DOE Hydrogen and Fuel Cells Program Record	
Record #: 17007	**Date:** September 30, 2017
Title: Fuel Cell System Cost - 2017	
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Item:

The cost of an 80-kW_{net} automotive polymer electrolyte membrane (PEM) fuel cell system based on next-generation laboratory technology[1] and operating on direct hydrogen is projected to be \$50/kW_{net} when manufactured at a volume of 100,000 units/year and \$45/kW_{net} at a volume of 500,000 units/year. The main changes that reduced the system cost compared with the FY2016 analysis are:

- A PtCo catalyst on high surface area carbon (HSC) that increased power density by 46%,
- A slight (7%) reduction in Pt loading on the cathode,
- Improved bipolar plate stamping process assumptions, and
- Adjustment in assumptions for the hydrogen sensors, based on industry input, and including them in the vehicle, rather than as part of the fuel cell system.

The projected cost of automotive PEM fuel cell systems based on advances expected[2] by 2020 and 2025 are approximately \$47/kW_{net} and \$40/kW_{net}, respectively, when manufactured at a volume of 100,000 units/year and \$43/kW_{net} and \$36/kW_{net}, respectively, when manufactured at a volume of 500,000 units/year [1].

Rationale:

The DOE Fuel Cell Technologies Office (FCTO) focuses on early-stage R&D to enable cost reductions and improvements in durability and performance of advanced fuel cell technologies. To help guide and prioritize this early-stage R&D, FCTO also supports technically rigorous, peer-reviewed projects that perform and update detailed analyses to estimate the cost status of fuel cell systems on an annual basis. In fiscal year 2017, Strategic Analysis, Inc. (SA) updated their 2016 cost analysis [2] of an 80-kW_{net} direct hydrogen PEM automotive fuel cell system based on 2017 lab-scale technology advances, and projected to a maximum manufacturing volume of 500,000 units per year [1]. Results from the analysis were documented at the DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation [3], at a meeting of the U.S. DRIVE Fuel Cell Tech Team (FCTT) [4], and in a detailed written report [1].

SA and Argonne National Laboratory (ANL) worked closely together to establish a representative system design and realistic operating conditions to be used as the basis of the

[1] The projected cost status is based on an analysis of state-of-the-art components that have been developed and demonstrated through the DOE Program at the laboratory scale. Additional efforts would be needed for integration of components into a complete automotive system that meets durability requirements in real-world conditions.
[2] System and component advances include input from Argonne National Laboratory (ANL), National Renewable Energy Laboratory (NREL), and the U.S. DRIVE Fuel Cell Technical Team (FCTT).

annual cost analysis. Power system cost projections are based on beginning of life stack performance using membrane electrode assemblies (MEA) made with PtCo on a high surface area carbon (PtCo/HSC-e)[3] cathode catalyst [5], Pt/C anode catalyst, and a 14 micron reinforced PFSA membrane. Full operating conditions and associated cost assumptions for the catalysts analyzed in 2017 are summarized in Table 1.

As in past analyses, the Pt commodity price was fixed at $1,500 per troy ounce to remove year-to-year Pt price fluctuations from the analysis that could otherwise obscure improvements due to technology advancements. This cost estimate is based on materials price quotes obtained between 2012 and 2017. All calculations were performed using nominal year dollars.

In 2017, the following specific changes were made to the baseline system for the cost analysis:

- Reduced total Pt loading (from 0.134 to 0.125 mg_{Pt}/cm^2), increased air stoichiometry (from 1.4 to 1.5) and power density at rated power (from 749 to 1,095 mW/cm^2).
- Membrane fabrication process was changed from dip-coating an expanded polytetrafluoroethylene (ePTFE) porous substrate in perfluorosulfonic acid (PFSA) to a method of sequential slot die coating inspired by Gore's Direct-Coat MEA manufacturing process.
- Reduced the number of simultaneous production lines required for bipolar plate progressive stamping process to reflect expected demands placed on bipolar plate manufacturers at high volume by increasing the number of plates stamped simultaneously from 1 to 2, increased the length of the stainless steel coil (from 0.2 to 20 km), and increased the number of hours of operation per year from 3,360 hours per year (2x7 hour shifts, 240 days/year) to 6,000 hours per year (3x8 hour shifts, 250 days/year).
- Removed hydrogen sensor cost from the fuel cell system. Hydrogen sensors are expected to be included in the vehicle passenger cabin; however, they are not included in the fuel cell system cost per FCTT guidance.
- Added a demister on the anode exhaust line (to minimize liquid water accumulation in the H_2 recirculation system) and addition of a hydrogen/air mixer (to dilute the hydrogen exhaust below flammability limits).
- Added two injectors within the Dual-Ejector hydrogen recirculation system: one injector upstream of the ejectors for finer control of H_2 flow and one injector for bypass around the ejectors during purge events.
- Updated stainless steel 316, 3-mil thick, coil cost from $11.10/kg to $13.19/kg based on a 2017 quotation from ATI Metals.
- Added 0.25 of an extra full time equivalent (FTE) laborer for each process line to serve as a line tender (to supply parts to the machines and conduct any miscellaneous tasks not done by the machine operator).

