V.I.2 Fuel Cell Transportation 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) 2014 Objectives

- Update 2013 automotive and bus FCS cost projections to reflect latest performance data and system design information.
- Define design and analyze cost of alternate catalyst fabrication and application methods.
- Define design and analyze cost of alternate compressor-expander-motor (CEM) 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 costs estimates for integrated transportation FCSs operating on hydrogen. These values can help inform future technical targets:

- DOE fuel cell system cost target: $40/kWe in 2020
- DOE fuel cell system ultimate cost target: $30/kWe

FY 2014 Accomplishments

- Updated automotive FCS cost analysis to include the most up-to-date fuel cell stack performance data provided by Argonne National Laboratory (ANL).
- Projected the fuel cell power system 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 kilowatt-electric (kWe) FCS for a bus at 1,000 systems per year.
- Analyzed a platinum, nickel, and carbon (PtNiC) de-alloyed catalyst fabrication process with greater detail for Pt recycle cost.
- Analyzed an Eaton-style Roots technology air compressor unit for the automotive and bus systems.

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INTRODUCTION

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 40-foot transit bus applications. The FCSs consume a hydrogen gas fuel stream from an onboard compressed hydrogen storage system (not part of this analysis). The impact of annual production rate 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 the efforts to update the existing DFMA® cost model of the automobile FCS as well as efforts to design and cost-model the bus FCS. These systems' stack and balance of plant designs and performance parameters are discussed and the methods of cost-modeling each 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) 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 principals stack model created by ANL and validated against 3M nano-structured, thin film (NSTF) 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 CEM unit, and hydrogen recirculation ejectors. For each of these, a manufacturing process train detailed the specific manufacturing and assembly machinery, and processing conditions are identified and used to assess component cost. For the 2014 analysis, full DFMA® analyses were conducted on the PtNiC de-alloyed catalyst fabrication and on the Eaton-style CEM unit. (DFMA® analysis was not conducted on the motor component, rather, motor cost was based on a vendor quotation.)

For lower cost components such as valves, heat exchangers, sensors, and piping, a less detailed method of cost estimate is applied. These methods include simplified DFMA®-style techniques or 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 2014 analysis is out of phase with the annual reporting schedule and thus 2014 final system costs are not yet available. This was also the case for last year's annual report. Consequently, this report documents a blend of the final 2013 cost results (reported for the first time) and 2014 component results. Substantial progress has been made on analyzing alternative component technologies, specifically a de-alloyed PtNiC catalyst and Roots-type air CEM.

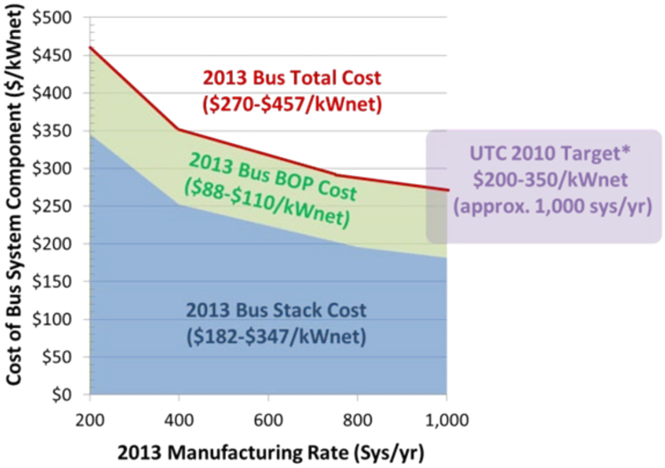
The 2013 automotive and bus system models underwent significant changes since 2012. For the automotive system, changes are described in Table 1 with the changes leading to the largest cost impacts being 1) updated polarization data,

TABLE 1. List of Changes between the 2012 and 2013 Final Auto System Cost at 500,000 Systems/Year

Change	Comment	Change from previous value	Cost at 500k sys/year, ($/kW)
2012 Final Cost Estimate		NA	$46.95
Plate Frame Humidifier	Switch to lower volume membrane plate frame humidifier from tube humidifier	$0.51	$47.46
Improved Catalyst Deposition Modeling	Re-examination of NSTF application including wastage and Pt recycle	($0.20)	$47.26
Realigned Compressor and Expander Efficiencies	Air compressor: (75% to 71%) FC air exhaust gas expander: (80% to 73%) Motor: (85% to 80%)	$1.87	$49.13
Updated Material Costs	New 316 SS and other material price quotes	$0.13	$49.26
Updated Quality Control System	To ensure full functionality and improve cost realism	$0.00	$49.26
Increased Platinum Cost	Increase from $1100/oz t to $1500/oz t	$3.19	$52.45
Other Misc. Changes	Improve and correct model i.e. LT and HT loop, CEM, and membrane adjustments	($0.86)	$51.59
Updated Polarization Data, Stack Operating Condition Optimization, and Imposition of Radiator Area Constraints	Improved MEA performance data for 3M NSTF experimental results. Performed stack condition optimization to achieve lowest system cost. Limited radiator Q/ΔT for volume management within the auto.	$3.24	$54.83
Final 2013 Value		**$7.88**	**$54.83**

