V.E.5 Fuel Cell Vehicle Cost Analysis

Brian D. James (Primary Contact),
Jennie M. Huya-Kouadio, Cassidy Houchins,
Daniel A. DeSantis
Strategic Analysis, Inc. (SA)
4075 Wilson Blvd., Suite 200
Arlington, VA 22203
Phone: (703) 778-1114
Email: bjames@sainc.com

DOE Manager: Adria Wilson
Phone: (202) 586-5782
Email: Adria.Wilson@ee.doe.gov

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Subcontractors:
- Argonne National Laboratory (ANL), Argonne, IL
- National Renewable Energy Laboratory, Golden, CO

Project Start Date: October 1, 2016
Project End Date: September 30, 2021

Overall Objectives

- Provide thorough, annually updated assessment of the technical status of current on-road and advanced (2020 and 2025) proton exchange membrane (PEM) fuel cell (FC) power systems for light-duty vehicles (LDVs), medium and heavy-duty vehicles (MDVs/HDVs), and buses, detailed to the extent necessary to track system performance and manufacturability.
- Report cost estimates of the fuel cell systems (FCSs) described above to reflect optimized components and manufacturing processes at various rates of production, and to update these on an annual basis.
- Conduct sensitivity analyses of FCS cost and identify key system cost parameters with the goal of fully understanding the cost drivers.
- Identify most promising pathways to system/lifecycle cost reduction.
- Perform review of all components of the analysis, both internally and with the help of perspectives external to the project, and document analysis assumptions and results through various media (presentations and a complete, comprehensive report).

Fiscal Year (FY) 2017 Objectives

- Conduct model validation of currently manufactured, representative, industry accepted hydrogen FCSs, subsystems, or components for production passenger vehicles.
- Update 2016 automotive FCS cost projections to reflect the latest performance data and system design information.
- Extend automotive cost projections to 2020 and 2025 future year analyses.
- Conduct an MDV/HDV fuel cell electric truck (FCET) scoping study to identify the system(s) for study in subsequent years (e.g., issues, power level, architecture, level of hybridization).

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

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

Characteristic	Units	Project Status	DOE 2020 Targets	DOE Ultimate Target
Cost of Transportation FC Power Systems[1]	\$/kW$_{net}$	45	40	30
Cost of Transportation FC Stacks[1]	\$/kW$_{net}$	19	20	15
Cost of Bipolar Plates[1]	\$/kW$_{net}$	5	3	NA

[1] Based on high production volume of 500,000 vehicles per year.
NA - not applicable

FY 2017 Accomplishments

- Projected the FCS cost for an 80 kW$_{net}$ LDV application using a Design for Manufacture and Assembly (DFMA®) methodology at annual production rates of 1,000 to 500,000 FCSs per year.
- Projected a cost reduction (~\$7.50/kW$_{net}$) from improved electrochemical performance (749 mW/cm^2 to 1,095 mW/cm^2) made possible by use of a General Motors (GM) high surface area carbon (HSC) support in conjunction with a platinum cobalt on carbon (PtCo/C) cathode catalyst.
- Estimated the automotive FCS cost to be \$45/kW$_{net}$ for 2017, \$43/kW$_{net}$ for 2020, and \$36/kW$_{net}$ for 2025 at 500,000 vehicles produced per year.

- Cost modeled the Toyota Mirai FCS (88.5 kW_{net}, 114 kW_{gross}), estimating FCS materials and manufacturing cost at \$183/kW_{net} and a total projected sales price of \$56,965 at 3,000 systems per year (sys/yr) (compared to Toyota's manufacturer's suggested retail price (MSRP) of \$57,500).

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INTRODUCTION

This project assesses the cost and performance impact of research advancements on FCs for transportation applications using a DFMA®-style [1] cost analysis methodology. Results from this analysis provides assistance to the Fuel Cell Technologies Office 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 PEM FCSs operating on hydrogen with peak electrical capacities of current (2017) and future (2020 and 2025) 80 kW_{net} for LDV, and MDV/HDV applications are analyzed. Onboard compressed hydrogen storage, battery energy storage, and traction drive motor subsystems are not included in this cost assessment. The impact of annual production rates on the cost of the automotive and truck systems is examined to assess the difference between a nascent and a mature product manufacturing base. LDV FCSs are analyzed at six annual production rates: 1,000, 10,000, 20,000, 50,000, 100,000, and 500,000 FCSs per year. DFMA® analysis of MDV/HDV systems will be conducted in 2018 at annual production rates between 1,000 and 250,000 FCSs per year.

