Fuel Cell Systems Analysis

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Subcontractors:
- Argonne National Laboratory, Lemont, 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, medium-duty, and heavy-duty vehicles (LDVs, 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 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/life cycle 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 presentations and a complete, comprehensive report.

Fiscal Year (FY) 2018 Objectives

- Update 2017, 2020, and 2025 automotive FCS cost projections to reflect the latest performance data and system design information.
- Conduct an MDV fuel cell electric truck (FCET) cost analysis based on system design and performance studies completed in 2017.
- Evaluate the cost of electrospun materials for use in the membrane electrode assembly.

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[1]:

(B) Cost.

Technical Targets

Table 1 shows the DOE technical targets and current project status.

FY 2018 Accomplishments

- Projected the FCS cost for an 80 kW_{net} LDV application using a Design for Manufacture and Assembly (DFMA) methodology to be $\$47/kW_{net}$ for 2018, $\$44/kW_{net}$ for 2020, and $\$39/kW_{net}$ for 2025 at 500,000 vehicles produced per year, reaching the DOE target of $\$40/kW_{net}$ by 2025.
- Cost modeled an MDV FCS (160 kW_{net}), resulting in $\$98/kW_{net}$ for 2018, $\$91/kW_{net}$ for 2020, and $\$80/kW_{net}$ for 2025 projections at an annual production rate of 100,000 vehicles per year.

[1] https://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

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

Characteristic	Units	Project Status	DOE 2025 Targets	DOE Ultimate Target
Cost of transportation fuel cell power systems[a]	$/$kW_{net}$	47	40	30
Cost of transportation fuel cell stacks[a]	$/$kW_{net}$	19	20	15
Cost of bipolar plates[a]	$/$kW_{net}$	5	3	NA
Air compression system cost[a]	$/system	850	500	NA
Cathode humidifier system cost[a]	$/system	60	100	NA

[a] Based on high production volume of 500,000 vehicles per year

INTRODUCTION

This project assesses the cost and performance impact of research advancements on fuel cells for transportation using a DFMA-style [1] cost analysis methodology. Results from this analysis provide 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 (2018) and future (2020 and 2025) of 80 kW_{net} for LDV and 160 kW_{net} for MDV applications are analyzed. Onboard compressed hydrogen storage, battery energy storage, and traction drive motor subsystems are not included in this cost assessment. To examine the difference between a nascent and a mature product manufacturing base, LDV FCSs are analyzed at 1,000, 10,000, 20,000, 50,000, 100,000, and 500,000 FCSs per year. MDV FCSs are analyzed at 200, 500, 1,000, 10,000, 50,000, and 100,000 FCSs per year.

Fuel cell 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. Argonne National Laboratory (ANL) first principles fuel cell performance models [2] and Strategic Analysis, Inc. (SA) DFMA cost models are used to identify cost and performance optimized conditions, which are then vetted by the U.S. DRIVE 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. 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. The costs of lesser components are determined by price quote or analogy to similar commercial components.

RESULTS

The final 2018 system cost results for the LDV and MDV FCSs are described in this report. Full analysis assumptions and results are available in SA's 2018 Final Report [3]. A graphical comparison of system cost results at all production volumes appears in Figure 1.

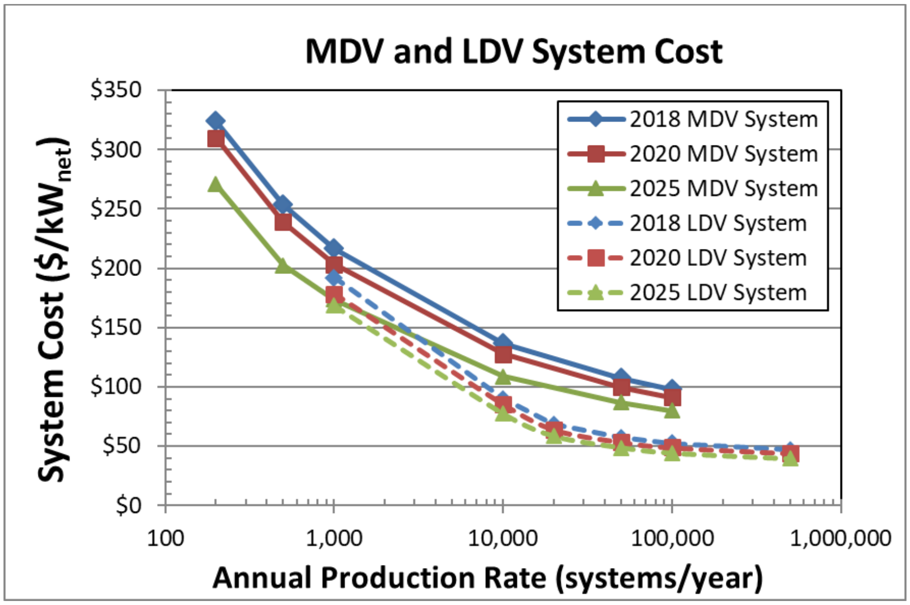

Figure 1. MDV and LDV system cost at each production rate for 2018, 2020, and 2025 systems

