V.A.2 Mass-Production Cost Estimation for Automotive Fuel Cell Systems

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Fiscal Year (FY) 2012 Objectives

- Update 2011 automotive fuel cell cost model to include latest performance data and system design information.
- Examine costs of fuel cell systems (FCSs) for light-duty vehicle and bus applications.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells 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

Technical Targets

This project conducts cost modeling to attain realistic, process-based system costs estimates for integrated transportation FCSs operating on direct hydrogen. These values can help inform future technical targets:

- DOE fuel cell system cost target: 30 $/kilowatts-electric (kWe)

FY 2012 Accomplishments

- Updated automotive FCS cost analysis to include the most up-to-date fuel cell stack performance data provided by Argonne National Laboratory (ANL) and 12 additional significant innovations to FCS performance and manufacture.
- Projected the FCS cost for a 80-kW light-duty vehicle application using a Design for Manufacturing and Assembly (DFMA®) methodology at an annual production rate of 500,000 FCSs per year to be $48.47/kWe.
- Initiated cost analysis of a 150-kWe FCS for bus application based on automotive proton exchange membrane (PEM) stacks.

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Introduction

This project represents an update to the ongoing PEM FCS cost model for 80-kWe systems. New technologies, materials data, and optimization modeling were incorporated to give an up-to-date value for system cost. In addition, a new system was modeled based upon the existing automotive system; preliminary costs of a PEM FCS for 150-kWe bus applications were computed.

FCSs for transportation applications are a longstanding area of fuel cell product development. Numerous prototype vehicles exist for a variety of transportation applications and research continues into improving the competitiveness of fuel cells as compared to the internal combustion engine. To better assess the potential usefulness and market-worthiness of fuel cells for transportation applications, this work describes a DFMA®-style [1] analysis of the cost to manufacture two different transportation FCSs. The systems analyzed are low-temperature (LT) PEM FCSs with peak electrical capacities of 80 kWe for light-duty vehicle (automobile) applications and 150 kWe for bus applications. The FCSs consume a hydrogen gas fuel stream from an onboard compressed hydrogen storage system. The impact of annual production rate on the cost of both systems is examined to assess the difference between a nascent and a mature product manufacturing base. The annual production rates analyzed are 1,000, 10,000, 30,000, 80,000, 130,000, and 500,000 FCSs per year.

This work focuses primarily on the efforts to update the existing DFMA® cost model of the automobile FCS as well as new efforts to design and cost-model the bus FCS. These systems' stack and balance-of-plant (BOP) designs and performance parameters are discussed and the methods of cost-modeling each explained. Cost trends are evaluated in terms of the capital costs per unit of installed electrical capacity ($/kWe) and system annual production rate.

Approach

A DFMA®-style analysis is conducted to attain cost estimates of PEM FCSs for automobiles and buses at low to high manufacturing production rates. Important fuel cell stack parameters are optimized by ANL and included in the PEM FCS performance and cost model. In addition, industry partners provide feedback on the design, materials, and manufacturing and assembly of FCS components and overall system. Fuel cell stack polarization data was updated for 2012 based on modeling results [2] from ANL, in turn based on data from 3M for their nano-structured, thin-film membrane electrode assemblies (MEAs). The FCS is sized based on rated power operating parameters. System performance is based on performance estimates of individual components, built up into an overall system energy budget. Overall system and component performance are cross checked against estimates made by the Argonne detailed models [2]. DFMA® process-based cost estimation techniques are applied to the major system components (and other specialty components) such as the fuel cell stack, membrane humidifier, air compressor/expander/motor unit, and hydrogen recirculation ejectors. For each of these, a manufacturing process train detailed the specific manufacturing and assembly machinery, and processing conditions is identified and used to assess component cost. For lessor components such as valves, heat exchangers, sensors, and piping, a less detailed method of cost estimate is applied. hese methods include simplified DFMA®-style techniques or price quotation from vendors. Frequent communication with vendors to obtain price quotes, discuss component design and characteristics, and manufacturing methods is used to ensure the validity of the assumptions used in the cost estimates.

