V.F.6 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) 2016 Objectives

- Update 2015 automotive and bus fuel cell power system cost projections to reflect latest performance data and system design information.
- Benchmark automotive FCS cost estimate against commercial fuel cell vehicle.
- Re-evaluate multiple fuel cell stack components: bipolar plates (BPPs), laser welding of coolant gasket, and gas diffusion layer (GDL).
- Investigate lifecycle cost (LCC) of two fuel cell bus system designs incorporating fuel usage for multiple drive cycles.

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 fuel cell power systems operating on direct hydrogen. These values can help inform future technical targets as seen in Table 1.

TABLE 1. DOE Technical Targets for 80-kW_{net} Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen

Characteristic	Units	DOE 2020 Targets	DOE Ultimate Targets
Cost of Transportation Fuel Cell Power Systems	$/$kW_{net}$	40	30
Cost of Transportation Fuel Cell Stacks	$/$kW_{net}$	20	15
Cost of Bipolar Plates	$/$kW_{net}$	3	NA

NA – Not applicable

FY 2016 Accomplishments

- Projected the fuel cell power system cost for an 80 kW_{net} light-duty vehicle application using a Design for Manufacturing and Assembly (DFMA®) methodology at annual production rates of 1,000 to 500,000 FCSs per year.
- Projected the fuel cell power system cost of a 160 kW_{net} fuel cell power system for a bus at annual production rates of 200 to 1,000 systems per year.
- Analyzed improvement in performance of de-alloyed platinum nickel on carbon (PtNi/C) catalyst cells to show cost reduction compared to ternary platinum cobalt manganese (PtCoMn) nano-structured thin film (NSTF) catalyst.
- Investigated BPP forming, coating, and laser welding process to enhance model details and refine cost to align with original equipment manufacturer reported values (between $7–$100/kW_{net}).
- Analyzed cost of 91 kW_{net} (114 kW_{gross}) Toyota Mirai FCS design, estimating $233/$kW_{net}$ for materials and manufacturing cost at 1,000 systems per year.
- Conducted fuel cell bus LCC analysis, projecting a range of $2.40/mi to $3.50/mi for two different real-world drive cycles.

INTRODUCTION

This project assesses the cost and performance impact of research advancements on fuel cells for transportation applications using a DFMA®-style [1] cost analysis methodology. Results from this analysis provides insight into the cost and performance impact for the Fuel Cell Technologies Office, which is useful in assessing the impact of current project portfolios and in identifying areas where R&D is still needed to address shortfalls in meeting cost targets. Low temperature (LT) PEM FCSs operating on hydrogen with peak electrical capacities of 80 kW_{net} for light-duty vehicle (automobile) applications and 160 kW_{net} for 40 ft transit bus applications are analyzed. Onboard compressed hydrogen storage, battery energy storage, or traction drive motor subsystems are 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 balance of plant (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 provide updated system cost. Cost trends are evaluated in terms of the capital costs per unit of installed electrical capacity ($\$/kW_{net}$) and system annual production rate.

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 Fuel Cell Tech Team. ANL first principles models of fuel cell stack operating conditions [2] and Strategic Analysis (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 kW_{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 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 2016, the full DFMA® analysis was extended to the Toyota Mirai system based on publicly available sources.

RESULTS

As in previous years, the 2016 high volume manufacturing cost will be reported separately in a DOE data record when available later this year. A blend of the final 2015 cost results (reported for the first time) and 2016 component results are described in this report.