This 2017 work focused primarily on a continuation of a previous DOE award (DE-EE0005236 between 2011 and 2016). Existing FCS DFMA® cost models for current and future year LDV system designs were analyzed, and a scoping study of the system design parameters for MDV/HDV FCSs was conducted. Stack and balance of plant 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 80 kW_{net} LDVs at various manufacturing production rates. The optimum stack operating conditions and operating point are selected in collaboration with ANL and the Fuel Cell Tech Team. ANL first principles models of FC 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 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 FC 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.

RESULTS

A blend of the final 2016 system cost results (reported for the first time) and 2017 system cost results are described in this report.

2016 and 2017 Automotive System Cost

The operating conditions and assumptions used to project costs for the 2016, 2017, 2020, and 2025 auto systems are summarized in Table 2. A significant reduction in projected system cost occurred between 2016 and 2017 (from \$53/kW_{net} to \$45/kW_{net} at 500,000 sys/yr) primarily due to an increase in power density from 749 mW/cm^2 to 1,095 mW/cm^2 with a simultaneous decrease in total Pt loading (0.134 mg/cm^2 to 0.125 mg/cm^2). The difference in performance and Pt loading is based on a recent GM study [3] where a proprietary HSC was used for the support of a PtCo/C cathode catalyst. In 2016, ANL modeled de-alloyed PtNi/C catalyst performance for optimized conditions. In 2017, PtCo/C cathode catalyst was used for the baseline. Although ANL had not modeled PtCo/C for optimized conditions, there was a consensus between ANL and GM that de-alloyed PtNi/C (used as the 2016 catalyst) would have similar performance to a PtCo/C (used for the 2017 and 2020 catalysts) if both catalysts were supported by GM's proprietary HSC support. The similarity in performance is due to the expectation of similar cathodic kinetic reaction rates whether using PtNi or PtCo. The PtCo synthesis process was not conveyed in detail to SA, but GM states that it would be very similar to that of PtNi. Consequently, the 2017 and 2020 catalyst synthesis cost is based on de-alloyed PtNi/C.

2020 and 2025 Future Automotive system Cost

The system parameters chosen for the 2020 year analysis assume reasonable and attainable performance

TABLE 2. PEM FC Auto Systems Operating Conditions and Assumptions

Auto System Year	2016	2017	2020	2025
System Gross Power (kW_{net})	87.68	87.90	87.90	87.90
System Net Power (kW_{net})	80	80	80	80
Power Density (mW/cm^2)	749	1,095	1,165	1,500
Cell Voltage (mV)	659	663	663	663
Stack Temp (Coolant Exit Temp) (°C)	94	94	94	94
Pressure (atm)	2.5	2.5	2.5	2.5
Pt Loading (mg/cm^2)	0.134	0.125	0.125	0.088
Platinum Group Metal Total Content (g/ kW_{gross})	0.191	0.124	0.116	0.064
Air stoichiometry	1.4	1.5	1.5	1.5
Cathode Catalyst System*	Disp. d-PtNi/C	Disp. PtCo/ HSC-e	Disp. PtCo/ HSC-f	Disp. Adv. High Perf. Catalyst
Cells per System	379	377	377	377
Total System Cost ($\$/kW_{net}$) (100,000 sys/yr)	$59	$50	$47	$40
Total System Cost ($\$/kW_{net}$) (500,000 sys/yr)	$53	$45	$43	$36

* Disp. = Dispersed. All years assume dispersed Pt/C on the anode.

and manufacturing methods that have been demonstrated at the lab scale. In contrast, the system parameters for the 2025 year system are based on aggressive or optimistic technology advances, i.e., advances that might be possible in approximately 2025 if there was a focused and well-funded effort (or possibly in a later year if development efforts are not focused or well-funded). Figure 1 shows the key system assumptions and resulting cost for each system evaluated.

Between the current and future year studies, performance is assumed to increase while simultaneously reducing Pt loading. The system designs are very similar with the exception of the hydrogen recirculation system changing. The 2016 and 2017 systems include two fixed geometry ejectors to supply recirculation of H_2 while the 2020 and 2025 systems assume a pulsed ejector (injector upstream of the ejector) that is able to achieve the targeted H_2 recirculation even at the low flow conditions of FC part power operation (rather than using a battery at very low power). Even with multiple improvements in the performance and simplified system, the 2020 auto system cost ($\$43/kW_{net}$ at 500,000 sys/yr) does not meet the 2020 DOE target of $\$40/kW_{net}$. It is also noted that achievement of the power density specified for 2025 (1,500 mW/cm^2) may require a new, as yet undeveloped, catalyst.

