Fuel Cell Systems Analysis

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- Argonne National Laboratory, 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 (2025) proton exchange membrane (PEM) fuel cell 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 update these on an annual or biennial basis.
- Conduct sensitivity analyses of FCS cost and identify key system cost parameters with the goal of fully understanding the cost drivers.
- Identify the 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 various media (presentations and a complete, comprehensive report).

Fiscal Year (FY) 2019 Objectives

- Conduct an MDV and HDV fuel cell electric truck cost analysis for current (2019) and future (2025) technology years.
- Design and evaluate the cost to manufacture and assemble a unit cell utilizing a roll-to-stack or 2-D manufactured method.
- Investigate the recycling and disposal cost for fuel cell systems.
- Estimate the cost of Precor's functionalized carbon-based coating for metallic bipolar plates.
- Research and examine different perfluorosulfonic acid (PFSA) membrane chemical process pathways to determine high-cost contributors and areas for cost reduction.

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[1]:

- Cost.

Technical Targets

The DOE technical targets and our current project status are listed in Table 1.

FY 2019 Accomplishments

- Projected the FCS cost for a 170 kW_{net} MDV application using the Design for Manufacture and Assembly (DFMA) methodology to be \$108/kW_{net} for 2019 and \$88/kW_{net} for 2025 at 100,000 vehicles produced per year. DOE technical targets for MDV fuel cell systems have not yet been published.
- Cost modeled a Class 8 HDV long haul FCS (330 kW_{net}), resulting in \$97/kW_{net} for 2019 and \$76/kW_{net} for 2025 projections at an annual production rate of 100,000 vehicles per

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

year. DOE technical targets for HDV fuel cell systems have not yet been published.

- Evaluation of embossed flexible graphite bipolar plates (BPPs) for LDV systems showed that graphite plates can meet the DOE 2025 target of $3/kW$_{net}$ while metallic plates (>$5/kW$_{net}$) currently suffer from both high material and manufacturing cost at all production volumes.

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 Target	DOE Ultimate Target
Cost of transportation fuel cell power systems[a, b]	$/kW$_{net}$	47	40	30
Cost of transportation fuel cell stacks[a, b]	$/kW$_{net}$	19	20	15
Cost of bipolar plates[a]	$/kW$_{net}$	5[b] / 3[c]	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 LDVs per year
[b] Based on stamped SS316 bipolar plates
[c] Based on embossed flexible graphite bipolar plates

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 system electrical production of 330 kW$_{net}$ for a Class 8 line haul HDV system and 170 kW$_{net}$ for a Class 6 MDV system are analyzed for 2019. Onboard compressed hydrogen storage, battery energy storage, and traction-drive motor subsystems are not included in this cost assessment. To examine the difference between nascent and mature product manufacturing bases, MDV and HDV FCSs are analyzed at 200, 500, 1,000, 10,000, 50,000, and 100,000 FCSs per year. Cost estimates are also made for two technology years (2019 and 2025). The 2019 systems reflect current lab-based technology while the 2025 systems represent a far-term system utilizing optimistic and more aggressive assumptions (not always using 2025 DOE target values) vetted with the Fuel Cell Technical Team.

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 costs. 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 170 kW$_{net}$ MDVs and 330 kW$_{net}$ HDVs. Argonne National Laboratory (ANL) first principles fuel cell performance models [2] and Strategic Analysis (SA) DFMA cost models are used to identify cost and performance-optimized conditions, which are then presented and vetted in three ways: (1) oral presentation to the Fuel Cell Technical Team, (2) oral presentation at the DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, and (3) a questionnaire distributed to MDV/HDV FCS developers (i.e., Ballard Power Systems, US Hybrid, Loop Energy, and Fuel Cell Powertrain, to name a few). Output from the ANL performance 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. System performance is based on estimates for individual components, built up into an overall system power 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 is defined to detail the specific manufacturing and assembly machinery and processing conditions used to assess component cost. The costs of lesser components are determined by price quote or analogy to similar commercial components. All cost values in this report, unless otherwise specified, are reported in 2016$ to align with other related DOE work.