2015 Automotive and Bus System Cost

The operating conditions and assumptions used to calculate costs for the 2015 auto and bus systems are summarized in Table 2. The 2015 automotive system cost at 500,000 systems per year is $\$52.84/kW_{net}$ compared to the 2014 projected cost of $\$54.84/kW_{net}$. The major changes in 2015 result from switching from ternary PtCoMn NSTF catalyst to a dispersed de-alloyed PtNi/C catalyst. Although the 2015 system with de-alloyed PtNi/C catalyst has lower power density (834 mW/cm^2 to 746 mW/cm^2), the overall Pt group metal total content increased (0.0189 g/kW_{gross} to 0.204 g/kW_{gross}) and the air stoichiometry was lowered (2 to 1.5), leading to an overall lower system cost ($-\$1.04/kW_{net}$) in 2015. Additional changes include improved parasitic load calculations for coolant pump and fans and air pressure drop between system components ($-\$0.92/kW_{net}$). Further, hydrogen sensor costs were updated to reflect current market pricing ($-\$0.23/kW_{net}$) and a re-evaluation of the active to total cell area ratio (to better reflect current designs) from 0.8 to 0.625 increased the fuel cell stack cost ($+0.87/kW_{net}$). Other minor changes to the stack and BOP components resulted in a reduction in system cost ($-0.68/kW_{net}$).

The projected bus FCS cost decreased from $\$278.62/kW_{net}$ to $\$261.97/kW_{net}$ at 1,000 systems per year production between 2014 and 2015. Similar changes that were made for the automotive system were also applied to the bus system. The catalyst changed from PtCoMn NSTF to dispersed Pt on carbon, and parasitic load calculations, hydrogen sensor costs (single largest cost reduction of $-\$15.84/kW_{net}$), and active to total cell area ratio were updated.

TABLE 2. PEM Fuel Cell (FC) Auto and Bus System Operating Conditions and Assumptions

	2015 Auto System	2015 Bus System
System Gross Power (kW_{net})	88.22	194.7
System Net Power (kW_{net})	80	160
Power Density (mW/cm^2)	746	739
Cell Voltage (mV)	661	659
Stack Temp (Coolant Exit Temp) (°C)	94	72
Pressure (atm)	2.5	1.9
Platinum Group Metal Total Content (g/ kW_{gross})	0.204	0.721
Air Stoichiometry	1.5	1.8
Catalyst System	Anode: Dispersed Pt/C Cathode: Dispersed d-PtNi/C	Anode and Cathode: Dispersed Platinum on Carbon
Cells per System	378	758

2016 Automotive Fuel Cell Stack Component Investigation

In an effort to obtain current manufacturing costs for automotive fuel cell components, vendors were asked to provide feedback on SA's manufacturing process assumptions. The feedback from these vendors led to changes in cost estimates for BPP forming, laser welding the coolant gasket, and GDLs.

In the auto baseline analysis, BPP forming is modeled as progressive stamping of coiled stainless steel sheets (3 mil). Hydroforming has also been investigated, but will likely not be used at high production volumes (>150 million plates per year). The intricacy of BPP flow fields has become quite detailed, at nine channels per centimeter. The force required for stamping these intricate designs can be greater than 1,500 tons in a progressive stamping machine. At these stamping forces, stamping speeds start to decline to approximately 20 strokes per minute. The capital costs can also range between $1.5–2M depending on the stamping force. Previously modeled high volume BPP stamping costs were approximately$7/$kW_{net}$ based on <200 tons stamping force at 60 strokes/min. Updated projections at high volume are $8.50/$kW_{net}$ based on an 1,800 ton press at 20 strokes/min, inclusive of materials, forming, and anti-corrosion coating.

Previously modeled BPPs were welded together along their perimeter to form cooling cells. To reflect recent input from vendors, the model was updated to include additional welding over the active area of the BPPs to ensure excellent electrical contact between the plates. The length of laser welding increased from 1.5 m in 2015 to 4.2 m in 2016, increasing total plate welding time from 6 s per weldment to ~33 s per weldment. However, additional high volume production manufacturing changes were postulated to increase the number of laser welding heads and the number of progressive welding stations. This reduced the effective cycle time per welded bipolar plate assembly to ≤6 s. The combined increase in laser welding length and reduction in effective cycle time resulted in an increase in total laser welding cost from $0.38/$kW_{net}$ in 2015 to $0.50/$kW_{net}$ in 2016.