Key assumptions used in the 2017 cost analysis are summarized in Table 1 and are compared with cost breakdowns for the years 2012–2016 [6, 7, 8, 9, 10]. The results of the current year cost analysis are graphically compared with prior year results in Figure 1. A significant drop in projected system cost occurs between 2016 and 2017 due to the above cited technology advances and analysis changes.

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[3] GM's PtCo/HSC-e cathode catalyst is one in a series of PtCo catalysts with different high performing high surface area carbon supports.

Table 1. System Design Parameters and System Cost Evaluated at Rated Power from 2012 to 2017

Characteristic	Units	2012	2013	2014	2015	2016	2017
Net system power	kW_{net}	80	80	80	80	80	80
Gross stack power	kW_{gross}	88.2	89.4	92.8	88.2	87.7	87.9
Stack efficiency	%	55	57	55	53	52	52
Cell voltage	V	0.676	0.695[a]	0.672[a]	0.661[a]	0.659[a]	0.663[a]
Air stoichiometric ratio		1.5	1.5[a]	2	1.5[a]	1.4[a]	1.5[a]
Stack inlet pressure	atm	2.5[a]	2.5[a]	2.5[a]	2.5[a]	2.5[a]	2.5[a]
Stack exit coolant temperature	°C	82[a]	92[a]	95[a]	94.1[a]	94[a]	94[a]
Total PGM[b] loading	mg_{PGM}/cm^2	0.196[a]	0.153[a]	0.153[a]	0.142[a]	0.134[a]	0.125[a]
MEA areal power density	mW/cm^2	984	692	834	746	749	1,095
Q/ΔT[c]	kW/°C	1.78	1.37[d]	1.45	1.45	1.45	1.45
System cost (100k sys/yr)	$\$/kW_{net}$	56	67	66	60	60	50
System cost (500k sys/yr)	$\$/kW_{net}$	47	55	55	53	53	45

[a] Optimization parameter.
[b] PGM: platinum group metal.
[c] Q/ΔT is a measure of radiator size and is defined as [Stack Gross Power x (1.25 V – Cell Voltage at Rated Power) / (Cell Voltage at Rated Power)] / [(Stack Coolant Exit Temperature (°C) – ambient temperature (40°C)].
[d] In 2013, the heat of condensation was accounted for in the Q/ΔT calculation resulting in an operating point satisfying Q/ΔT with a higher cell voltage than would be calculated using the definition in footnote c above.

A new cathode catalyst system was evaluated in 2017: GM's PtCo/HSC-e.[4] Power density when using the new GM cathode catalyst is 46% higher than when using the d-PtNi/C catalyst of the 2016 analysis (from 749 to 1,095 mW/cm^2), an improvement due to GM's proprietary high surface area carbon support (HSC-e). ANL and GM both agree that given the same HSC-e support material, both d-PtNi/HSC and PtCo/HSC catalysts would have similar performance. ANL adapted existing first principles models for d-PtNi/HSC to estimate the GM HSC-e support material's performance [11]. The resulting PtCo/HSC-e achieved higher performance through a reduction in mass transfer over-potential due to a 20% higher limiting current density. The GM experimental data was from 50 cm^2 single cell measurements at conditions similar, but not identical to those found to be cost optimal by ANL. The operating conditions for both the GM test data and ANL's model (the 2017 baseline) are summarized in Table 2. GM testing conditions were at O_2 stoichiometry of 2 while ANL's cost optimized model was 1.5, and GM's pressure was measured at stack outlet rather than stack inlet. To adjust for these differences, ANL projected the power density based on alignment of stack inlet pressure and O_2 stoichiometric ratio. Optimized system cost was obtained through SA's simplified cost model supplied to ANL. SA then used ANL's optimized 2017 parameters within their Design for Manufacture and Assembly (DFMA) cost analysis. Per FCTT guidance, the GM PtCo/HSC-e cathode catalyst was selected for the 2017 update, resulting in a final estimate of $\$50/kW_{net}$ (at 100,000 systems per year) under the system cost optimized conditions of an O_2 stoichiometric