2018 Baseline Automotive System Cost

The operating conditions and assumptions used to project costs for the 2018, 2020, and 2025 auto systems are summarized in Table 2. An overall increase in projected system cost occurred between 2017 and 2018 (previously $45/kW$_{net}$, now $47/kW$_{net}$ at 500,000 systems per year [sys/yr]). The same catalyst utilized in 2017 (de-alloyed platinum cobalt on high-surface-area carbon [PtCo/HSC]) [4] was used for 2018; however, more relevant experimental data of this catalyst provided by General Motors was incorporated into ANL's performance model. This led to an increase in power density from 1,095 mW/cm^2 to 1,183 mW/cm^2, reducing total system cost ~$0.90/kW$_{net}$. Despite this reduction in cost, multiple changes were made in 2018 to improve the validity of the cost model resulting in an overall cost increase for the 2018 system. Air valves were added to prevent air backflow and to provide stack isolation during shutdown. The largest cost impact was inflation adjustment of the air compression system cost, ~$1.70/kW$_{net}$, which had been erroneously constant for multiple years. Although this does not reflect a technological advancement, it is necessary in order to project a realistic cost for the 2018 LDV FCS. The air compression system is one of the most cost-sensitive components in the FCS, as seen in the tornado chart in Figure 2.

2020 and 2025 Future Automotive System Cost

The system parameters chosen for the 2020-year analysis assume reasonable and attainable performance and manufacturing methods that have been demonstrated at lab scale. In contrast, the system parameters for the 2025-year system are based on aggressive/optimistic technology advances, that is, advances that might be possible in approximately 2025 if there was a focused/well-funded effort (or possibly in a later year if development efforts are not focused or well-funded).

Between the current and future year studies, performance is assumed to increase while simultaneously reducing Pt loading. Assuming 1,500 mW/cm^2 power density with only 0.088 mg/cm^2 Pt loading, the 2025 auto system cost ($39/kW$_{net}$ at 500,000 sys/yr) now meets the 2025 DOE target of $40/kW$_{net}$. However, achievement of the 2025 power density target may require a new higher-performing and/or lower-loaded catalyst.

Table 2. PEM Fuel Cell Auto Systems Operating Conditions and Assumptions

Auto System Year	2017	2018	2020	2025
System gross power (kW_{net})	87.90	88.37	88.37	88.37
System net power (kW_{net})	80	80	80	80
Power density (mW/cm^2)	1,095	1,183	1,260	1,500
Cell voltage (mV)	663	657	657	657
Stack temp. (coolant exit temp.) (°C)	94	95	95	95
Pressure (atm)	2.5	2.5	2.5	2.5
Pt loading (mg/cm^2)	0.125	0.125	0.125	0.088
Platinum group metal total content (g/kW_{gross})	0.124	0.115	0.108	0.064
Air stoichiometry	1.5	1.5	1.5	1.5
Cathode catalyst system[a]	Disp. PtCo/HSC	Disp. PtCo/HSC	Disp. PtCo/HSC	Disp. adv. high perf. catalyst
Cells per system	377	380	380	380
Total system cost ($/$kW_{net}$) (100,000 sys/yr)	$50	$52	$49	$44
Total system cost ($/$kW_{net}$) (500,000 sys/yr)	$45	$47	$44	$39

[a] Disp. = Dispersed. All years assume dispersed Pt/C on the anode.

