V.F.3 Fuel Cell Vehicle and Bus Cost Analysis

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Overall Objectives

- Define low temperature proton exchange membrane (PEM) fuel cell power system operational and physical characteristics that reflect the current status of system performance and fabrication technologies
- Estimate the production cost of the fuel cell systems (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) 2015 Objectives

- Update 2014 automotive and bus fuel cell power system cost projections to reflect latest performance data and system design information
- Define design and analyze cost of PtNi binary catalyst dispersion application methods
- Analyze material processing cost of alternative non-Pt catalyst fabrication
- Re-evaluate and analyze cost of automotive FCS component manufacturing processes at low production volumes

Technical Barriers

This project addresses the following technical barrier 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 fuel cell power systems operating on direct hydrogen. These values can help inform future technical targets:

- DOE 2020 fuel cell system cost target: $40/kilowatt-electric (kWe) (net)

FY 2015 Accomplishments

- Projected the fuel cell power system cost for an 80 kWe (net) 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 fuel cell power system cost of a 160 kWe (net) fuel cell power system for a bus at 1,000 systems per year
- Extended multi-variable sensitivity analysis to stack, balance of plant (BOP), and total system at all manufacturing rates for both the automotive and bus systems
- Analyzed a non-platinum catalyst fabrication process as a side study to compare to current platinum catalyst system
- Re-evaluated automotive fuel cell (FC) stack components at low production volume
  - Bipolar plate (BPP) forming and coating
  - Dispersed catalyst coating compared to 3M nano-structured thin film (NSTF)

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INTRODUCTION

Research is ongoing to make fuel cell electric vehicles cost and performance competitive with internal combustion engine vehicles. This work supports that research effort through a DFMA®-style [1] analysis of the cost to manufacture two different transportation FCSs. A detailed system-level cost analysis allows the assessment of individual FC research advancements and therefore provides insight into the most cost beneficial research directions. The cost and performance impact of research advancements on fuel cells for transportation applications is assessed. The systems analyzed are low-temperature (LT) PEM FCSs operating on hydrogen with peak electrical capacities of 80 kWe (net) for light-duty vehicle (automobile) applications and 160 kWe (net) for 40-foot transit bus applications. The onboard compressed hydrogen storage system is not included in this cost assessment. The impact of annual production rates on the cost of the automotive and bus 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 200, 400, 800, and 1,000 systems per year for the bus systems.

This work focuses primarily on updating the existing automobile FCS DFMA® cost model as well as efforts to design and model the manufacturing cost of bus FCSs. Stack and BOP designs and performance parameters are discussed, and the methods of modeling each are explained. New technologies, materials data, and optimization modeling are incorporated to give an up-to-date value for system cost. Cost trends are evaluated in terms of the capital costs per unit of installed electrical capacity ($/kWe [net]) and system annual production rate.

To assist the DOE and FC companies in charting the transition from prototype and low-volume production to high-volume manufacturing, it is important to understand the crossover point ("break-point") for switching from a low-volume to a high-volume manufacturing process. In 2015, low-volume (1,000–5,000 systems/year) manufacturing techniques were studied for BPP stamping and catalyst deposition to better understand how they differ from high-volume (30,000–500,000 systems/year) manufacturing processes. One goal of this analysis is to better understand the most cost-effective low-volume manufacturing processes and their corresponding break-points.

APPROACH

A DFMA®-style analysis is conducted to estimate the manufacturing cost of PEM FCSs for automobiles and buses at various manufacturing production rates. The optimum stack operating conditions and operating point are selected in collaboration with Argonne National Laboratory (ANL) and the United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S. DRIVE) Fuel Cell Tech Team. ANL first principles models of fuel cell stack operating conditions [2] and SA DFMA® cost models are used to identify cost and performance optimized conditions, which are vetted by the Fuel Cell Tech Team. Output from the ANL model provides insight into cell voltage, stack pressure, cathode catalyst loading, air stoichiometry, and stack outlet coolant temperature while the DFMA® cost model provides insight into cost and performance tradeoffs. The FCS is sized to provide 80 kWe (net) based on rated power operating parameters. System performance is based on performance estimates of individual components, built up into an overall system energy budget.

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 (CEM) 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 2015, the full DFMA® analysis was extended to the examination of non-Pt polyaniline-iron-carbon (PANI-Fe-C) catalyst fabrication and alternative manufacturing processes for FC stack components at low production volumes.

RESULTS

As in previous years, the 2015 high-volume manufacturing cost will be reported separately in a DOE data record when available later this year. Final 2014 cost results (reported for the first time) and 2015 component results are described in this report.