[4] GM PtCo/HSC-e cathode catalyst system is used in conjunction with a dispersed Pt/C catalyst on the anode.

ratio of 1.5, stack inlet pressure of 2.5 atm, cell voltage of 663 mV/cell, and power density of 1,095 mW/cm^2.

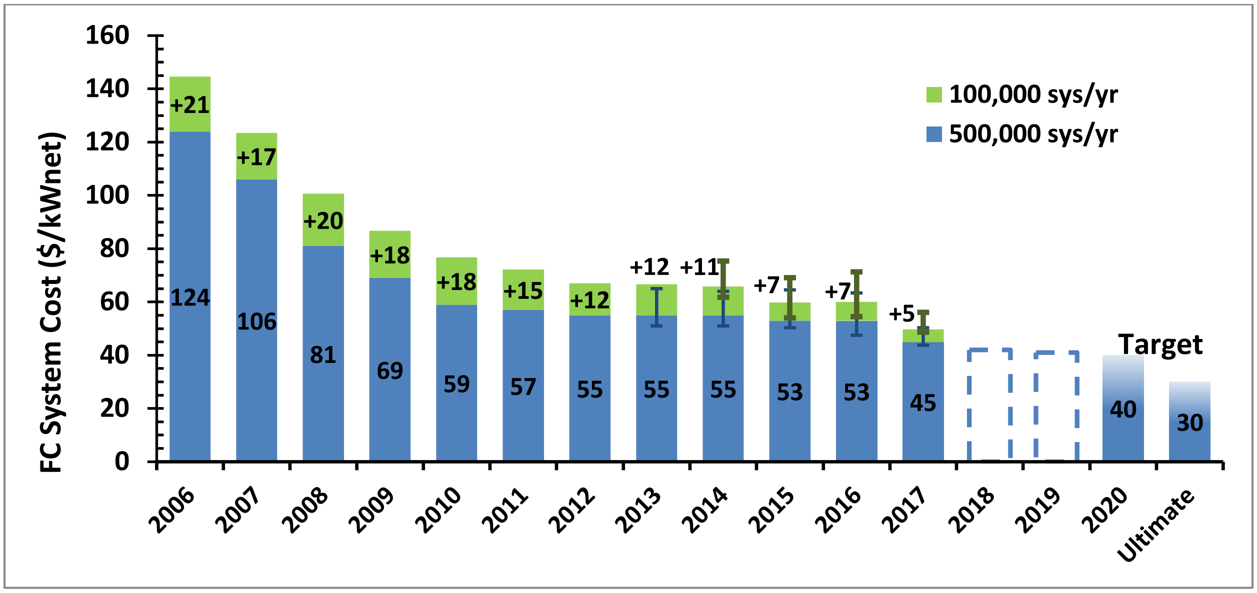


Figure 1. Modeled cost of an 80-kW_{net} PEM fuel cell system based on projection to high-volume manufacturing (100,000 and 500,000 units/year). Reported values from 2012 and earlier were adjusted to account for higher platinum price, realigned compressor and expander efficiencies, and the Q/ΔT requirement introduced in 2013 (see 2013 cost record) [7]. Error bars represent the 90% confidence interval from a stochastic uncertainty analysis and reflect manufacturing uncertainty in the modeled system.

Table 2. Comparison of GM Testing and 2017 Operating Conditions

Cathode Catalyst	Units	PtCo/HSC-e (GM Testing Conditions)	PtCo or d-PtNi/HSC (2017 Operating Conditions)
Anode Catalyst	--	Dispersed Pt/C	Dispersed Pt/C
Pressure	atm	2.5 (stack outlet)	2.5 (stack inlet)
O_2 Stoich	--	2	1.5
Stack Coolant Exit Temperature	°C	94	94
Total PGM	mg_{PGM}/cm^2	0.125	0.125
Voltage	mV	663	663
Power Density	mW/cm^2	1,239	1,095