stack operating condition optimization and imposition of radiator volume constraints; and 2) increase in Pt cost from \$1,100/troy ounce (Pt price used between 2006 and 2012) to \$1,500/troy ounce (to align with market changes). The 2013 automotive system cost at 500,000 systems per year is \$54.83/kW$_{net}$, higher than 2012's projected cost of \$46.95/kW$_{net}$. Over the last several years, the projected cost of high-volume manufactured automotive FCS decreased from year to year, however in 2013, the system cost became more expensive.

Similar changes to the auto system were also made for the 160-kW$_e$ bus system with an additional change in non-vertical integration. Vertical integration describes the extent to which a single company conducts many (or all) of the manufacturing/assembly steps from raw materials to finished product. High degrees of vertical integration can be cost efficient by decreasing transportation costs and turn-around times, and reducing nested layers of markup/profit. However, at low manufacturing rates, the advantages of vertical integration may be overwhelmed by the negative impact of low machinery utilization or poor quality control due to inexperience/lack-of-expertise with a particular manufacturing step. For the 2012 analysis, both the automotive and bus fuel cell power plants were cost modeled as if they were highly vertically integrated operations. However for the 2013 analysis, the automotive fuel cell system retains the assumption of high vertical integration but the bus system assumes a non-vertically integrated structure. This is consistent with the much lower production rates of the bus systems (200 to 1,000 systems/year) compared to the auto systems (1,000 to 500,000 systems/year). The effect of non-vertical integration reduced the total bus FCS cost between 2012 and 2013. However, other additional changes (including updated performance operating conditions) caused the total bus FCS cost to increase from \$190/kW$_{net}$ to \$270/kW$_{net}$ at a manufacturing rate of 1,000 systems per year between 2012 and 2013. As shown in Figure 1, the cost of the 2013 bus system is within the range of the UTC 2010 Target of \$200-\$350/kW$_{net}$ at 1,000 systems per year.



* 2010 DOE AMR Joint DOE/DOT Bus Workshop, "Progress and Challenges for PEM Transit Fleet Applications", Tom Madden, UTC, 7 June 2010: 2010 UTC Preliminary Bus Fleet Cost Target: \$200-350/kW in 1,000's per year.

FIGURE 1. DFMA® Cost Results for the 2013 Final Bus System Cost between 200 and 1,000 Systems/Year