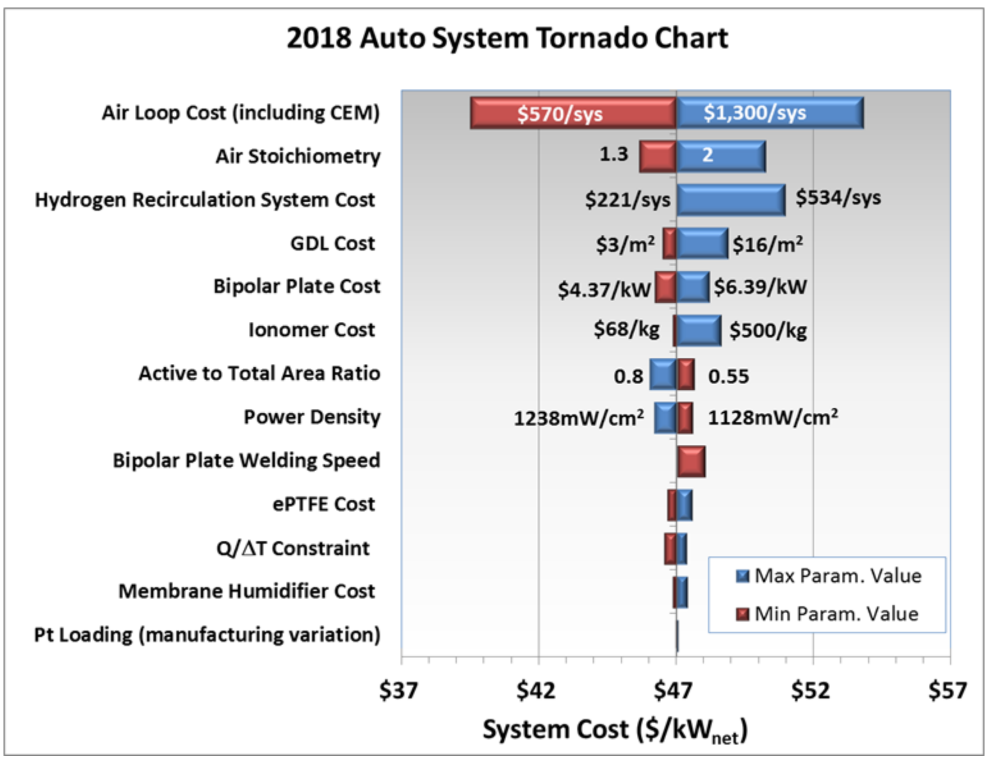

Figure 2. 2018 auto system tornado chart showing air loop cost (including compressor/expander/motor [CEM]) being the most sensitive cost component

2018 MDV Fuel Cell Electric Truck System Cost

To determine the system design for MDV FCETs and to assess their similarities to bus FCSs, information was gathered on current FCET demonstration projects. SA chose a fuel-cell-dominant 160 kW_{net} Class 6 MDV system as the baseline type of truck on which to perform a detailed DFMA cost analysis. In a fuel-cell-dominant system, the fuel cell is sized for the peak sustained power and the battery is only for short-term power augmentation. The system utilizes two 80-kW stacks and thus offers synergies with LDV stacks. Feedback from bus FCS manufacturers suggests that the FCSs in buses, with minor adjustments, could be used in FCETs. From this input, the system was designed to be quite similar to a fuel cell bus system. The parameters contained in Table 3 were used to define the systems analyzed for the 2018 DFMA cost estimate. Because the Toyota Mirai stacks have been demonstrated in a fuel cell heavy-duty truck [5], a few of the operating parameters for the truck system (such as Pt loading ~30 g Pt/stack [6], stack pressure, and temperature) were aligned with the Mirai system. Similar to the bus system, the FCET operating temperature is lower than that of the LDV system so as to reduce degradation and increase longevity of the stack. The power density was derived from ANL's performance modeling for the de-alloyed PtCo/HSC catalyst. A range in production volume from 200 to 100,000 systems per year reflects a demonstration size fleet (at the low end) up to a mass-produced system (at the high end) likely supplied to multiple truck integrators.

Table 3. PEM Fuel Cell Bus and MDV FCET Systems Operating Conditions and Assumptions

System Analyzed	2016 Bus	2018 MDV	2020 MDV	2025 MDV
Annual production (FCSs/year)	200–1,000	200–100,000	200–100,000	200–100,000
Target stack durability (hours)	25,000 [7]	25,000 [7] / 5,000 [8]	25,000 [7] / 5,000 [8]	25,000 [7] / 5,000 [8]
Total Pt loading (mg Pt/$cm^2_{total\ area}$)	0.5	0.35	0.35	0.3
PGM total content (g/kW_{gross})	0.719	0.321	0.316	0.242
Power density (mW/cm^2)	739	1,178	1,200	1,350
Cell voltage (V/cell)	0.659	0.68	0.68	0.68
Net power (kW_{net})	160	160	160	160
Gross power (kW_{gross})	195	196	189	185
Operating pressure (atm)	1.9	2.4	2.4	2.4
Stack temp (coolant exit temp) (°C)	72	63[a]	63[a]	63[a]
Total system cost ($/$kW_{net}$) (100,000 sys/yr)	NA	$97	$90	$81