RESULTS

This report serves as a summary of findings for the 2019 HDV and MDV systems. Full analysis assumptions and results are available in SA's 2019 Final Report [3]. (A cost analysis of LDV systems was conducted in 2018 and will be repeated in 2020.) Many side studies are conducted to assess various fuel cell components that may not be incorporated into the final system cost. The results from these side studies are also included below.

2019 and 2025 Baseline Class 8 Line Haul HDV and Class 6 MDV System Cost

Operating conditions chosen for the 2019 and 2025 HDV and MDV systems are summarized in Table 2 and are based on fuel-cell-dominant systems. In order to achieve 25,000 hours of operation, parameters and components that have been proven to offer longevity were selected for both the MDV and HDV systems—for example, high Pt loading of 0.4 mg-Pt/cm^2, low stack temperature of 85°C, and annealed platinum on high-surface-area carbon (a-Pt/HSC) [4]. Stacks configured electrically in parallel can also extend lifetime by allowing the flexibility to operate each stack individually and in more conservative modes. Embossed flexible graphite BPPs are also used in the MDV and HDV systems (in contrast to metallic plates used in LDV systems) because graphite plates have demonstrated >25,000 hours [5]. Analysis of the total cost of ownership for fuel cells in heavy-duty systems [6, 7] reveals that fuel cost is often one of the most significant cost contributors. Consequently, a cell voltage of 769 mV at rated power is selected to obtain the benefit of relatively higher stack efficiency and thereby increases overall fuel economy.

The main differences between the 2019 and 2025 systems are an increased power density (estimated 10% improvement with the same Pt loading) and a more efficient air compression system. The 2019 MDV and HDV systems each contain a roots air compressor (without an exhaust-gas expander) while the 2025 systems contain a centrifugal air compressor with an expander. The cost differences between the types of compressors and the addition of the expander are included in the cost estimate along with the difference in compression system efficiencies that impacts the gross power and system efficiency. Switching to a centrifugal compressor and adding an expander reduces the overall parasitic load of the compression system from 54 kW to 30k W, thereby reducing the size of the stack and system cost. The air compression system makes up more than 60% of the total parasitic power load for the 2019 HDV system, while a further 35% goes to the 30kW radiator fan required for a sustained uphill climb when little ram air is available for system cooling [4].

At low production volumes of 200 systems per year, the 2019 HDV system increases to $283/kW$_{net}$ while the 2019 MDV system increases to $333/kW$_{net}$. Both systems are dominated by stack cost at all production rates, making up 60% (high production) to 70% (low production) of the system cost.

Table 2. PEM Fuel Cell Medium- and Heavy-Duty System Operating Conditions and Assumptions

System	2019 HDV	2025 HDV	2019 MDV	2025 MDV
System gross power (kW$_{gross}$)	415	391	215	202
System net power (kW$_{net}$)	330	330	170	170
Power density (mW/cm^2)	840	924	840	924
Cell voltage (mV)	769	769	769	769
Stack temperature (coolant exit temperature) (°C)	85	85	85	85
Pressure (atm)	2.5	2.5	2.5	2.5
Pt loading (mg-Pt/cm^2)	0.4	0.4	0.4	0.4
Platinum group metal total content (g/kW$_{gross}$)	0.476	0.433	0.476	0.433

Air stoichiometry	1.5	1.5	1.5	1.5
Cathode catalyst system[a]	Dispersed a-Pt/HSC	Dispersed a-Pt/HSC	Dispersed a-Pt/HSC	Dispersed a-Pt/HSC
Cells per system	1,563	1,563	782	782
Stacks per system (in parallel)	3	3	2	2
System voltage (at rated power)	400	400	300	300
Total system cost ($/kW$_{net}$) (100,000 systems/yr)	$96.73	$76.41	$107.56	$88.05
[a] All years assume dispersed Pt/C on the anode.				