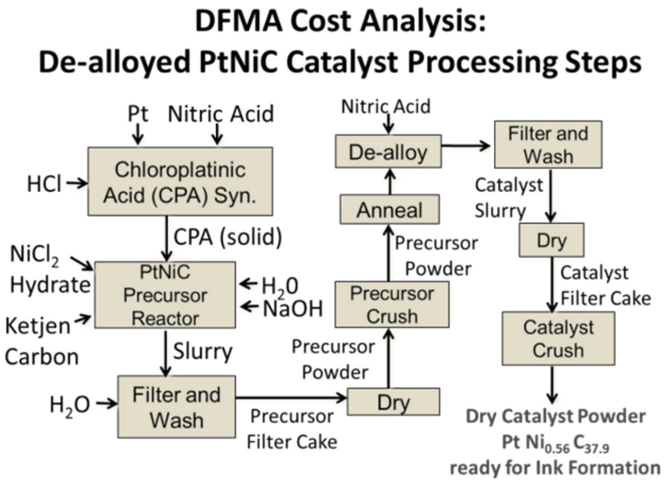


FIGURE 2. DFMA® Cost Analysis of De-Alloyed PtNiC Catalyst Processing Steps

In previous SA transportation FCS cost studies, the membrane electrode assemblies have been modeled as using a 3M NSTF Pt/cobalt/manganese catalyst. As an alternative to this ternary catalyst, a binary catalyst, de-alloyed PtNiC, was explored. The 3M PtCoMn NSTF remains the 2014 baseline catalyst although the analysis may switch to the de-alloyed PtNiC catalyst in future years after its cost and performance is further experimentally vetted. A flow diagram of the de-alloyed PtNiC processing steps is shown in Figure 2. Processing steps are based on open-source descriptions of Johnson-Matthey de-alloyed catalyst procedures combined with hypothesized materials and operations where information was missing. Thus the manufacturing steps should be viewed as Johnson-Matthey-inspired rather than a duplication of their exact procedures. As shown in Table 2, Pt material cost is the dominant catalyst cost contributor, and represents over 98% of the total cost of the de-alloyed PtNiC powder. Other than the Pt material cost, the chloroplatinic acid synthesis and PtNiC precursor reaction (step 1) are the most expensive in materials (\$4.26/system at 500,000 systems/year) and manufacturing (\$2.75/system at 500,000 systems/year). To understand the possible range in cost for the de-alloyed catalyst fabrication process, a single-variable sensitivity was performed on the PtNiC de-alloyed catalyst system. From this sensitivity study, it is evident that many parameters have only a small impact on the bottom line cost. Vendor quotes indicate that the cost of chloroplatinic acid can be as high as \$1/g, much higher than SA's DFMA® projection of ~\$0.11/g. Recovering excess

TABLE 2. PtNiC Catalyst Processing Cost Breakdown ($/system)

	All at 500k Systems per Year			
Component Costs per 80kW$_{net}$ Fuel Cell System	Materials	Manuf.	Markup	Total
Platinum Cost	$1,190.35	$0.00	$0.00	$1,190.35
Step 1: Catalyst PtNiC Precursor	$4.26	$2.75	$2.80	$9.80
Step 2: Precursor Filtration	$0.00	$0.19	$0.08	$0.27
Step 3: Precursor Wash	$0.00	$0.03	$0.01	$0.04
Step 4: Precursor Drying	$0.00	$0.31	$0.13	$0.44
Step 5: Precursor Crushing	$0.00	$0.08	$0.03	$0.11
Step 6: Precursor Annealing	$0.00	$0.68	$0.27	$0.95
Step 7: Catalyst De-alloying	$0.99	$0.55	$0.62	$2.16
Step 8: Catalyst Filtration	$0.00	$0.19	$0.08	$0.26
Step 9: Catalyst Wash	$0.00	$0.03	$0.01	$0.04
Step 10: Catalyst Dry	$0.00	$0.22	$0.09	$0.31
Step 11: Catalyst Crushing	$0.00	$0.10	$0.04	$0.14
Total	$1,195.60	$5.13	$4.15	$1,204.88

Pt used in the fabrication process is also vital to the catalyst cost. If no Pt were to be recovered, it would add $0.97/kW$_{net}$ to the baseline cost.

The air compression system for the automotive power system is based on a Honeywell-style centrifugal air compressor mated to a radial inflow exhaust gas expander and a 165,000 rpm permanent magnet motor. In search for alternative and less expensive CEM units, an Eaton-style twin vortex, Roots-type air CEM was analyzed. A complete DFMA® analysis of the Eaton-style CEM was conducted based on a 5-shaft design (2 compressor drive shafts, 2 expander drive shafts, and a motor shaft) consisting of a motor, motor controller, compressor rotors, expander rotors, drive shafts, couplings, bearings, housing, and other components. The design represents SA's interpretation of Eaton technology applied to the particular specifications of the baseline automotive FCS. The baseline compressor is modeled on Eaton's R340 supercharger which is in Eaton's Twin Vortices Series. The unit is a Roots-type supercharger featuring 2 four-lobed rotors, high-flow inlet and outlet ports, and the capability to achieve high efficiency over a wide air flow range. The compressor is mechanically mated to a 20,000 rpm (max) high efficiency brushless motor. The auto Eaton-style air compressor unit (including motor and motor controller) is estimated at $816 at 500,000 units per year. This value incorporates material, manufacturing, and assembly with a 15% Tier 1 markup on compressor and expander components and a 10% Tier 1 markup on the motor and motor controller components.