A wide range in cost quotes for GDL material from distributors prompted a more thorough investigation. A preliminary DFMA® analysis was completed in 2016 to compare with quotations and to gain better insight on the current process and its cost. The GDL with microporous layer is based on the Ballard Material Products process flow [3]. The projected GDL cost is ~$6/$m^2$ at 500,000 systems per year for a 150 µm thick uncompressed (inclusive of MPL) material.

Benchmarking Against Toyota Mirai FCS

The unveiling of the Toyota Mirai system provides a unique opportunity for SA to compare the baseline system to a mass produced automotive FCS. While Toyota has not released many of its operating conditions, SA was able to make educated guesses for various aspects of the Mirai system using Toyota news releases and publications [4], discussions with original equipment manufacturers and the DOE Fuel Cell Tech Team, and the patent literature [5,6]. Given reported sizing and operating techniques such as internal cell humidification and power output, SA was able to make educated guesses for operating conditions that were deemed reasonable by the DOE Fuel Cell Tech Team. External stack humidification is one of the key differences between SA's baseline system and the Toyota Mirai system. In order to humidify the membrane within the stack, a thin membrane is used to facilitate water transport across the membrane and into the hydrogen flow. A hydrogen recirculation blower is then used to circulate humidified hydrogen from the anode exhaust back to the anode inlet where it can humidify the membrane.

The power density estimate (1.3 W/cm^2) is derived from the estimated total active area (9 m^2/stack) and Toyota reported gross power (114 kW) [4]. The calculation for the active area is based on Toyota's documented stack sizing (37 L, at 1.34 mm thickness per cell) and number of cells (370 cells/stack) [4], SA's estimate for ratio of active cell height to active cell width (0.5:1), SA's estimate for the housing thickness (1 cm), and SA's estimate of the cell active to total area ratio (0.4:1). The net power of the stack is not specified by Toyota; however with air compressor sizing and other ancillary loads from the system, net power is estimated to be 91 kW. Ancillary loads include 20 kW for the air compressor, 1 kW for the hydrogen recirculation blower, and 1 kW for the coolant loop pumps and fans.

The estimated cost for the Toyota Mirai FCS is \$233/kW$_{net}$ at 1,000 systems per year production and is approximately 18% higher than the \$197/kW$_{net}$ projected cost of SA's baseline automotive system (scaled to 91 kW$_{net}$, also at 1,000 systems per year). Figure 1 is a bar chart comparing the component and sub-system costs for the two systems and illustrates the few obvious components that make up the difference. For example the titanium BPPs used in the Mirai have high material cost (compared to the stainless steel used in the baseline) for very thin sheets (estimated to be 3–4 mils thick). The Pt loading estimated for the Mirai stack is likely much higher than the baseline assumption to ensure durability (estimated at 0.3 mgPt/cm^2 compared to 0.142 mgPt/cm^2 for the baseline). The balance of stack for the Mirai is much higher than the SA baseline balance of stack due to extra components in the Mirai stack, including a manifold for gas feed connections. The baseline system uses a combination of low and high flow ejectors for hydrogen recirculation while the Mirai system incorporates a hydrogen recirculation pump. Due to internal humidification, the Mirai does not require an external humidifier like the one used within the baseline system. This trade-off in BOP components makes the systems surprisingly close in BOP cost, making it quite clear that variation in the stack components is the primary source of the cost variation.