Side Study: 2-D Manufacturing Cost Analysis

SA investigated 2-D manufacturing to assess potential cost savings associated with this alternative roll-to-stack method of cell assembly. The essence of 2-D manufacturing is to realize lower cost and increased processing rates by maintaining the stack elements in a rolled format until the final assembly step. Each of the six sub-assemblies is unrolled onto the final assembly line before cutting and stacking the cells, as depicted in Figure 1. Common to most developing technology, current fuel cells are designed for performance and durability. While those aspects are most important in the near term, ideas are needed for larger production capacities in the future. For example, metallic BPPs are a common design for LDV FCSs as they satisfy performance, weight, and volume restrictions. Current metallic plate designs require high press tonnage, making the process slow (>2 sec/plate). However, for a single BPP production line to produce 500,000 LDV systems per year, BPPs would need to be produced at roughly 0.1 sec/plate. Consequently, faster processing of BPPs is required.

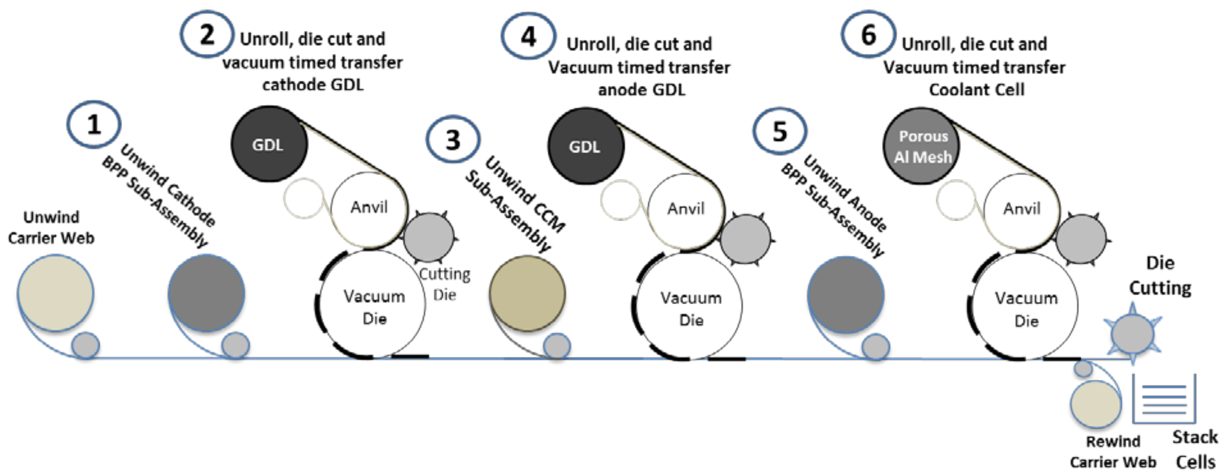

Figure 1. SA's 2-D manufacturing unit cell final assembly process line

Based on the tenets of DFMA, SA designed a manufacturing process in conjunction with the design features of the cell. The bipolar plate is now a flat separator plate where gas flow fields are incorporated into the gas diffusion layer (GDL). This reduces the thickness of the BPP material and eliminates the expensive process of BPP stamping. Overall, the cost of the BPPs is cut in half and, most importantly, they can easily be rolled onto the final assembly line. The flow fields are gang milled into a thick 0.5 mm GDL (inspired by American Fuel Cell [8]) suitable for re-rolling. The coolant cell is formed by two separator plates bracketing a porous aluminum mesh, which serves as a coolant flow field.

This design was vetted by multiple professionals experienced in fuel cell roll-to-roll processing and judged to be conceptually sound although not yet proven. While questions remain about the feasibility of such a process, 2-D manufacturing cost is compared to the LDV baseline system to assess its cost reduction potential. At high volume, the system cost is estimated to be reduced by almost $3/kW$_{net}$, primarily driven by reduced BPP material. Sensitivity analysis reveals that the GDL and gasket materials are the most cost-sensitive components due to high uncertainty in cost of the thicker GDL and the polyethylene naphthalate gasket material.