2014 Automotive and Bus System Cost

The operating conditions and assumptions used to calculate costs for the 2014 auto and bus systems are summarized in Table 1. The operating conditions and assumptions did not change significantly from 2013. The 2014 automotive system cost at 500,000 systems per year is $54.84/kWe (net) and is similar to the 2013 projected cost of $54.83/kWe (net). While the cost remained stable between 2013 and 2014, the underlying system and modeling assumptions were altered but with nearly exactly offsetting cost impact. Increased power density at a lower operating voltage, higher stack temperature, and higher air stoichiometric ratio contributed to a reduction of $0.37/kWe (net), while updated material costs and component models with improved assumptions contributed to an increase of $0.38/kWe (net). The waterfall chart in Figure 1 shows a potential pathway to meeting the DOE's 2020 automotive fuel cell system cost target of ~$40/kWe (net) from the current status system cost of $54.84/kWe (net). The step improvements are based on U.S. DRIVE cost targets plus additional assumed BOP cost reductions.

Between 2013 and 2014, the bus FCS cost increased from $269.95/kWe (net) to $278.62/kWe (net). The changes between 2013 and 2014 include the same material cost changes that were made to the automotive system, minor changes to the compressor component manufacturing process, and changes to the efficiency of the compressor (from 71% to 58%) and motor (from 80% to 95%) based on recent test data.

In previous years, sensitivity analyses for the automotive and bus FCSs were only conducted at the highest production rates for the total system cost. In 2014, the Monte Carlo analysis was extended to all manufacturing rates with multi-

TABLE 1. PEM FC Auto and Bus System Operating Conditions and Assumptions

	2014 Auto System	2014 Bus System
System Gross Power (kWe)	92.75	187.6
System Net Power (kWe)	80	160
Power Density (mW/cm^2)	834	601
Cell Voltage (mV)	672	676
Stack Temp (Coolant Exit Temp) (˚C)	95	74
Pressure (atm)	2.5	1.8
Platinum Loading (kWe (gross)/g)	92.75	187.6
Air Stoichiometry	2	2.1
Catalyst System	PtCoMn NSTF	PtCoMn NSTF
Cells per System	372	740

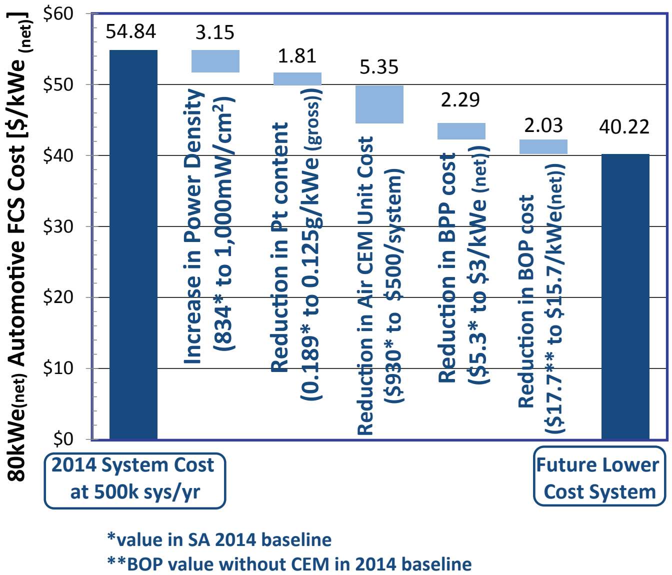

FIGURE 1. Waterfall chart for projection of automotive fuel cell system cost from $54.84/kWe (net) down to $40/kWe (net) [4]

variable sensitivities showing the middle 90% confidence range for stack cost, BOP cost, and total system cost. Figure 2 shows the automotive and bus FCS costs at each manufacturing rate with the Monte Carlo results shown as error bars for the stack and total system. At 500,000 systems per year, the automotive system, with 90% confidence, would be between $50.81/kWe (net) and $63.70/kWe (net). At 1,000 systems per year, the bus system cost range is between $256.92 kWe (net) and $341.49/kWe (net). The larger error bars for the bus system reflect greater uncertainty in the cost projections at low production rates. Indeed, it is surprising that the bus system cost curve falls in line so closely with the automotive system curve given the lower power density and higher platinum loading required in the bus system.