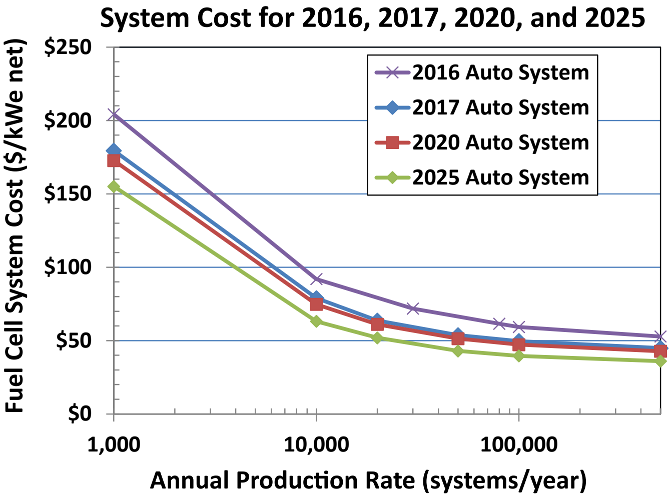

FIGURE 1. System cost for 2016, 2017, 2020, and 2025 analyses at all production rates

MDV/HDV Fuel Cell Electric Truck Scoping Study

A scoping study was conducted to define the MDV/HDV FCSs to be cost analyzed in the next year of the project. To determine representative system(s) for MDV/HDV FCETs, information was gathered on current demonstrations of FCETs and to assess their similarities to bus FCSs. ANL provided data from their recent FCET study [4] regarding the power levels required by both MDV/HDV trucks. The ANL study was based on commercial fleet vehicle operation data for 12 different applications and weight classes of trucks (seen in Figure 2). All of these trucks, with the exception of the Nikola One truck, are based on a FC dominant system with a battery for peak acceleration events. Although most upcoming demonstrations size the FC for range extension, where the FC charges the battery and the battery is sized for peak power, SA chose FC dominant systems as the baseline type of truck in which to perform a detailed DFMA® cost estimate. In FC dominant systems, the FC is sized for the peak sustained power and the battery is only for power augmentation. Future work may incorporate a comparison for a FC dominant versus a battery dominant system. As

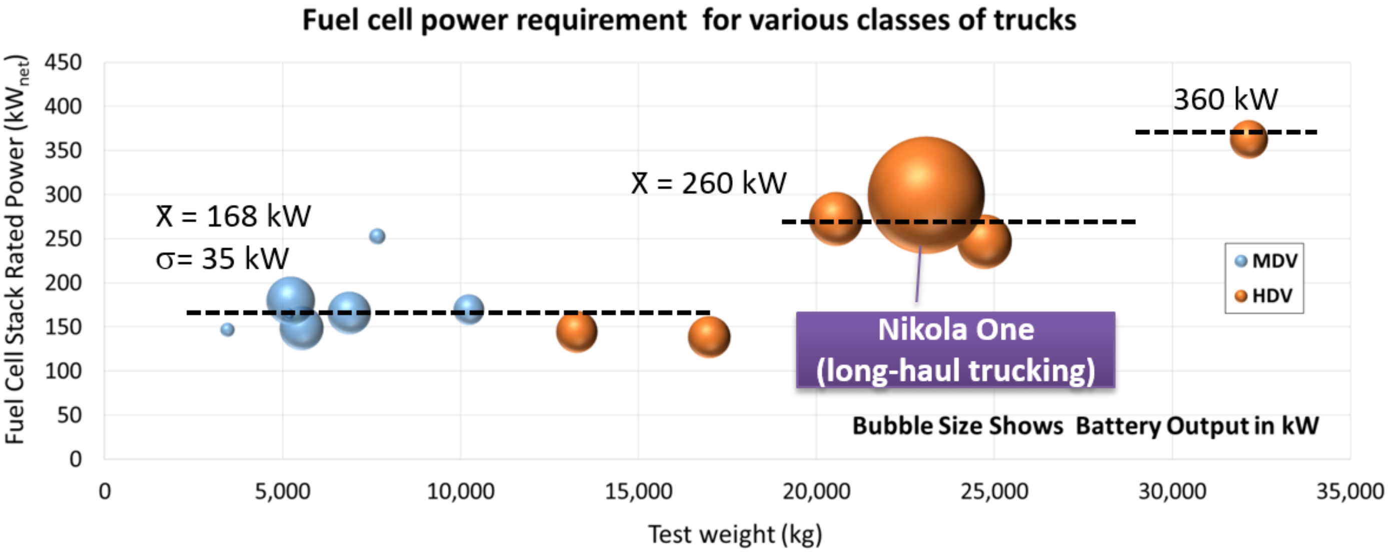

FIGURE 2. FC power requirements for different FCET applications based on vehicle weight

