V.H.2 Fuel Cell Transportation Cost Analysis

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Overall Objectives

- Define low-temperature proton exchange membrane (PEM) fuel cell system (FCS) operational and physical characteristics that reflect the current status of system performance and fabrication technologies.
- Estimate the production cost of the FCSs for automotive and bus applications at multiple rates of annual production.
- Identify key cost drivers of these systems and pathways to further cost reduction.

Fiscal Year (FY) 2013 Objectives

- Update 2012 automotive and bus FCS cost projections to reflect latest performance data and system design information.
- Define design and analyze cost of alternate catalyzed membrane fabrication methods.
- Define design and analyze cost of plate-frame air humidifier systems.

Technical Barriers

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

(B) Cost

Technical Targets

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

- DOE fuel cell system cost target: $30/kWe

FY 2013 Accomplishments

- Updated automotive FCS cost analysis to include the most up-to-date fuel cell stack performance data provided by Argonne National Laboratory (ANL).
- Analyzed the W.L. Gore and Associates Inc. (Gore) low-cost catalyzed membrane fabrication process and compared its cost to nano-structured thin-film (NSTF) catalyst application using a more conventional Nafion® membrane.
- Analyzed a plate-frame membrane humidifier and compared its cost to the previously analyzed tubular membrane humidifier.
- Projected the FCS cost for an 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.
- Projected the cost of a 160-kWe FCS for a bus.

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INTRODUCTION

This project represents an update to the ongoing PEM FCS cost model for 80-kWe automotive power systems. New technologies, materials data, and optimization modeling are incorporated to give an up-to-date value for system cost. In addition, costs of a PEM FCS for 160-kWe bus applications were analyzed.

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 PEM FCSs with peak electrical capacities of 80 kWe for light-duty vehicle (automobile) applications and 160 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, 100,000, and 500,000 FCSs per year for automotive systems and 400 and 1,000 systems per year for the bus systems.

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 various manufacturing production rates. Fuel cell stack polarization performance is supplied 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 performance is based on output from a detailed, first principles stack model created by ANL and validated against 3M NSTF membrane electrode assembly (MEA) performance. Output from the detailed ANL model is used to create a simplified stack polarization model that returns predicted current density for a specified cell voltage, stack pressure, cathode Pt catalyst loading, air stoichiometry, and stack outlet coolant temperature. This simplified 5-variable model is incorporated into the overall FCS cost model to allow complete flexibility in specification of stack operating conditions. A sweep over the entire potential stack operating condition design space can then be used to determine conditions that lead to the lowest system cost. 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 ANL 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 details the specific manufacturing and assembly machinery, and processing conditions are identified and used to assess component cost. For lesser components such as valves, heat exchangers, sensors, and piping, less detailed methods of cost estimation are applied. These methods include simplified DFMA®-style techniques and price quotations from vendors. An approach of frequent communication with vendors to obtain price quotes, and to discuss component design characteristics and manufacturing methods, is used to ensure the validity of the assumptions used in the cost estimates.

RESULTS

The 2013 cost update of the automotive and bus fuel cell power system is currently underway but not yet complete. While complete system cost estimates are not yet available, substantial progress has been made on analyzing alternative component technologies, specifically catalyst-coated membranes (CCMs) and air humidifiers.

To explore potential cost reduction of the CCMs of the FCS, a novel low-cost catalyzed membrane fabrication method [2] developed by Gore was analyzed. The modeled system draws exclusively from non-proprietary input and is composed of three sequential roll-to-roll fabrication steps: 1) cathode formation, 2) supported electrolyte formation, and 3) anode formation. Cathode formation is modeled as deposition of cathode catalyst ink onto a reusable Mylar substrate via die-slot coating followed by a moderate-temperature drying furnace. Electrolyte formation is modeled as die-slot coating of a Nafion® ionomer onto the cathode layer followed by unrolling and lowering of an expanded polytetrafluoroethylene (ePTFE) layer onto the wet ionomer, followed by furnace drying. Anode formation is modeled as die-slot coating of anode catalyst ink onto the electrolyte layer followed by furnace drying. A full DFMA® analysis of each step was conducted based on capital cost of the equipment, processing speed, material usage, expected yields, labor usage, and utility consumption. The membrane is modeled as a "bought" item, meaning that it is purchased from a sub-tier vendor rather than being fabricated in-house by the fuel cell system integrator. As such, markup for profit, research and development, and other general and administrative expenses is included for the membrane only within the CCM cost projection.