System cost was projected at a number of manufacturing rates from 1,000 to 500,000 per year as shown in Figure 2. Single variable sensitivity analyses at 100,000 and 500,000 systems per year are shown in Figure 3 and indicate the system cost impact from a change in a single variable. The main difference between the two manufacturing volumes is that the GDL has not yet reached economies of scale, where at 500,000 systems per year it has. Both volumes are shown because a manufacturing volume of 100,000 units per year is comparable to manufacturing volumes for alternative advanced automotive technologies, and the 500,000 units per year volume shows the relative impact of the cost of constituent components on total system costs when at economy of scale. In both scenarios, air loop cost is the highest contributor to system cost variability; enhanced MEA performance would be one way to relax air management requirements (that is, the need for higher pressure) and lower CEM cost.

Monte Carlo analysis was used to estimate uncertainty in the total system cost due to multiple variables changing simultaneously. The uncertainty parameters for the 100,000 units per year scenario are summarized in Table 3.[5] Based on the Monte Carlo results, the system cost at 100,000 units per year is projected to be between \$49/kW and \$56/kW (Figure 4) with 90% confidence. In previous years, uncertainty in Pt loading and power density reflected the range of possible values within the automotive fuel cell market as a whole, inclusive of technology differences and design choices. In contrast, the 2017 analysis assumes that Pt loading variations are due only to manufacturing effects rather than variation in design set-point. Likewise, variations in 2017 power density reflect uncertainty in the ANL model predictions for a fixed design and set of operating conditions, and not for changes in hardware or operating point. Consequently, the 2017 confidence bars are relatively narrow and should not be misinterpreted to encompass the full range of costs from all fuel cell manufacturers.

[5] The range in parameter values for the single variable sensitivity analysis are the same as the multi-variable sensitivity analysis parameter values except for the $Q/\Delta T$ parameter, which only occurs in the single variable analysis. The $Q/\Delta T$ range is: Low 1.35 kW/°C, Baseline 1.45 kW/°C, and High 1.55 kW/°C. Range based on +/- 0.1 kW/°C.

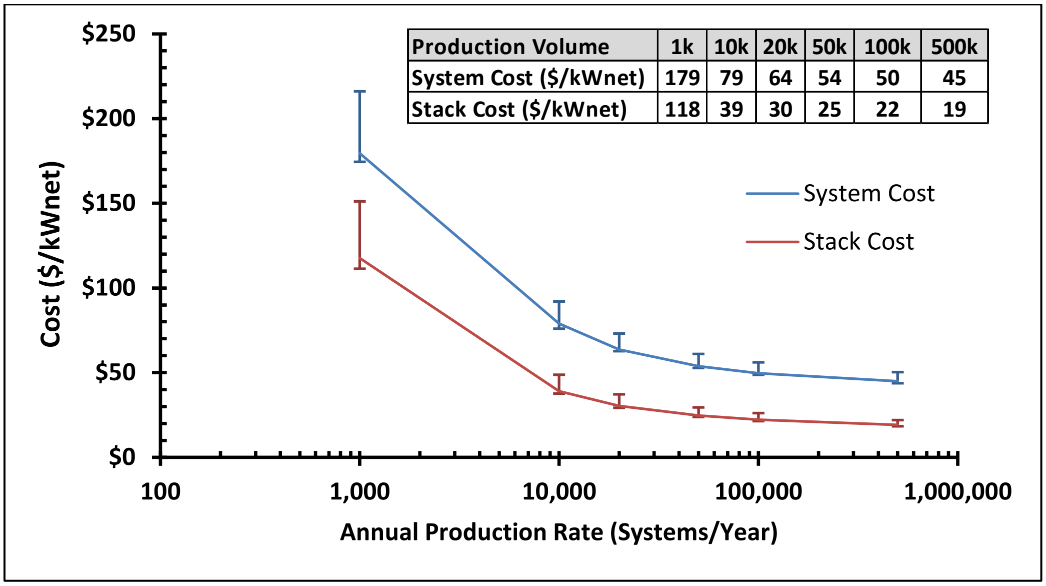


Figure 2. Projected cost of 2017 80-kW_{net} transportation fuel cell stacks and systems at 1,000, 10,000, 20,000, 50,000, 100,000, and 500,000 units/year.