can be seen in Figure 2, three power levels (168 kW, 260 kW, and 360 kW) capture the majority of MDV/HDV FCET applications. Coincidentally, these sizes are approximate multiples of 80–90 kW stacks and thus offer synergies with LDV stacks. Feedback from bus FCS manufacturers suggests that the FCSs in buses, with minor adjustments, could be used in FCETs. Based on this scoping study, the preliminary parameters contained in Table 3 are proposed for possible systems to analyze for the 2018 DFMA® cost study of FC dominant MDV/HDV FCETs. The number and types of systems analyzed will be determined based on additional feedback from system integrators and input from DOE. The remaining FCS parameters will be selected as part of the 2018 analysis.

Model Validation Study

Since Toyota Motor Co. has published numerous open literature reports on the Mirai FC vehicle, the Mirai FCS was selected for a validation study. All data was derived from open sources and Toyota did not provide input specifications or comment on the cost results. Two areas of SA cost model validation are of interest: (1) validation of the system design and (2) validation of the projected system cost. For the validation of system design, SA researched and modeled, to some degree, every component listed by Toyota in publically available documentation. Comparisons were made between SA's baseline automotive system and the Mirai system. Key differences include a projected higher Pt loading, use of titanium bipolar plates (instead of stainless

TABLE 3. PEM FC Bus and MDV/HDV FCET Systems Operating Conditions and Assumptions

	2016 Bus System	2017 MDV System	2017 HDV System
Annual Production (sys/year)	200–1,000	Up to 150,000 (total market) [5]	Up to 250,000 (total market) [5]
Target Stack Durability (hours)	25,000 [6]	25,000 [6] / 5,000 [7]	25,000 [6]
Total Pt loading (mgPt/cm$^2_{\text{total area}}$)	0.5	0.5	0.5
Pt Group Metal (PGM) Total Content (g/kW$_{gross}$)	0.719	0.719	0.719
Power Density (mW/cm^2)	739	TBD	TBD
Cell Voltage (V/cell)	0.659	prelim. 0.659 (subject to time-at-power analysis)	prelim. 0.659 (subject to time-at-power analysis)
Net Power (kW$_{net}$)	160	~160	240/360
Gross Power (kW$_{gross}$)	195	TBD	TBD
Operating Pressure (atm)	1.9	prelim. 1.9 (to be cost optimized)	prelim. 1.9 (to be cost optimized)
Stack Temp. (Coolant Exit Temp) (°C)	72	72*	72*

*Lower temperature selected for durability
TBD – to be determined; prelim. – preliminary

steel), use of hydrogen recirculation pump, removal of an external humidifier, and other minor differences as discussed in SA's 2016 Annual Progress Report [8]. Since Toyota-supplied cost data was not available, SA validated its cost model projections against the Toyota Mirai's MSRP. To convert DFMA® projected costs into a corresponding sales price, the following assumptions were made: 17% markup for production overhead on the FCS and hydrogen storage system [9], $17,600 for other auto component costs (including battery; electric traction motor; inverter; gear box; glider; regenerative braking system; and heating, ventilation, and cooling system) [10], 20% markup for marketing and warranty [9], and 9% markup for corporate overhead and profit [9].

As seen in Figure 3, SA examined cost at both 1,000 sys/yr and 3,000 sys/yr production rates, with price projections effectively bracketing Toyota's MSRP of $57,500 for 2017. At 3,000 vehicles per year, SA estimates the FC manufacturing cost to be ~$183/kW$_{net}$ ($16,204 per system) for the 114 kW$_{gross}$ (88.5 kW$_{net}$) Mirai FCS and $6,168 per system for the H_2 storage system. With the markup and overhead rates mentioned previously, this equates to ~$56,965 per system in total projected vehicle price and is an excellent match with Toyota's MSRP of $57,500.