[a] Lower temperature selected for durability

2020 and 2025 MDV Fuel Cell Electric Truck System Cost

Given that FCETs are in their infancy, currently only used in demonstration projects, there is interest and uncertainty as to the configuration and technology for future year systems. Compared to the 2018 FCET baseline system design, the modeled 2020 and 2025 systems assume a more advanced air compression system with an expander. The gross power is thus smaller than for the baseline, leading to lower-cost systems. The assumed performance projections are based on the team's best engineering judgment, with consideration of current Mirai performance, assumed truck operating conditions, and the improvements expected in LDV polarization performance.

Electrospun Membrane and Catalyst Materials

As a side study to the baseline system, SA analyzed three different electrospun material sets: (1) membrane support (direct replacement of expanded polytetrafluoroethylene [ePTFE]), (2) co-spun membrane support and ionomer, and (3) Pt catalyst. Many of the assumptions used in the analysis came from open source documentation [9, 10] and discussions with experts from 3M and Vanderbilt University. Quotes for high-volume electrospinning production equipment were obtained from Inovenso and Elmarco.

Electrospun nanofiber mats made of a polyphenylsulfone (PPSU) membrane support material are projected to be ~$1/m^2 compared to $6/m^2 for the price of ePTFE mats at high production volume. These electrospun membrane supports are projected to replace ePTFE for the 2020 and 2025 LDV FCSs. A co-spun support and ionomer membrane is modeled as a dense Nafion layer reinforced with PPSU nanofibers. It is compared to the baseline ePTFE-supported Nafion membrane manufactured using a Gore Direct-Coat method. The electrospun catalyst is modeled as d-PtCo/HSC and is compared to a slot die coating process. Figure 3 shows various combinations of the three material sets to estimate the total price of a catalyst-coated membrane. The lowest price ($/m^2) catalyst-coated membrane at 500,000 sys/yr is comprised of an electrospun PPSU support with a Gore Direct-Coat membrane coating technique to coat Nafion, and slot die coated catalyst for the cathode and anode. All methods listed in Figure 3 have similar cost at high manufacturing rates. If electrospun materials perform better than conventional catalyst-coated membranes (seen in work by Vanderbilt [11]), there can be a reasonable cost savings in the stack.

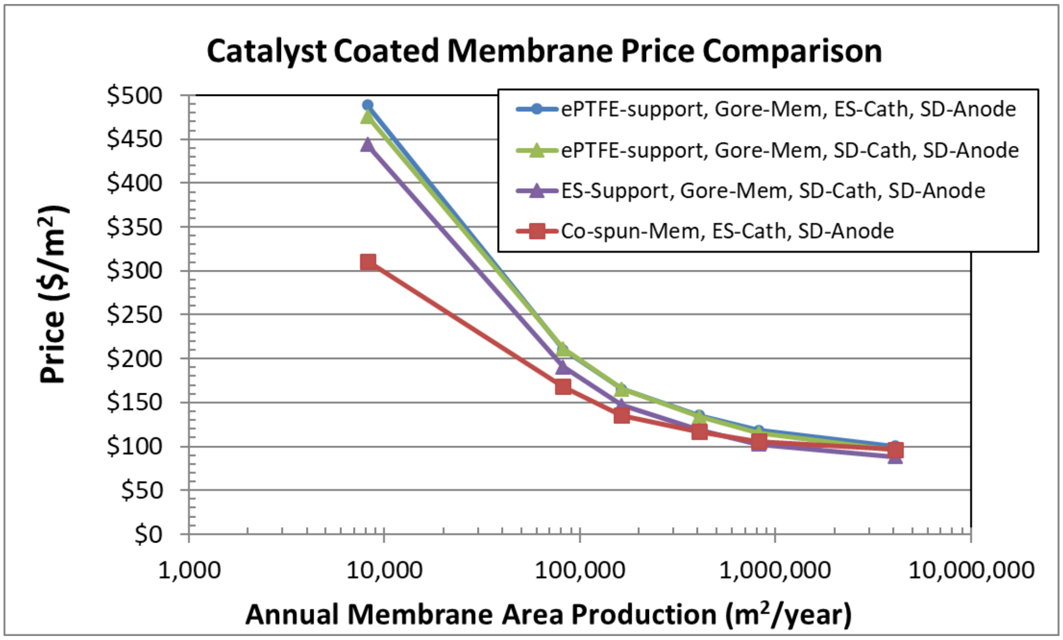

Figure 3. Comparison of catalyst-coated membrane prices with electrospun or conventional components (ES – electrospun, SD – slot die coated)