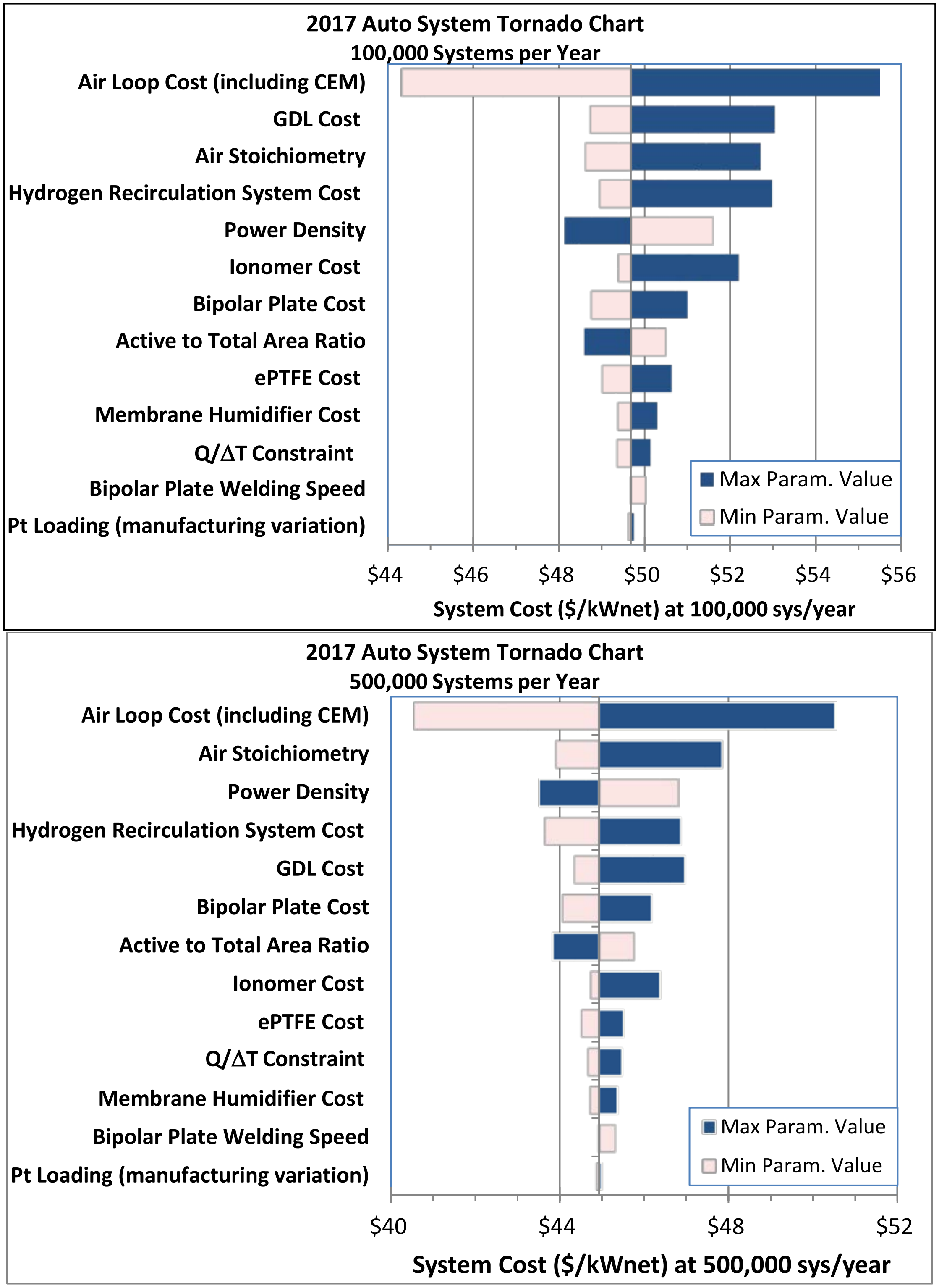


Figure 3. Tornado chart of single variable sensitivity analysis of system cost at 100,000 systems per year (top graph) and 500,000 systems per year (bottom graph). “CEM” refers to “compressor expander motor”.