CONCLUSIONS AND UPCOMING ACTIVITIES

- The use of GM's high performing PtCo catalyst on HSC catalyst support lowers automotive FCS projected cost by $7.50/kW$_{net}$ (a 14% reduction from $53 in 2016 to $45/kW$_{net}$ in 2017 at 500,000 sys/yr).
- Future projections for automotive FCS cost are $43/kW$_{net}$ for 2020 and $36/kW$_{net}$ for 2025 at 500,000 sys/yr.
- FCSs for MDV/HDV trucks are expected to be very similar to buses. When designed for FC dominant operation, FCET would utilize multiple 80–90 kW FC stacks. Three possible system sizes of FCSs may be analyzed in 2018 (160 kW$_{net}$, 240 kW$_{net}$, 360 kW$_{net}$) and possible comparison to FC range extenders.
- The SA cost model has been validated against the Toyota Mirai FCS in design and estimated vehicle price ($56,965 compared to Toyota's $57,500 MSRP).
- Future work includes evaluation of an electrospun membrane support material, and ionomer material such as perfluoro imide acid as an alternative to perfluorosulfonic acid.

FY 2017 PUBLICATIONS/PRESENTATIONS

1. James, B.D., Huya-Kouadio, J. M., Houchins, C., "Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2016 Update," Strategic Analysis report for DOE FCTO, September 30, 2016.

2. James, B.D., Huya-Kouadio, J.M., Houchins, C., "Bipolar Plate Cost and Issues at High Production Rate," presented at the DOE Workshop on Research and Development Needs for Bipolar Plates for PEM Fuel Cell Technologies, Southfield, MI, February 14, 2017.

3. James, B.D., Huya-Kouadio, J.M., Houchins, C., "Fuel Cell Vehicle Cost Analysis," presented to the Fuel Cell Technical Team, Southfield, MI, May 17, 2017.

4. James, B.D., Huya-Kouadio, J.M., Houchins, C., DeSantis, D.A., "2017 DOE Hydrogen and Fuel Cells Program Review: Fuel Cell Systems Analysis," presented at the 2017 DOE FCTO Annual Merit Review Meeting, Washington, DC, June 8, 2017.

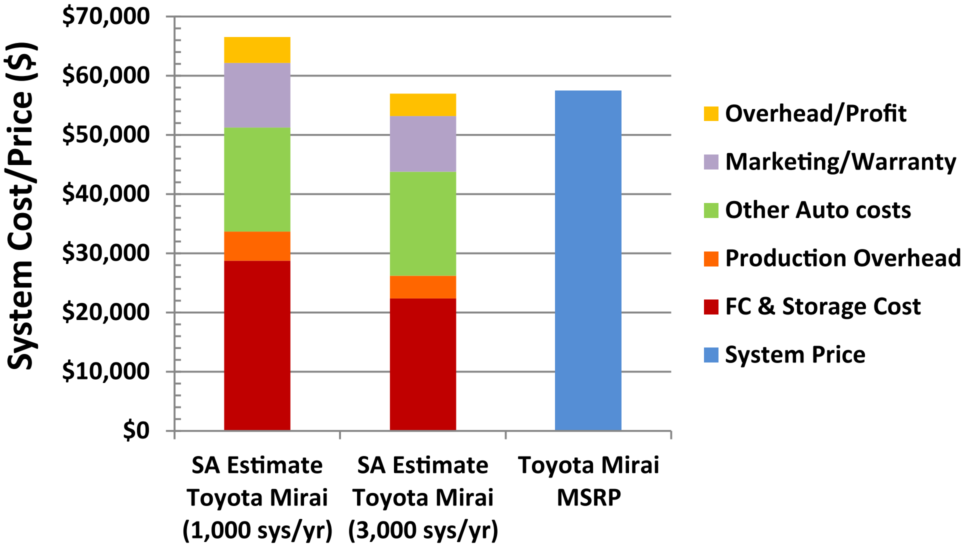

FIGURE 3. Validation of SA's DFMA® model of the Toyota Mirai FC vehicle

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8. James, Brian D., Huya-Kouadio, Jennie M., Houchins, Cassidy, and DeSantis, Daniel A., "Fuel Cell Vehicle and Bus Cost Analysis," Annual Progress Report written by Strategic Analysis Inc. for DOE FCTO, 2016.

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10. Greene, David, "Status and Prospects of the Global Automotive Fuel Cell Industry and Plans for Deployment of Fuel Cell Vehicles and Hydrogen Refueling Infrastructure," report by Oak Ridge National Laboratory for the DOE FCTO, July 2013.