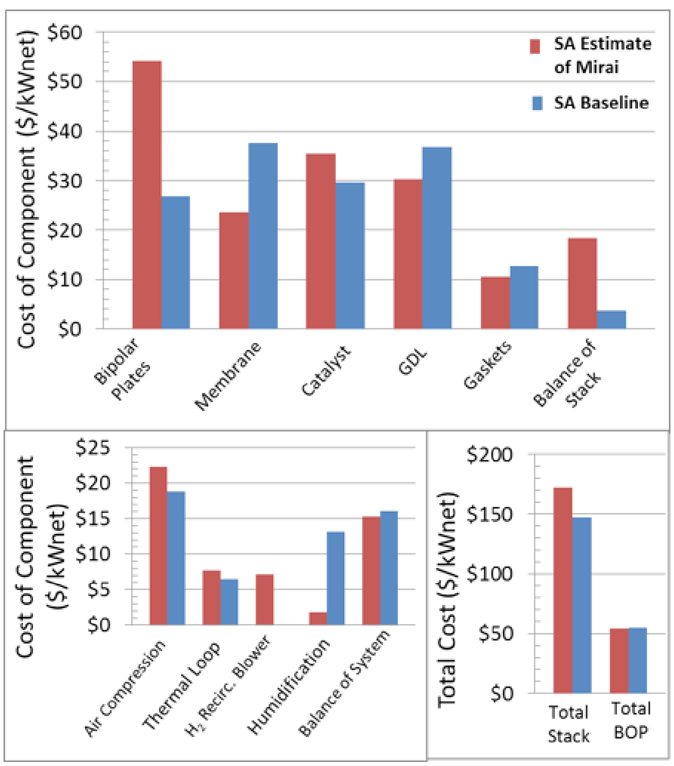
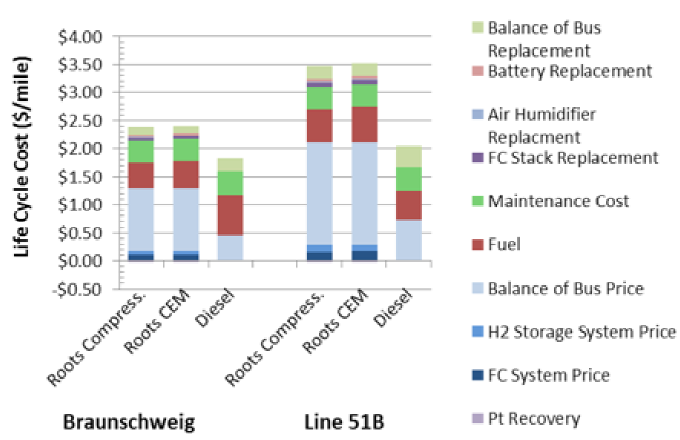


FIGURE 1. Comparison of SA's DFMA® baseline system scaled to 91 kW$_{net}$ (\$197/kW$_{net}$ at 1,000 systems per year) to SA's estimate of the Toyota Mirai FCS (\$233/kW$_{net}$ at 1,000 systems per year)

Fuel Cell Bus LCC Analysis

In collaboration with ANL and Aalto University, SA conducted a bus LCC analysis using performance modeling data (built from experimental results) to determine fuel consumption over a drive cycle. Fuel consumption was provided to SA by ANL/Aalto and used to construct the LCC model. Aalto University has conducted a similar study of bus LCC with the same bus routes, but with different parameter assumptions and capital cost [7] than the present study. ANL modeled bus system performance for two types of air compressor designs for this study: (1) roots air compressor-only and (2) roots air compressor/expander/motor. Aalto University used the FCS operating conditions within the Autonomie vehicle simulation software[1] to obtain the energy requirements for each system at various drive cycles. The modeling results for the roots compressor-only had the lowest fuel consumption (kg H_2/100 km) and highest efficiency

[1] Autonomie is a Matlab©- based vehicle simulation software used for automotive control-systems analysis. http://www.autonomie.net/expertise/Autonomie.html



CEM – compressor/expander/motor

FIGURE 2. Lifecycle cost results for two fuel cell system types for two different bus routes: Braunschweig and Line 51B Berkeley compared to a diesel bus

for all types of drive cycles. The roots air compressor-only system was used in the 2015 bus final DFMA® analysis.