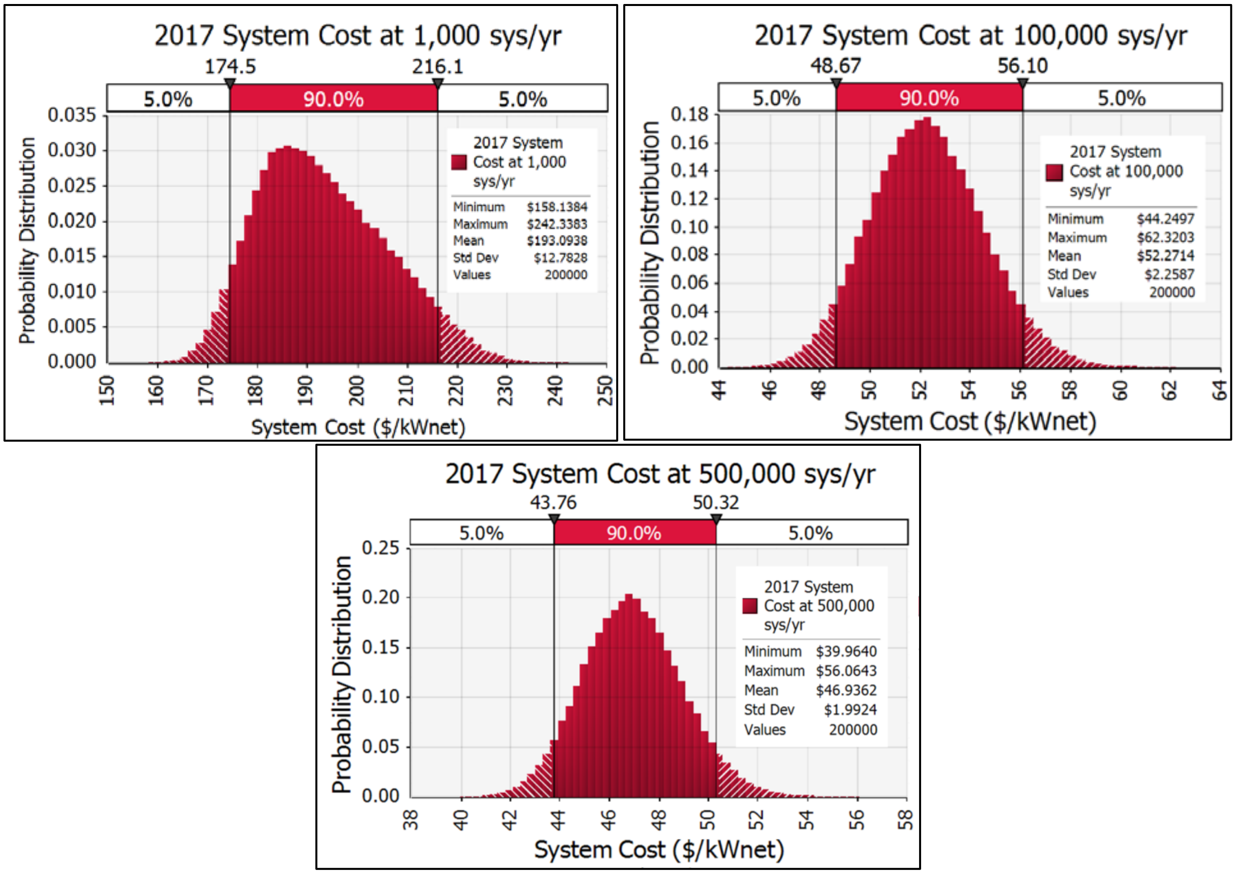


Figure 4. Monte Carlo analyses of system cost probability at 1,000, 100,000, and 500,000 systems per year.

Table 3. 2017 Technology Tornado and Monte Carlo Analysis, 100,000 Systems per Year

Parameter	Unit	Minimum Value	Likeliest Value	Maximum Value[c]	Bounds Rationale
Power Density [a, b]	**mW/cm^2**	986	**1,095**	1,205	+/- 10% based on variations in ANL modeling for power density
Pt Loading [a]	**$mgPt/cm^2$**	0.124	**0.125**	0.126	+/- 1% based on manufacturing variation
Ionomer Cost	**$/kg**	$92.00	**$153.33**	$682.32	Min. Value = -40% (approx. same % swing as recommended by 2012 FCTT at 500k/yr) Max. Value = +4.45x (same % swing as used at 500k/yr, based on source input of ~ $750/kg at 35 tons/yr)
Gas Diffusion Layer (GDL) Cost	**$\$/m^2$**	$4.93	**$9.66**	$26.18	Min. Value = -50%, Max Value = 270% Based on range of 2016 reported GDL prices at 500k sys/yr ($\$3/m^2$ to $\$16/m^2$)
Bipolar Plate Welding Speed	**m/min**	2.5	**7.5**	15	Min. Value = Lower bound of vendor recommendations Max. Value = Double the baseline value