CONCLUSIONS AND UPCOMING ACTIVITIES

- The estimated cost for an 80 kW_{net} automotive FCS is $47/$kW_{net}$ at 500,000 sys/yr. When projecting the cost utilizing future year technology, it is estimated to be $44/$kW_{net}$ in 2020, and $39/$kW_{net}$ in 2025, meeting the DOE 2025 target of $40/$kW_{net}$.
- FCSs for MDV/HDV trucks are expected to be very similar to buses. When designed for fuel-cell-dominant operation, a 160 kW_{net} MDV FCS is estimated to cost $97/$kW_{net}$ at 100,000 sys/yr. Future projections for MDV FCS cost are $90/$kW_{net}$ for 2020 and $81/$kW_{net}$ for 2025 at 100,000 sys/yr.
- Electrospun PPSU fibrous supports can be lower price compared to an ePTFE membrane support. Co-spun Nafion and support membranes and electrospun catalysts are estimated to be very similar in price to conventional membranes and electrodes. Given the same or better performance, electrospun materials can present a price reduction opportunity for the stack.

- Future work includes evaluation of high-speed roll-to-roll cell assembly (2-D manufacturing), review of the cost impact of various stack durability methods, estimation of the cost to recycle and dispose a fuel cell membrane electrode assembly, and continued evaluation of air compression systems.

FY 2018 PUBLICATIONS/PRESENTATIONS

1. B.D. James, J.M. Huya-Kouadio, and C. Houchins, "Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2017 Update," Strategic Analysis report for DOE Fuel Cell Technologies Office, September 30, 2017.
2. J.M. Huya-Kouadio, B.D. James, and C. Houchins, "Meeting Cost and Manufacturing Expectations for Automotive Fuel Cell Bipolar Plates," Presentation at the 2017 Fuel Cell Seminar, November 2017.
3. B.D. James, J.M. Huya-Kouadio, and C. Houchins, "Medium & Heavy-Duty PEM Fuel Cell Electric Truck Analysis: A Comparison with Fuel Cell Electric Buses and Light-Duty Vehicles and Their Potential to Lower Costs in Early Market," Presentation at the 2017 Fuel Cell Seminar, November 2017.
4. J.M. Huya-Kouadio, B.D. James, and C. Houchins, "Meeting Cost and Manufacturing Expectations for Automotive Fuel Cell Bipolar Plates," Fuel Cell Seminar Conference Article, *Electrochemical Society Transactions*, December 2017.
5. B.D. James, J.M. Huya-Kouadio, and C. Houchins, "Fuel Cell Vehicle Cost Analysis," Presented to the Fuel Cell Technical Team, Southfield, MI, February 21, 2018.
6. B.D. James, "2018 Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-Duty Vehicles," DOE Fuel Cell Technologies Office webinar presentation, April 25, 2018.
7. B.D. James, J.M. Huya-Kouadio, C. Houchins, and D.A. DeSantis, "2017 DOE Hydrogen and Fuel Cells Program Review: Fuel Cell Systems Analysis," Presented at the 2018 DOE Hydrogen and Fuel Cells Program Annual Merit Review Meeting, Washington, DC, June 15, 2018.

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8. "Medium- & Heavy-Duty Fuel Cell Electric Truck: Action Plan for California," Report written by the California Fuel Cell Partnership (October 2016). Accessed June 27, 2018: http://cafcp.org/sites/default/files/MDHD-action-plan-2016.pdf.

9. Peter Pintauro, "Composite Membranes, Methods of Making Same, and Applications of Same," U.S. Patent 9,350,036 B2, filed August 6, 2012, and issued May 24, 2016.

10. Jason Ballengee, "Preparation of Nanofiber Composite Proton Exchange Membranes from Dual Fiber Electrospun Mats," *Journal of Membrane Science* 442 (2013): 187–195.

11. Peter Pintauro, "Fuel Cell Membrane-Electrode-Assemblies with Ultra-Low Pt Nanofiber Electrodes," Presented at the DOE Hydrogen and Fuel Cells Program Annual Merit Review Meeting, Washington DC, June 6, 2017.