Side Study: Disposal and Recycle Cost Analysis

The disposal and recycling cost analysis is different than other side analyses because it estimates a cost at the end of life of the vehicle rather than at the beginning of life. Balance of plant components are anticipated to be disposed/recycled in a manner analogous to internal combustion engine vehicle powertrain components. Consequently, this study focuses on the value of the stack at end of life. Two main processes were evaluated: (1) recovery of Pt material and (2) recovery of BPP base material and coating materials. Recovering the Pt is a much more lucrative business than BPP material recycling. SA's model consisted of a hydrometallurgical method using metal leaching and filtration to separate the Pt from the rest of the membrane electrode assembly and the other catalyst materials. Some of the processing methods and assumptions were based on BASF's patented process [9] and Sasol Technology's patent for gas-to-liquid catalysts [10]. Figure 2 shows SA's estimate for Pt recycling cost in $/troy ounce at three levels of markup compared to a 2016 quote and Kromer's study [11]. Recycling cost is presented as the recycling cost per gram of Pt recovered (assuming 94% recoverable), exclusive of the intrinsic value of the Pt. However, SA's estimate does not account for the added costs of assay and sampling of material prior to recycling or additional markup for a mid-level recycler who would prepare the MEAs for Pt recycle.

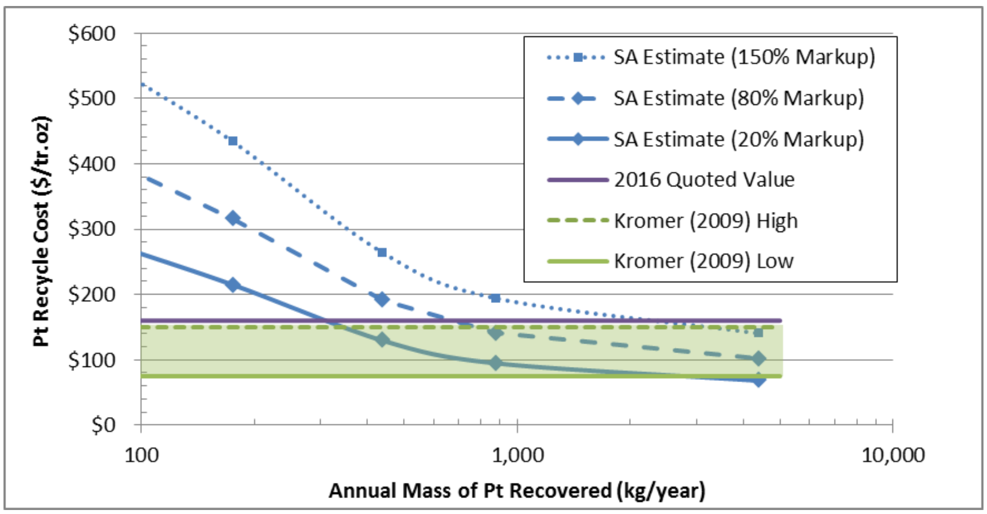

Figure 2. Comparison of SA's estimate at three different markup values with reference cost for recovered Pt

Side Study: Precors Metallic Bipolar Plate Coating

Coatings from Precors GmbH (whose name derives from Preventative Corrosion Solutions) have a nominal thickness of 10 nm and are distinguished by their modified carbon-based composition (no precious metals) and their non-vacuum ambient pressure (non-physical vapor deposition [PVD]) application method. The coating may be applied to continuous metal coil (for coating prior to metal forming) or to discrete parts (for coating post-metal-forming). Table 3 shows that at high volume, given the same performance, Precors coating can have similar, if not lower, cost than other coatings currently on the market.