Parameter	Unit	Minimum Value	Likeliest Value	Maximum Value[c]	Bounds Rationale
Air Stoichiometry[a, b]		1.3	**1.5**	2	Min. Value = FCTT recommendation Max. Value = Reasonable system operating condition
Membrane Humidifier Cost	**$/system**	$72.38	**$96.51**	$144.77	Min. Value = 25% decrease Max. Value = 50% increase (30% due to extra degradation allowance, 20% other cost increase)
Compressor Efficiency [a, b]	**%**	64.7%	**71%**	80%	Based on ANL's assumptions for range in centrifugal compressor/expander/ motor/controller efficiencies. Motor Effic.: 86% min (baseline) to 92% max Controller Effic.: 87.3% min (baseline) to 92% max Combined Motor/Controller Effic.: 75% min (80% baseline) to 84.6% max
Expander Efficiency [a, b]	**%**	71.6%	**73%**	80%	
Motor/Controller Efficiency [a, b]	**%**	75%	**80%**	84.6%	
Air Compressor Cost	**$/system**	$514.37	**$740.96**	$889.15	Min. Value = 30% decrease Max. Value = 120% of calculated cost
Balance of Air Compressor Cost	**$/system**	$127.59	**$191.39**	$325.36	Min. Value = 66% of calculated cost Max. Value = 170% of calculated cost 1.5x base value with added 30% more for three $30 components possibly included (gas-capture filter, resonator, and shut-off valve)
Hydrogen Recirculation System Cost	**$/system**	$279.16	**$333.62**	$529.53	Min. Value = Pulsed-Ejector configuration cost Max. Value = Blower-Ejector configuration cost
Expanded Polytetrafluoroethylene (ePTFE) Cost	**$\$/m^2$**	$4.63	**$9.25**	$15.73	Range of industry quotes
Active to Total Area Ratio		0.55	**0.625**	0.8	Min. Value = Based on discussions with vendors Max. Value = Based on value used in previous years studies
Bipolar Plate Material Cost	**$/kg**	12.22	**$13.19**	$15.83	Min. Value = SS 304 material Max. Value = +20%
Bipolar Plate Forming Cost	**$\$/kW_{net}$**	$1.23	**$1.75**	$2.28	+/- 30%
Bipolar Plate Coating Cost	**$\$/kW_{net}$**	$0.79	**$0.99**	$1.19	+/- 20%

[a] The Monte Carlo analysis treats each parameter as an independent variable with respect to power density. Thus changes to operating conditions (such as catalyst loading, pressure, etc.) do not alter the power density for purposes of the Monte Carlo analysis.
[b] Variation of some parameters (such as air stoichiometry, compressor efficiency, etc.) may affect the system Q/ΔT value causing a violation of the $Q/\Delta T < 1.45$ constraint within the Monte Carlo analysis.
[c] For all parameters, the "likeliest value" is set to the 2017 cost analysis baseline value for that parameter.

The SA analysis indicates that the fuel cell stack would account for 66% and 43% of the total system cost at 1,000 and 500,000 systems per year, respectively. A breakdown of stack component cost is shown in Figure 5. Of the various components, two (catalyst and bipolar plates) are dominated by commodity materials costs (platinum and stainless steel, respectively), which are relatively insensitive to manufacturing volume. The rest of the component costs are dominated by specialty materials and processing costs, which are more sensitive to manufacturing volume. Thus, an increase in production volume causes the membrane and gas diffusion layer (GDL) cost elements to decrease as a fraction of the total, while the catalyst and bipolar plate cost elements increase.