For automotive systems, DFMA® results in Figure 1 compare the projected costs of the Gore CCM manufacturing method described previously with those of the CCM fabrication method used in the 2012 cost analysis. The 2012 CCM fabrication method is based on a 3M NSTF catalyst application onto an ePTFE-supported Nafion® ionomer membrane. Catalyst application is modeled as vacuum magnetron sputtering of Pt/Co/Mn catalyst onto a high-surface-area substrate of PR-149 whiskers grown by sublimation followed by annealing. Membrane fabrication is modeled as occlusion of ePTFE in Nafion® ionomer solution within a separate factory setting. A DFMA® analysis was conducted and yielded results detailing the final estimated capital cost of the CCMs at different manufacturing rates. As shown in Figure 1, the capital cost of both CCMs is seen to decrease with increasing automotive system annual

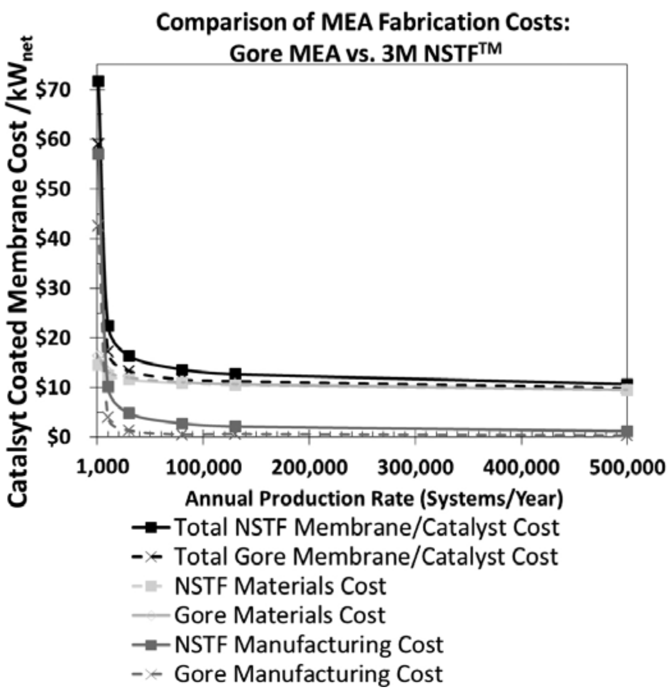

FIGURE 1. Cost Comparison of Gore and 3M MEAs

production rate. While the materials costs for both Gore and 3M CCMs are similar, the processing costs for the 3M CCM are greater than for the Gore CCM. Overall, the Gore CCM is estimated to be slightly less expensive than the 3M CCM. As production rate increases, the cost differential between the two different CCMs decreases in absolute terms. At the highest production rates considered (500,000 automotive systems per year), the Gore CCM processing costs are projected to approach just a few cents per kWe. Note that this analysis compares CCM costs on a per-square-meter-of-membrane basis, assuming the exact same engineering performance of the CCMs; the analysis does not capture potential differences in polarization performance and durability between the two CCMs.

A plate frame air humidifier is examined as a potentially lower cost and smaller volume alternative to the previously modeled tubular membrane humidifier. The plate frame humidifier design and projected manufacturing methods are based on publicly available information from Gore and dPoint Technologies Inc. [3]. For the automotive application, the modeled design is based on use of 80 “cell pouches” (loops of membrane with a metal spacer within the loop, total humidifier membrane area is 1.6 m^2) that allow dry primary inlet air to flow through the inside of the pouch and humid secondary outlet oxygen-depleted air from the cathode to flow cross-wise across the outside of the pouch. Stamped metal “ribs” are used to separate the pouches and thus enable gas flow between the pouches. The cells are arranged in a simple aluminum cast-metal housing to direct the gas flows. The postulated manufacturing process for the plate frame membrane humidifier is broken down into eight steps, as seen in Table 1, with costs further subdivided into materials, manufacturing, tooling, markup, and total costs. The greatest cost driver for the membrane humidifier is the material cost of the membrane at ~$29/humidifier. Consequently, costs are strongly impacted by the quantity of membrane material needed for the humidifier. The membrane is modeled as a four-layer integrated composite consisting of a 10-micron ePTFE layer, 5-micron Nafion® ionomer layer, 10-micron ePTFE layer, and 180-micron polyethylene terephthalate layer. The ePTFE layers bracket and mechanically support the very thin, and thus high water flux, ionomer layer and are arranged in a symmetrical orientation to minimize stresses during thermal cycling and thereby enhance lifetime. The much thicker polyethylene terephthalate layer provides