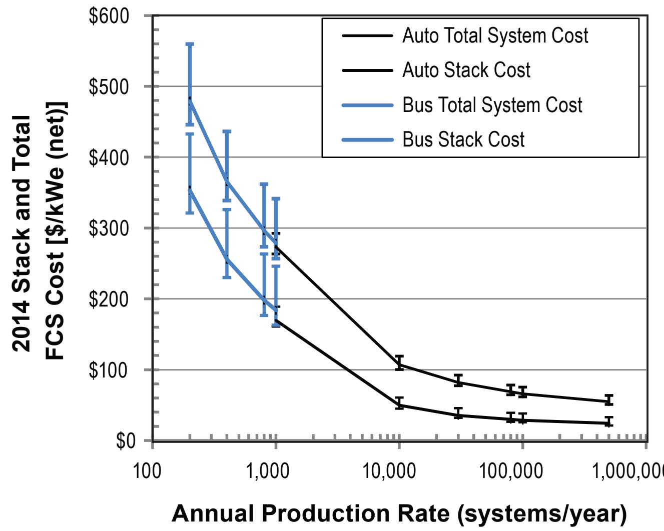

FIGURE 2. Automotive stack and total system cost at all manufacturing rates with error bars based on the Monte Carlo sensitivity results with middle 90% confidence range

Future analysis will seek to improve the confidence in the bus cost results and explore differences between the auto and bus systems at their overlapping manufacturing rate of 1,000 systems per year.

PANI-Fe-C Manufacturing Cost Analysis

For 2015, a DFMA® analysis was completed for a non-Pt PANI-Fe-C catalyst developed by researchers at Los Alamos National Laboratory. The catalyst materials manufacturing process is outlined in Figure 3 and includes seven processing steps: (1) oxidation of carbon, (2) reagent mixing and polymerization, (3) belt drying, (4) grinding, (5) rotary calcining, (6) acid leaching and filtration, and (7) oven pyrolysis. The results show PANI-Fe-C catalyst has a much lower cost per mass of material ($74/kg compared to Pt-based catalysts at ~$41,000/kg); however, the performance of cells using the PANI catalyst is much lower (330 mW/cm^2 at ~0.5 V compared to 834 mW/cm^2 at 0.672 V for PtCoMn catalyst). At such reduced areal power density, and combined with a higher catalyst loading (~4 mg/cm^2 vs. ~0.15 mg/cm^2), 17 times the mass of catalyst powder is required along with substantially larger stack(s) to achieve equal net system power. Total system catalyst cost is still reduced, but the cost of the stack components (membranes, BPP, etc.) is so much larger that the non-Pt PANI-Fe-C stack(s) would cost more than a Pt-based catalyst FC stack.

Low-Volume Cost Analysis

During 2015, multiple component design and manufacturing processes were re-evaluated to assess low-production-rate issues. BPP forming, BPP material and coating, and catalyst ink application (other than NSTF) were each considered.