The analysis explicitly includes fixed factory expenses such as equipment depreciation, tooling amortization, utilities, and maintenance as well as variable direct costs such as materials and labor. However, because this analysis is intended to model manufacturing costs, a number of components that usually contribute to the original equipment manufacturer price are explicitly not included in the modeling. The following costs are not included in this analysis: profit and markup, one-time costs such as non-recurring research/design/engineering, and general expenses such as general and administrative costs, warranties, advertising, and sales taxes.

Results

The automotive cost model update included several changes that altered the final predicted cost relative to the results from 2011. Table 1 summarizes the main design and manufacturing features of the 2012 automotive system. Table 2 summarized the changes and their cost impacts that occurred between 2011 and 2012. System and cost parameters for the 2012 bus application are not yet available.

TABLE 1. PEM FCV system design assumptions (light-duty vehicle applications)

	2012 Auto System Technology System
Power Density (mW/cm²)	984
Total Pt loading (mgPt/cm²)	0.196
Gross Power (kW gross)	88.24
Operating Pressure (atm)	2.50
Peak Stack Temp. (°C)	87
Active Cells	369
Membrane Material	Nafion® on 25-micron ePTFE
Radiator/Cooling System	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler
Bipolar Plates	Stamped SS 316L with TreadStone Coating
Air Compression	Centrifugal Compressor, Radial-Inflow Expander
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Microporous Layer
Catalyst Application	Nanostructured Thin Film (NSTF)
Air Humidification	Tubular Membrane Humidifier
Hydrogen Humidification	None
Exhaust Water Recovery	None
MEA Containment	Injection-Molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E
Coolant & End Gaskets	Laser Welding/ Screen-Printed Adhesive Resin
Freeze Protection	Drain Water at Shutdown
Hydrogen Sensors	2 for FC System 1 for Passenger Cabin (not in cost estimate) 1 for Fuel System (not in cost estimate)
End Plates/ Compression System	Composite Molded End Plates with Compression Bands
Stack Conditioning (hrs)	5

DI - deionized; SS - stainless steel; M&E - membrane and electrode

The cost analysis yields results detailing the final estimated capital cost of the entire system at different manufacturing rates. As shown in Figure 1, the capital cost of both the fuel cell stack and the overall FCS per unit of electric output ($/kWe) is seen to decrease with increasing system annual production rate for automobile FCSs. The steepest reduction in cost that is plotted is between 1,000 and 10,000 systems per year. In comparing these curves to each other, one also can see that the proportion of the capital cost that is attributable to production of the stack itself represents 45% of the total FCS cost at the highest manufacturing rates, with the rest of the cost attributable to BOP and FCS assembly.

To help probe the primary cost drivers of the automobile FCS, a sensitivity analysis was conducted for a variety of stack and system parameters. Parameter ranges were chosen

TABLE 2. Summary of major changes between 2011 and 2012 (light-duty vehicle applications)