Table 3. Comparison of TreadStone, Sandvik, and Precors BPP coatings

	TreadStone	Sandvik	Precors
BPP coating type	PVD	PVD	Ultrasonic spray
Material	Ti + Au or other precious metal	Ti, Carbon	Functionalized carbon
Coated sides per BPA	2 (welded over active area)	4	4
Ability to pre-coat (coat prior to forming)	No	Yes	Yes
SA cost estimate (2016$) (assuming all have the same performance)	$0.56-$0.85/kW	$1.55/kW (10 m/min) $1.03/kW (20 m/min)	$0.67/kW (10 m/min)
Laser welding over active area?	Yes	No	No
Laser welding cost (2016$)	$0.94/kW	$0.85/kW	$0.85/kW
Total BPA cost (coating and welding)	$1.50–$1.79/kW	$1.88–$2.40/kW	$1.52/kW

BPA – bipolar plate assembly

Side Study: Advanced PFSA Ionomer Membrane Cost Analysis

A preliminary ionomer production cost analysis was conducted to scope the level of effort required to conduct a detailed DFMA-style analysis. Based on past studies by General Motors Inc. (GM) in 2010 [12] and Roland Berger Strategy Consultants in 2013 [13], and on quoted values of PFSA ionomers, there is a significant disparity in projected costs at production rates of 200–600 metric tons per year. From the GM and Roland Berger studies, one of the leading cost drivers is the material cost for hexafluoropropylene oxide (HFPO), which represents 89% of material costs and more than half of the total ionomer cost. HFPO is typically produced via liquid-phase epoxidation of hexafluoropropylene (HFP); however, recent studies claim a reduction in HFPO cost via a continuous gas-phase HFP epoxidation process [14]. To verify this claim in cost reduction, SA assessed the cost of HFPO via the continuous gas-phase epoxidation of HFP. At 500 metric tons of ionomer per year, enough to produce membrane for 2.5 million PEM fuel cell vehicles per year, SA estimates the cost of HFPO to be $41/kg (2019$) without markup. At the same volume, HFPO prices have been quoted at $55.50/kg (2019$). It is difficult to quantify the amount of markup that would be applied to HFPO, particularly at these volumes. To obtain a better understanding, SA would need to also cost model the liquid-phase process cost for fabricating HFPO to determine the types of markups that may be applied to HFPO and whether the gas-phase process is actually a lower-cost pathway. Further study in this area is anticipated next year.

Side Study: Flexible Graphite Bipolar Plates for LDV Systems

In collaboration with Ballard Power Systems, SA evaluated the cost to manufacture embossed flexible graphite BPPs for LDV systems [5]. Figure 3 shows embossed flexible graphite plates can be lower cost than metallic plates at all production volumes evaluated and shows that flexible graphite plates can meet the DOE target of $3/kW for BPPs. The estimate for flexible graphite plates is based on the latest low-cost design and fabrication processes such as low-resin-content plates, roller embossing, batch resin impregnation while in rolled coil, and electron beam curing. Figure 4 illustrates that at high production volumes, flexible graphite plates result in lower cost than metallic plates in both material and processing cost.

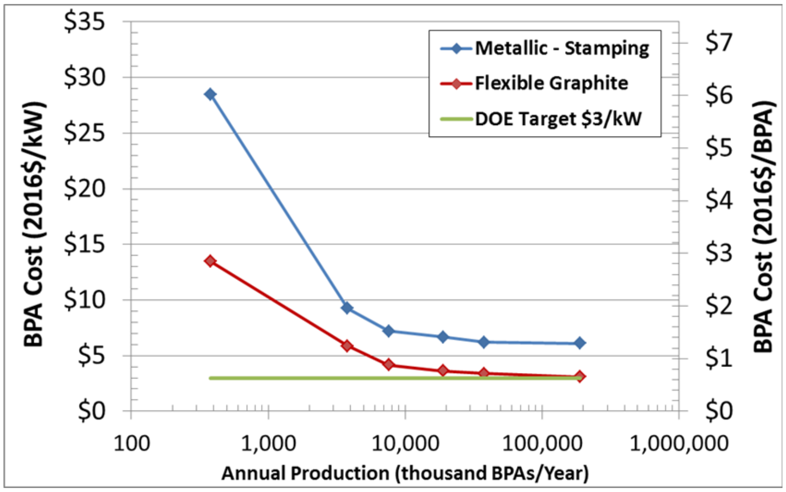

Figure 3. Comparison of metallic and flexible graphite BPP cost for LDV system at different production volumes

