEM Fuel Cell Systems

Fuel cell power systems may be used to provide backup power in the event of a grid outage for a variety of applications. Factors such as prevention of injury, loss of revenue or commodity stock, or continuity of security and communication in the event of a power outage drive end users to purchase backup power systems. The telecom industry in particular makes extensive use of backup power systems for cellular towers to ensure that their towers remain operational in the event of a grid outage. Battelle evaluated LTPEM systems for use as a backup power system. The power levels considered for this portion of the project were 5 kW and 10 kW. Conventional reciprocating gas- or diesel-based generators, battery banks, and fuel cell systems are each capable of providing backup power at this rate; however, fuel cell systems offer many advantages over conventional generators or battery-based systems. Fuel cell systems operating on compressed hydrogen can provide backup power for a significantly longer time than batteries, depending on the amount of on-site hydrogen storage, and provide more reliable backup power than diesel generators due to less moving parts. Moreover, compressed hydrogen is more energy-dense than batteries, and the storage cylinders require no special housing or space conditioning.

Battelle's evaluation included defining representative systems that could serve this market. The representative system concepts were subjected to a detailed cost evaluation based on industry feedback and the application of standard design for manufacturing and assembly analysis methods, including the application of the BDI DFMA® software for specific hardware and assembly evaluation. A sensitivity analysis was performed to evaluate the influence of specific high-cost items and components with a high degree of cost uncertainty.

PEM stack costs were less than 50% of overall system cost for all sizes and production volumes considered, and were typically less than 15% at higher production volumes (greater than 10,000 units per year). The DC/DC converter represented the largest cost associated with the BOP, followed by high-pressure regulators to step hydrogen down from its stored pressure to operating pressure for the PEM fuel cell. At the largest annual production volume (50,000 units per year), the overall system cost per kilowatt was found to be $1,875 for a 5-kW system and $1,215 for a 10-kW system.

A sensitivity analysis on some of the major cost contributors showed the potential for further cost reductions. Battelle found the price of platinum to have a minor overall impact on the PEM system. This outcome primarily results from the relatively small quantity of platinum used with this specific cell configuration. Major cost drivers included the assumed current density of the fuel cell (assumed to be 1.5 A/cm^2) and the DC/DC converter as part of the BOP.

A life cycle cost analysis evaluated the various non-monetary advantages offered by a PEM fuel cell backup power system. These advantages include the ability to store fuel for long durations without regard to degradation or theft, reduced environmental permitting, elimination of noise and irritating pollutants, and general "good neighbor" characteristics. While the financial incentive is not yet sufficient to choose a fuel cell over a conventional backup power system, these non-monetary advantages need to be considered when selecting a backup power technology.

Auxiliary Power Units: 1- and 5-kW Fuel Cell Systems

Costs were estimated for the manufacture of 1-kW and 5-kW SOFCs designed for APU applications using high-volume manufacturing processes at annual production volumes of 100, 1000, 10,000, and 50,000 units. Battelle identified the operational and performance requirements (e.g., hours of operation, frequency, lifetime expected) of the target application and market. This information formed the basis for selecting the right system design and fuel cell type for user requirements and the appropriate production volumes to consider in the modeling exercise.

A fuel cell APU design was developed as a system representative of typical design based on literature, manufacturer feedback, and Battelle's engineering expertise. Vendor quotes were gathered for material costs, production equipment, and outsourced components. Custom manufacturing process models were defined where necessary and were parametrically modeled based on knowledge of the machine, energy requirements, and labor requirements for individual steps that comprise the custom process. Finally, a sensitivity analysis was performed to determine which design parameters or assumptions had the most effect upon the stack and system cost. Life cycle costs of the fuel cell APU were compared to competitive technologies (internal combustion engine genset and idling truck engine) in the market at the time of the report in 2012. A positive ROI was not found for any cases over the competitive technologies. Overall, the final cost was analyzed in four distinct categories: the capital cost of manufacturing equipment, the direct cost of material and assembly of the stack, the expense of BOP hardware, and the final cost of complete system assembly and testing.

The primary driver of overall APU system cost was the BOP hardware, accounting for 63% to 88% of total system costs across the production volumes analyzed. The complex nature of onboard fuel reforming and the high temperature requirements for SOFC operation kept the part count and material costs high.

The stack costs were most sensitive to changes in metal components, as the quantity of high-temperature steel makes up the bulk of the stack cost. BOP costs were most sensitive to heat transfer and power conversion equipment. Specifically, the amount of heat transfer required to heat fuel feed streams, cool reformate for desulfurization, and reheat upstream of the stack was significant.

Products Developed

Reports for each application were submitted to DOE and can be found on the DOE website at https://energy.gov/eere/fuelcells/fuel-cell-technical-publications under DOE Contract No. DE-EE0005250

Computer Models

Not applicable.