Change	Reason	Change from previous value	Cost (500k systems/year, $/kW)
2011 AMR Preliminary Cost Value		N/A	$47.81
Press force calculations & capital cost parameters for bipolar plate stamping	Analysis altered to account for swageing of material, as opposed to simple bending.	$0.06	$47.87
Gasket injection molding calculations	Model refined and molding cavity count re-optimized	$0.31	$48.18
GDL Thickness reduced from 300 µm to 150 µm		-$0.25	$47.93
Final system assembly calculations refined and expanded	Response to industry review	-$0.16	$47.78
Piping configuration/costing updated and expanded	Response to industry review	$0.66	$48.43
Air temperature sensor added to system to monitor coolant exit conditions	Response to industry review	$0.06	$48.49
Purge valve upgraded to multi-function model	Response to industry review	$0.33	$48.82
Hot pressing process removed and replaced with crimping roller process prior to cutting and slitting	Hot pressing incompatible with NSTF catalyst deposition, new method required for combining membrane & GDL layers	-$0.06	$48.76
Ionomer cost curve reduction	Ionomer cost curve changed to reflect industry estimated value at high production	-$0.23	$48.53
Pressure, platinum loading, power density, and temperature updated to 2012 ANL optimization values	New release of ANL optimization curves for performance parameters	$1.83	$50.36
Membrane air humidifier design change	Air humidifier changed to tubular design (effect offset by ionomer cost reduction)	$0.25	$50.61
Gaskets changed from frame gaskets to sub-gaskets with screen-printed seals	New manufacturing process modeled in response to industry discussions	-$2.14	$48.47
Final 2012 Value		**$0.66**	**$48.47**

NTSF - nanostructured thin film; GDL - gas diffusion layer

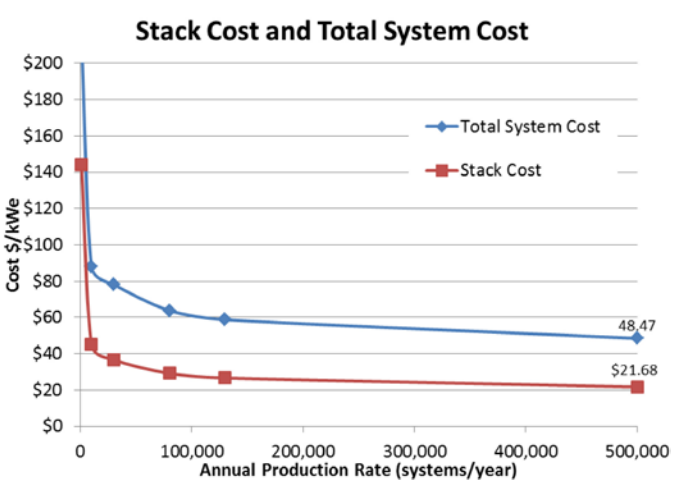

FIGURE 1. PEM fuel cell system and stack cost as a function of production rate (light-duty vehicle applications)

based on a 90%/10% confidence interval for expected variation in each parameter. Power density is determined to be the dominant cost parameter. The air compressor cost and the platinum loading are the top second and third most important cost parameters, respectively. Building on this single variable sensitivity analysis, a Monte Carlo simulation was conducted to show the likely range of systems costs. Figure 2 shows that middle 90% band ranges from $46.86/kwe to $55.83/kWe.

Finally, the cost results of the current iteration of transportation modeling are compared to previous years' results in Figure 3. In every year except for the current, predicted manufacturing costs for automobile FCSs have trended steadily downward. This is due to improvements in technology, modeling of new manufacturing and assembly methods, and improved level of detail within the cost model itself. However, the most recent results show a modest cost increase of $0.66/kWe in modeled cost at the highest manufacturing rates.