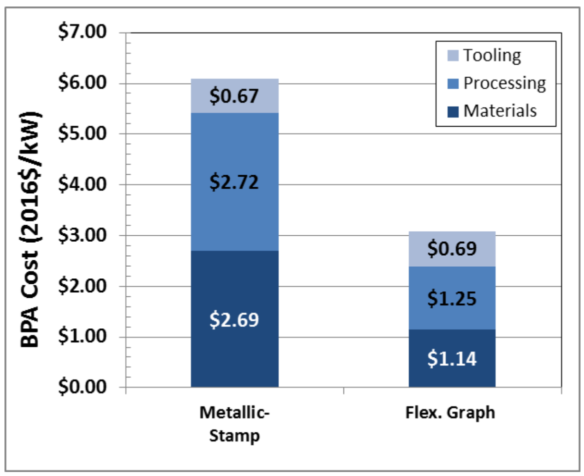

Figure 4. Breakdown of stamped metallic and flexible graphite BPP cost at 500,000 systems per year production

CONCLUSIONS AND UPCOMING ACTIVITIES

- SA cost modeled a generic Class 6 MDV fuel cell electric truck (160 kW_{net}) and projects a cost of \$108/kW_{net} for technology year 2019 and \$88/kW_{net} for technology year 2025, both at 100,000 systems per production.
- The estimated cost for a 330 kW_{net} Class 8 line haul fuel cell electric truck is \$97/kW_{net} for technology year 2019 and \$76/kW_{net} for technology year 2025, both at 100,000 systems per year production.
- SA's design for a 2-D manufacturing system, featuring flow fields milled into the GDL, can potentially reduce LDV system cost by \$3/kW_{net}. Further lab testing of such a process is needed to validate the design, processing concept, and resulting cell performance.
- Preliminary data suggests that a gas-phase epoxidation of HFP can potentially reduce the cost to produce HFPO, one of the greatest ionomer cost contributors.
- Embossed flexible graphite BPPs are necessary for MDV and HDV systems to last >25,000 h, but they can also be lower cost than metallic BPPs. At high volume, flexible graphite plates can meet the DOE target of \$3/kW.

- Future work includes ongoing investigation of the cost impact of various strategies to extend fuel cell life: materials, cell design, stack configuration, and operating strategies. Additional work in ionomer production cost is also anticipated for the next year.

FY 2019 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: 2018 Update*, Strategic Analysis report for DOE Fuel Cell Technologies Office, September 30, 2018.
2. B.D. James, J.M. Huya-Kouadio, and C. Houchins, "Fuel Cell Systems Analysis," presented at the Fuel Cell Technical Team Meeting, Detroit, MI, February 20, 2019.
3. B.D. James, J.M. Huya-Kouadio, C. Houchins, and D.A. DeSantis, "Fuel Cell Systems Analysis," presented at the 2019 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Washington, DC, May 1, 2019.
4. B.D. James, J.M. Huya-Kouadio, and C. Houchins, *Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2019 Update on Medium and Heavy-Duty Vehicles*, Strategic Analysis report for DOE Fuel Cell Technologies Office, September 30, 2019.

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8. D. O'Connel and J. Owejan, "FY17 SBIR Release 2: Over Molded Plate for Reduced Cost and Mass PEM Fuel Cells," presentation at the 2018 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, June 13, 2018. https://www.hydrogen.energy.gov/pdfs/review18/fc177_oconnell_2018_p.pdf.
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11. M. Kromer, F. Joseck, T. Rhodes, M. Guernsey, and J. Marcinkoski, "Evaluation of Platinum Leasing Program for Fuel Cell Vehicles," *Journal of Hydrogen Energy* 34 (2009): 8276–8288.

12. T. Xie, M.F. Mathias, C. Gittleman, and S.L. Bell, *High Volume Cost Analysis of Perfluorinated Sulfonic Acid Proton Exchange Membranes; Fuel Cell Activities* (General Motors: Honeoye Falls, NY, 2010).
13. W. Bernhardt, S. Riederle, and M. Yoon, "Fuel Cells—A Realistic Alternative for Zero Emission?," 2013.
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