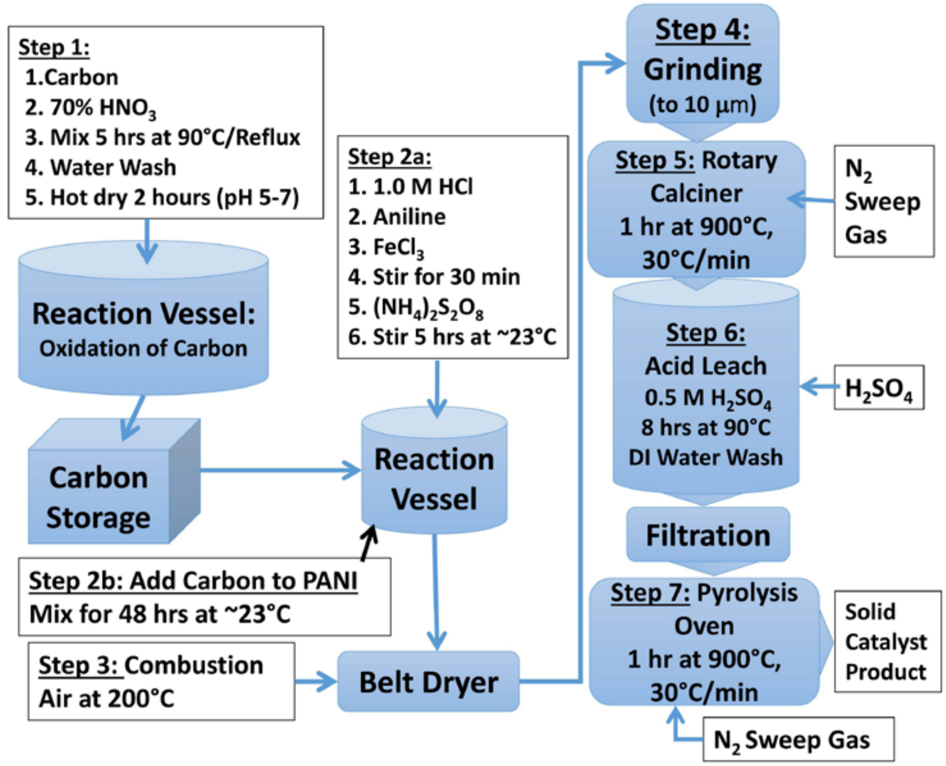

FIGURE 3. Non-Pt-based catalyst PANI-Fe-C material processing flow diagram

The baseline DFMA® model uses progressive die stamping to form the stainless steel (SS) BPP; however, sequential stamping and hydroforming (HF) are viable alternatives to form very thin (76 microns) metal plates. In discussions with stamping and HF equipment manufacturers, HF and stamping (both sequential and progressive) are noted to have significant differences: (1) typical HF cycle times are ~15–20 seconds while stamping is often less than 1 second, and (2) stamping dies (tooling) are typically more expensive (~$40,000) than HF dies (~$10,000–$15,000). Conventional wisdom from HF/stamping vendors suggested that HF would be less expensive than stamping at <50,000 parts per year (about 60 FCS/year) due to lower die costs. This result was confirmed by DFMA® analysis, which showed the manufacturing rate crossover point at which progressive stamping becomes less expensive than sequential stamping or HF is ~100,000 plates per year (~130 FCS per year). This analysis suggests progressive stamping will be less expensive than sequential stamping or HF at all but prototype runs of automotive FCS. Similar results were reported in a Massachusetts Institute of Technology HF/stamping comparison [3]. Non-traditional HF techniques that automate the process can reduce the processing times of HF, potentially reducing the HF cost at low volumes. An analysis of non-traditional HF is expected to be completed in 2016.

Titanium (Ti) BPPs were also investigated in 2015 to determine whether there is a low volume cost benefit to switching from 316 SS with a Treadstone anti-corrosion coating to Ti plates with a gold coating. Since Ti is more expensive per kilogram than SS, such a trade-off appears unlikely unless the cost for coating a SS plate offsets the difference in plate material cost. Commercially pure titanium Grade 2 at 76 microns thickness (quoted at $157/kg Ti) with a gold coating was compared to the baseline 76 micron SS 316 BPP ($11/kg SS 316) with Treadstone coating. At the production volumes specified for the automotive FCS, gold-coated titanium plates are more expensive than SS 316 plates with Treadstone coating. Quotations for thicker titanium sheets (533 microns thick), obtained for comparison, show mill cost (to achieve thin sheets) is a substantial cost contributor. However, use of thicker Ti plates (533 microns) to lower the effective cost of Ti to $27/kg still results in higher cost than the baseline coated SS plates due to the greater mass per area of BPP. Consequently, Ti plates do not appear to be a low-cost alternative to coated SS plates at any production rate of interest based on the current Ti pricing acquired.

Alternative approaches to catalyst application were also considered in 2015. The baseline NSTF catalyst coating approach includes multiple vacuum processes (sublimation of Paralene Red 149 followed by heating and deposition of catalyst metals), which results in high capital cost, particularly for low-volume production. In contrast, slot die coating is an established high-rate, non-vacuum catalyst application technique that is expected to be a lower-cost alternative to NSTF at low volumes. Pricing and operating data from multiple slot die coating companies (two of which

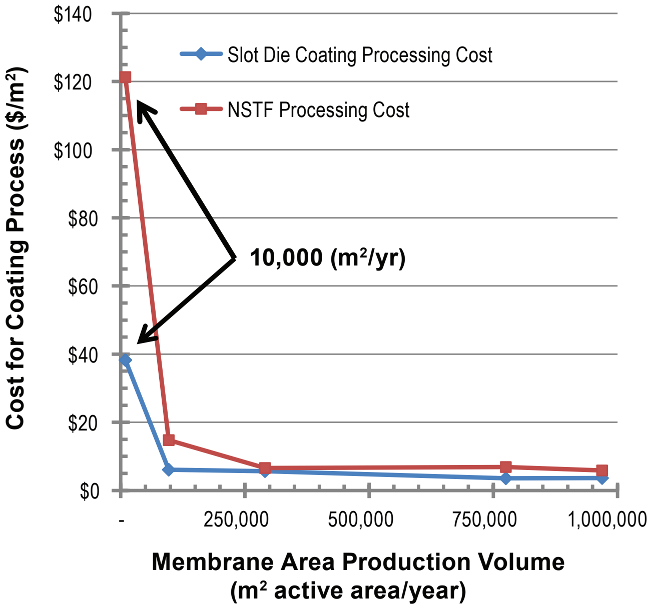

FIGURE 4. Comparison of slot die coating with NSTF coating production cost ($/m^2 active area) over production volume