Results from the bus LCC model do not show an appreciable difference between air compressor types, but there is a large impact based on the type of drive cycle and the annual distance driven. As seen in Figure 2, the LCC ranges from \$2.40/mi to \$3.50/mi depending on the drive cycle. In comparison to diesel bus LCCs for the same bus route, the FC bus LCC is 50% higher due to balance of bus cost (made up of power electronics, electric motor, and bus chassis and body).

CONCLUSIONS AND FUTURE DIRECTIONS

- The 2015 final auto and bus system cost results decreased since 2014, due to a series of specific analysis and assumption improvements. The 2016 final system cost analyses for the automotive and bus systems are to be reported in the 2016 DOE Cost Record.
- The automotive FCS cost for 2015 (\$52.84/kW_{net}) reduced exactly \$2/kW_{net} from the 2014 analysis (\$54.84/kW_{net}). The reduction in cost comes primarily from switching to a dispersed de-alloyed PtNi/C catalyst with a lower required air stoichiometric ratio.
- The 160 kW_{net} LT PEM FC bus system cost reduced from \$279–\$262/kW_{net} in 2015 due to the combination of updated sensor costs and increased power density (from 601–739 mW/cm^2).
- Feedback from the FC community prompted a re-evaluation of 2016 FC stack manufacturing process parameters for BPP forming, coolant gasket laser welding, and GDLs.
- To benchmark against a mass produced FC vehicle, the SA baseline DFMA® cost model was scaled to 91 kW_{net} and compared to SA's estimate of the Toyota Mirai system showing a cost of \$197/kW_{net} (baseline) compared to \$233/kW_{net} (Mirai).
- An LCC model was added for the 2016 analysis by incorporating ANL performance models for three types of systems for multiple bus drive cycles. The LCC for the Braunschweig bus route was ~\$2.40/mi while the Line 51B Berkeley bus route was ~\$3.50/mi. Two FC LCC projections are 50% to almost 100% higher than those of diesel buses under similar routes (~\$1.60–\$1.80/mi).

FY 2016 PUBLICATIONS/PRESENTATIONS

1. Moton, J.M., James, B.D., Houchins, C., DeSantis, D.A., "Re-evaluation of Cost and Identification of Risk for Low Volume Manufacturing Techniques Applied to Automotive Fuel Cell Systems," Presentation given at the 2015 Fuel Cell Seminar, Los Angeles, CA, November 17, 2015.

2. Houchins, C., Moton, J.M., DeSantis, D.A., James, B.D., "Assessment of Polymer Electrolyte Fuel Cell Catalyst Cost, Performance and Manufacturability," Presentation given at the 2015 Fuel Cell Seminar, Los Angeles, CA, November 17, 2015.

3. "Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2015 Update," Strategic Analysis Report prepared by Brian D. James, Jennie M. Huya-Kouadio, and Cassidy Houchins, December 2015.

4. James, B.D., Houchins, C., Huya-Kouadio, J.M., "Transportation Fuel Cells Cost Analysis Update Automotive Cost Analysis," Presented to the Fuel Cell Technical Team, Southfield, MI, May 18, 2016.

5. James, B.D., Huya-Kouadio, J.M., Houchins, C., DeSantis, D.A., "2016 DOE Hydrogen and Fuel Cells Program Review: Fuel Cell Vehicle and Bus Cost Analysis," Presented at the 2016 DOE Hydrogen and Fuel Cells Program Annual Merit Review Meeting, Washington, D.C., June 9, 2016.

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1. Boothroyd, Geoffrey, Peter Dewhurst, and Winston A. Knight. *Product Design for Manufacture and Assembly, Third Edition*. CRC Press, 2010.

2. Ahluwalia, Rajesh. "Fuel Cell Systems Analysis." presented at the DOE Fuel Cell Tech Team, Southfield, MI, July 15, 2016.

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7. Lajunen, Antti, and Timothy Lipman. "Lifecycle Cost Assessment and Carbon Dioxide Emissions of Diesel, Natural Gas, Hybrid Electric, Fuel Cell Hybrid and Electric Transit Buses." *Energy* 106 (2016): 329–342.