A cost comparison of the Eaton-style Roots-technology CEM and the Honeywell-style centrifugal-technology CEM is shown in Figure 3. The Eaton-style CEM is observed to be less expensive at lower volumes (1,000 systems/year), and more expensive at higher volumes (500,000 systems/year). This comparison has the following stipulations:

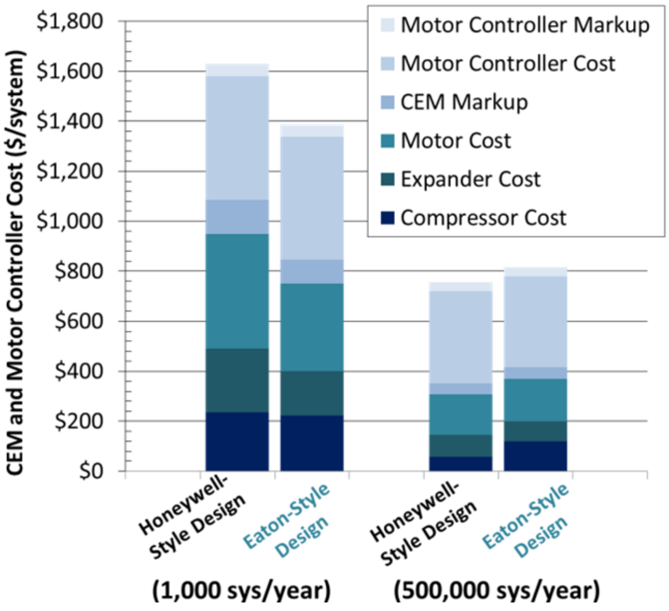


FIGURE 3. Comparison of the DFMA® Cost of Honeywell-Style and Eaton-Style Designs at 1,000 and 500,000 Systems/Year

- Both systems are modeled with the same efficiencies for the compressor, expander, motor, and motor controller.
- The motor controller costs are currently assessed at the same level even though the motors operate at different peak speeds (Eaton-style: 20,000 rpm, Honeywell-style: 165,000 rpm). Future analysis will investigate whether the controller for the Eaton-style system should be lower

cost as the insulated-gate, bipolar transistor switching frequency would be less stringent.

- Motor costs merit further scrutiny as the Eaton motor cost is based on scaled quotes rather than a DFMA® analysis as was used for the Honeywell-style system.

CONCLUSIONS AND FUTURE DIRECTIONS

- 2013 final auto and bus FCS cost results increased from 2012, due to a series of specific analysis and assumption improvements. The 2014 final system cost analysis for the automotive and bus systems are currently underway.
- The 2013 projected system cost of the 160-kWe low-temperature PEM bus FCS is ~$270/kW$_{net}$, and is consistent with other industry estimates. One of the main changes to the bus FCS for 2013 was the implementation of non-vertical integration.
- Other than Pt cost, the PtNiC de-alloyed catalyst cost is dominated by chloroplatinic acid synthesis cost. Pt recovery of greater than 80% is recommended to drive down cost. Future work on the de-alloyed catalyst includes the application to the membrane process and a final comparison to NSTF ternary catalysts, including the impact, if any, of polarization performance differences.
- The cost of the Eaton-style automotive CEM is projected to be $816 per system at 500,000 systems/year. Further 2014 analysis will update this value for recent dimensions and design changes suggested by Eaton.
- Projections of the overall fuel cell power system cost for both automotive and bus applications will be made for the 2014 analysis.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. Hydrogen and Fuel Cells Program Award. Awarded to Brian D. James by the Director of the Fuel Cell Technologies Office, Sunita Satyapal, June 17th 2014.

FY 2014 PUBLICATIONS/PRESENTATIONS

1. "Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2013 Update", Strategic Analysis Report prepared by Brian D. James, Jennie M. Moton, and Whitney G. Colella, January 2014.

2. James, B.D., Moton, J.M., Colella, W.G., "Fuel Cell Transportation Cost Analysis," Presented at U.S. Department of Energy's 2014 Annual Merit Review and Peer Evaluation Meeting for the Hydrogen and Fuel Cell Technologies Program in Washington, D.C., June 16th–20th, 2014.

3. James, B.D., Moton, J.M., Colella, W.G., "Fuel Cell Transportation Cost Analysis," Presented to DOE Fuel Cell Technology Team in Southfield, MI., July 16th, 2014.

4. James, B.D., Moton, J.M., Colella, W.G., "Design for Manufacturing and Assembly Analysis of Zero Emission Vehicular Power Plants," *Proceedings of the ASME 2014 8th International Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference (ESFuelCell2014)*, Boston, Massachusetts, June 30th – July 2nd, 2014 (ESFuelCell2014-6656).

5. James, B.D., Moton, J.M., Colella, W.G., "Definition and Cost Evaluation of Fuel Cell Bus and Passenger Vehicle Power Plants," *Presentation at the ASME 2014 8th International Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference (ESFuelCell2014)*, Boston, Massachusetts, June 30th – July 2nd, 2014.

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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.