have supplied fuel cell companies) were collected and used within a DFMA® analysis. As seen in Figure 4 (processing costs only), slot die coating is judged to be the least expensive manufacturing process (per active area of membrane electrode assembly [MEA]) at less than 40,000 m^2 per year (~30,000 FCS per year). Note that this assessment is meant to isolate the cost of catalyst application and is only valid if both catalyst application systems have the same power density. In future analyses, a comparison of dispersed and NSTF catalysts inclusive of all manufacturing and materials costs and power density impacts will be performed to provide a comprehensive assessment of the two catalyst approaches.

CONCLUSIONS AND FUTURE DIRECTIONS

- The 2014 final auto and bus system cost results increased slightly from 2013, due to a series of specific analysis and assumption improvements. The 2015 final system cost analyses for the automotive and bus systems are currently underway.
- The automotive FCS cost for 2014 ($54.84/kWe (net)) did not change significantly from the 2013 analysis ($54.83/kWe (net)). Minor changes were made to material costs, efficiency calculations, and operating conditions.
- The 2014 projected system cost of the 160 kWe (net) LT PEM FC bus system is ~$279/kWe (net), incorporating updated compressor and motor efficiencies.
- The Monte Carlo multi-variable sensitivity analysis was extended to all production volumes and for the stack and BOP for both the auto and bus systems. Future analysis will seek to improve the confidence in the low-production-rate results.
- A 2015 side study of the non-Pt-based catalyst (PANI-Fe-C) revealed a much lower cost per mass ($74/kg), albeit lower performance (330 mW/cm^2) compared to traditional Pt- based catalysts. Higher non-Pt-based catalyst polarization performance is needed to achieve a net stack cost reduction.
- Alternative low-cost processing methods for forming and coating BPP and coating catalyst onto membranes for the automotive system were examined. Hydroforming of the BPP was not found to be less expensive than progressive stamping. Titanium BPPs with gold coatings were not found to be less expensive than SS plates with Treadstone coatings.
- Slot die coating can be a lower-cost method for coating catalyst onto MEAs (on a cost per area basis) for production volumes lower than 300,000 m^2/year. Future analyses will compare dispersed and NSTF catalysts inclusive of all manufacturing and materials costs and power density impacts to provide a comprehensive assessment of the tradeoffs between cost and performance.
- Projections of the overall fuel cell power system cost for both automotive and bus applications will be made for the 2015 analysis and are anticipated to change by substituting auto PtCoMn NSTF ternary catalyst with a binary PtNi-C-based catalyst.

FY 2015 PUBLICATIONS/PRESENTATIONS

1. Moton, J.M., James, B.D., Colella, W.G., "Engineering and Economic Advances in Proton Exchange Membrane (PEM) Fuel Cell Vehicle (FCV) Design," Presented at the 2013 Fuel Cell Seminar and Exposition, Los Angeles, CA, November 13, 2014.

2. "Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2014 Update," Strategic Analysis Report prepared by Brian D. James, Jennie M. Moton, and Whitney G. Colella, December 2014.

3. James, B.D., Moton, J.M., Houchins, C., DeSantis, D.A., "2015 DOE Hydrogen and Fuel Cells Program Review: Fuel Cell Vehicle and Bus Cost Analysis," Presented at the 2015 DOE FCTO Annual Merit Review Meeting, Arlington, VA, June 10, 2015.

4. James, B.D., Houchins, C., Moton, J.M., "Transportation Fuel Cells Cost Analysis Update Automotive Cost Analysis," Presented to the Fuel Cell Technical Team, Southfield, MI, July 15, 2015.

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

2. Ahluwalia, R. "Fuel Cell Systems Analysis," Argonne National Laboratory, Presentation to DOE Fuel Cell Tech Team, 16 July 2014, Southfield, MI.

3. Hydroforming Die Cost Assumptions: Matwick, S.E., "An Economic Evaluation of Sheet Hydroforming and Low Volume Stamping and the Effects of Manufacturing Systems Analysis," Masters Thesis for Master of Science in Material Science and Engineering at MIT, pg. 40, February 2003. http://msl.mit.edu/theses/Matwick_S-thesis.pdf

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