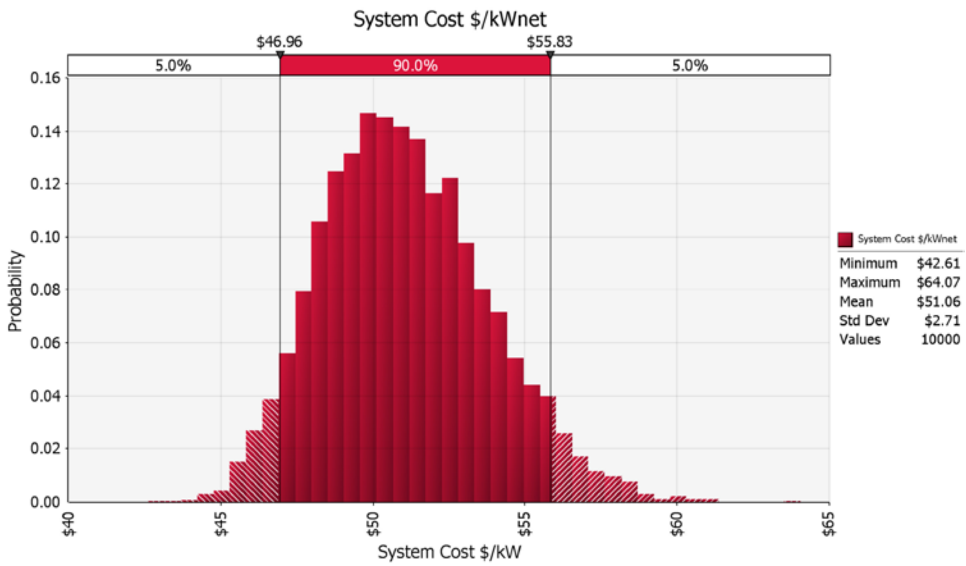

FIGURE 2. Monte Carlo simulation results for 80-kW FCS at 500,000 systems/year (light-duty vehicle applications)

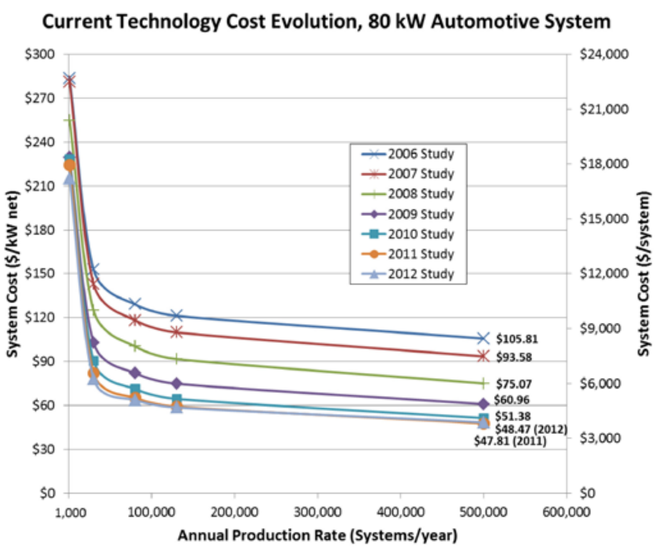

FIGURE 3. Evolution of FCS costs

Conclusions and Future Directions

The primary findings of this analysis of transportation FCSs relate to the key cost drivers of the automobile systems. Based on the analysis presented here, automobile FCS cost decreases dramatically between production rates of 1,000 and 10,000 systems per year, and then continues to decrease in a gentle curve for manufacturing rates through 500,000 systems per year. Additional results quantify that the relative cost contribution of the fuel cell stack is about 45% of the total FCS capital cost at high production volumes. The remaining contributors to system capital cost are from the BOP and assembly. The nominal 2012 fuel cell system cost for light-duty vehicle applications at 500,000 systems per year manufacturing rate is $48.47/kWe with an expected range of $46.96 to $55.83/kWe for the middle 90% confidence band (as predicted by Monte Carlo simulation). Finally, in every year except for the current, model results indicate that the expected capital costs for automobile FCSs trend steadily downward.

FY 2012 Publications/Presentations

1. James, Brian D., Spisak, Andrew, "Mass Production Cost Estimation for Direct Hydrogen PEM Fuel Cell Systems for Automotive Applications," Presentation to the Fuel Cell Tech Team, Southfield MI. July 18, 2012.

2. 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 14–18, 2012.

3. 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.

References

1. Boothroyd, G., P. Dewhurst, and W. Knight. "Product Design for Manufacture and Assembly, Second Edition," 2002.

2. Ahuwalia, R. "Fuel Cell Systems Analysis," Argonne National Laboratory, Presentation to DOE Fuel Cell Tech Team, 18 July 2012, Southfield MI.