TABLE 1. Cost Analysis of a New Plate Frame Membrane Humidifier Design by Gore

All at 500k systems per year						
Component Costs per Humidifier System		**Materials**	**Manuf.**	**Tools**	**Markup**	**Total**
Station 1: Membrane Fabrication	$/stack	$28.99	$2.65	$0.16	$7.95	$39.75
Station 2: Humidifier Etching (Flow Field Plates)	$/stack	$15.09	$11.13	$0.00	$0.00	$26.21
Station 3: Pouch Forming	$/stack	$0.44	$1.30	$0.05	$0.00	$1.79
Station 4: Stamp SS ribs	$/stack	$0.64	$1.45	$3.60	$0.00	$5.69
Station 5: Stack Forming	$/stack	$4.33	$7.23	$0.00	$0.00	$11.57
Station 6: Stack Housing	$/stack	$5.05	$0.50	$1.21	$0.00	$6.76
Station 7: Assembly of Stack into Housing	$/stack	$0.00	$1.70	$0.00	$0.00	$1.70
Station 8: System Test	$/stack	$0.00	$0.32	$0.00	$0.00	$0.32
	Totals =	**$54.54**	**$26.28**	**$5.02**	**$7.95**	**$93.78**

additional mechanical support and abrasion resistance. Fabrication of the composite membrane uses roll-to-roll processing steps analogous to those postulated for the Gore low-cost CCM line discussed previously. The second largest cost driver is the etching process for the humidifier flow field plates based on a material cost (stainless steel 316L) of ~$15/humidifier and an electrochemical etching manufacturing cost of ~$11/humidifier. Electrochemical etching is selected for the metal spacers as it grants the design flexibility and dimensional tolerance critical to achieving low pressure drop and high membrane water transport performance. The total cost for the plate frame membrane humidifier at 500,000 systems per year is projected to be ~$94/humidifier.

FCS costs for bus applications were analyzed in late 2012 and are currently being updated for 2013 advances in technology. While cost results for 2013 are not yet available, DFMA® results for 2012 indicate that the projected capital costs for a fuel cell bus in mass production are consistent with industry projections and DOE R&D guidelines. Figure 2 shows the components contributing to the 2012 cost of the bus fuel cell stacks. The gas diffusion layers, membranes, and NSTF catalyst ink and application are the largest cost contributors, followed by stamped bipolar plates and MEA gaskets. The total stack cost at 1,000 systems per year is estimated to be $21,651 for two 80-kWe stacks. Figure 3 plots the BOP costs as function of component source, at the same annual production rate. The BOP cost is estimated to be $8,707, roughly 40% of the stack costs. The sensors and air loop are the most significant cost contributors to the BOP.

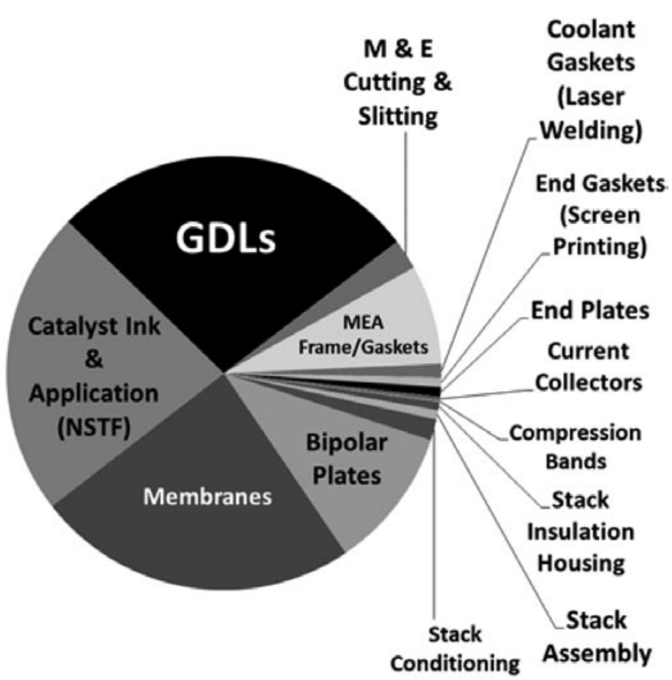

FIGURE 2. Cost Break-Down for PEM Fuel Cell Stacks for a Bus

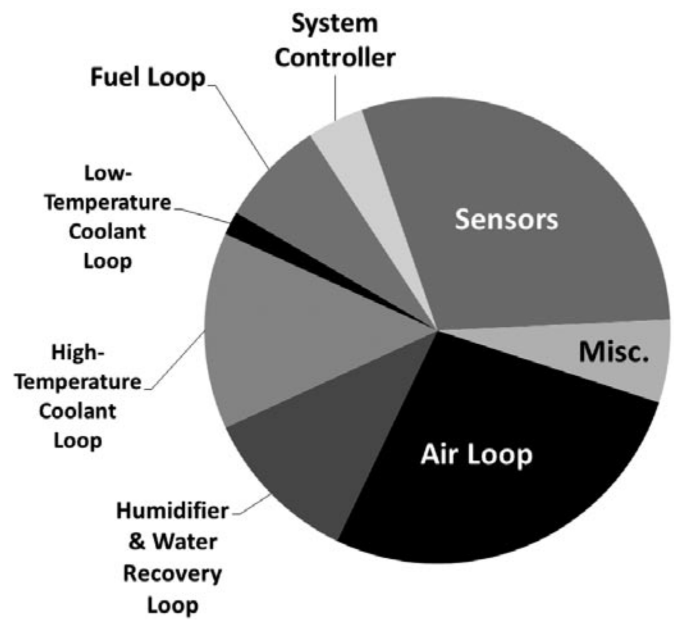

FIGURE 3. Cost Break-Down for PEM Fuel Cell Bus BOP

The projected DFMA® capital cost for both stacks and BOP is ~$170/kWe, consistent with both industry estimates and DOE goals.

CONCLUSIONS AND FUTURE DIRECTIONS

- Cost analysis of CCMs fabricated using the Gore roll-to-roll fabrication methods yields similar, but slightly lower costs than CCMs fabricated using previously analyzed fabrication methods (NSTF catalyst application on an ePTFE supported membrane), assuming that both CCMs have similar engineering and polarization performance.
- Costs of a plate frame air humidifier (based on designs from Gore and dPoint Technologies) are projected to be ~$100 per unit (sized for an 80-kWe automotive fuel cell system). The materials costs for the humidification membrane and the fabrication cost of the stainless steel spacers (fabricated by electrochemical etching) are the greatest cost drivers for the air humidifier.
- The 2012 projected cost of bus 160-kWe low-temperature PEM FCS is ~$170/kWe, consistent with both industry estimates and DOE goals. The three greatest cost drivers for the bus stack are the gas diffusion layers, membranes, and NSTF catalyst layer and application. The greatest cost drivers for the bus BOP are the sensors and air loop.
- An updated stack polarization model was obtained from ANL and integrated into the fuel cell cost models. A Monte Carlo analysis can then be used to identify FCS operating conditions that lead to the lowest FCS capital cost.

- Projections of the overall FCS cost for both automotive and bus applications will be made for a range of annual production rates.

FY 2013 PUBLICATIONS/PRESENTATIONS

1. James, B.D., Spisak, A.B., Colella, W.G., "Design for Manufacturing and Assembly (DFMA) Cost Estimates of Transportation Fuel Cell Systems," expected 2013 (accepted for publication).

2. Colella, W.G., "Advanced Electrochemical Systems," *California Renewable Energy and Storage Technology Conference*, California State University Northridge, Northridge, CA, May 4th, 2013.

3. James, B.D., Moton, J.M., Colella, W.G., "Energy Systems Design and Thermoeconomic Analysis of Advanced Vehicle Systems," *American Society of Mechanical Engineers (ASME) 2013 7th International Conference on Energy Sustainability*, Minneapolis, MN, July 14–19th, 2013.

4. James, B.D., Moton, J.M., Colella, W.G., "Fuel Cell Vehicle Design for Manufacturing and Assembly (DFMA) Analysis," *ASME 2013 11th Fuel Cell Science, Engineering and Technology Conference*, Minneapolis, MN, July 14–19th, 2013.

5. James, B.D., Spisak, A.B., Colella, W.G., "Hydrogen-fueled proton exchange membrane (PEM) fuel cell vehicles (FCVs) -- Conceptual and Physical Design and Capital Cost Estimates," *ASME 2012 International Mechanical Engineering Congress & Exposition*, Houston, Texas, Nov. 9th–15th, 2012, IMECE2012-88990.

6. James, B.D., Spisak, A.B., Colella, W.G., "Design for Manufacturing and Assembly (DFMA) Cost Estimates of Transportation Fuel Cell Systems," *Fuel Cell Seminar*, Uncasville, Connecticut, Nov. 5th–8th, 2012.

7. James, B.D., Moton, J.M., Colella, W.G., *Design for Manufacturing and Assembly of Fuel Cell Vehicles*, U.S. DOE EERE FCT Program Webinar Series, April 16th, 2013.

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

2. Busby, F. Colin. "Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies Engineered for Rapid Conditioning," W.L. Gore & Associates, Inc., presentation at the 2012 DOE Hydrogen and Fuel Cell Program Annual Merit Review, Washington, DC, 16 May 2012.

3. Johnson, William B. "Materials and Modules for Low-Cost, High Performance Fuel Cell Humidifiers," W.L. Gore & Associates, Inc., presentation at the 2012 DOE Hydrogen and Fuel Cell Program Annual Merit Review, Washington, DC, 17 May 2012.