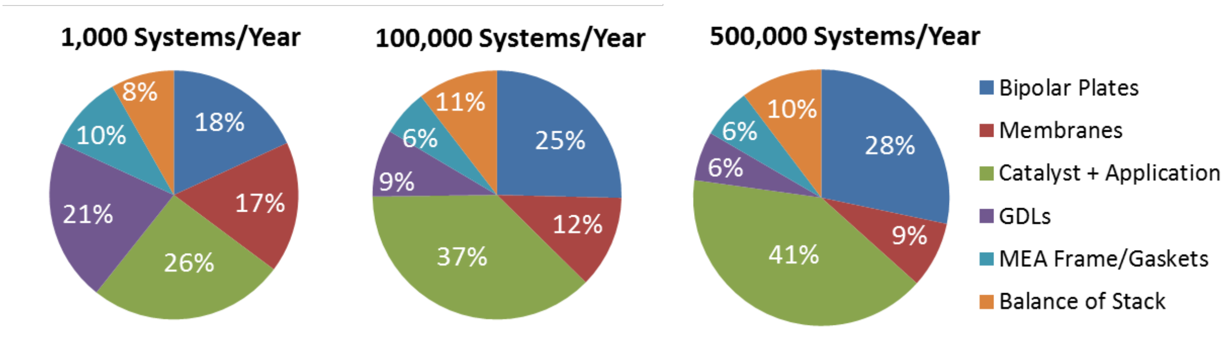
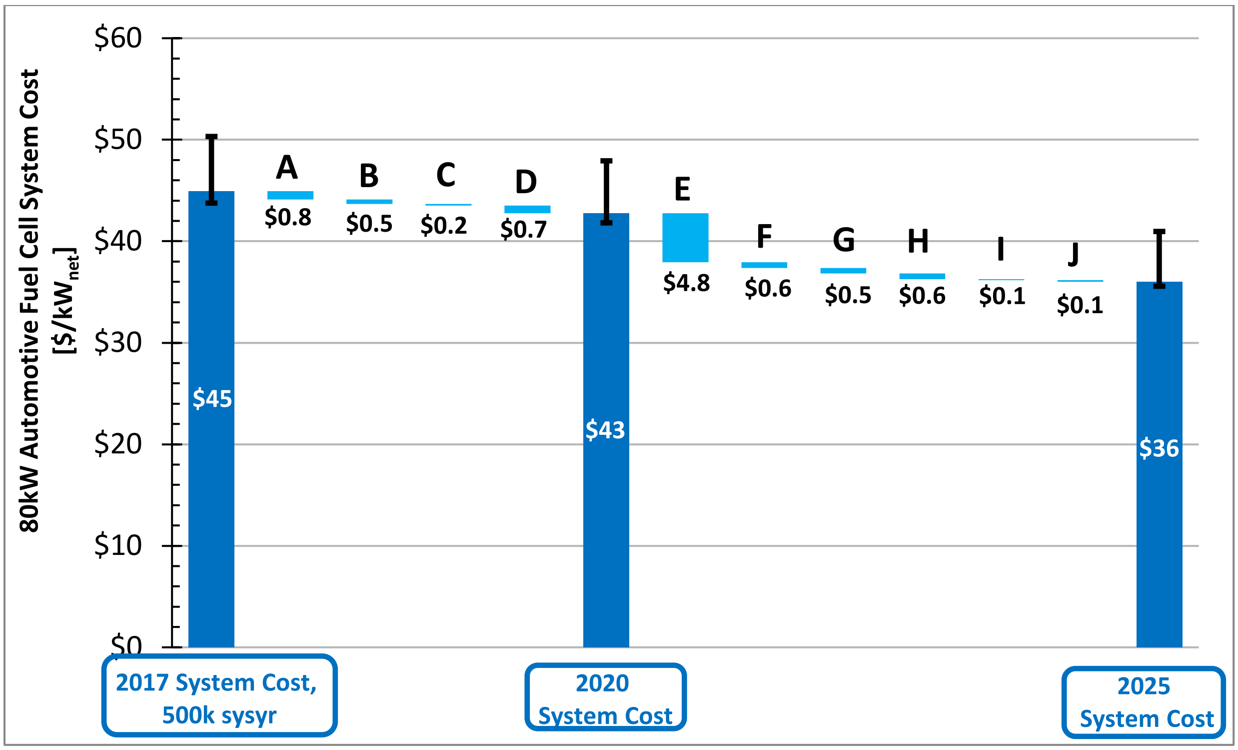


Figure 5. Breakdown of the 2017 projected fuel cell stack cost at 1,000, 100,000, and 500,000 systems per year.

The estimated cost to manufacture an automotive fuel cell system with current state-of-the-art technology at 1,000 systems per year is $\$180/kW_{net}$. The estimated cost to manufacture a fuel cell vehicle commercially available in 2017 at 1,000 systems per year is $\sim\$230/kW_{net}$. SA modeled a commercially available system cost based on publically available documentation and expert opinions of Toyota Mirai system design. The modeled system has a number of system design elements that differ from those assumed in the high-volume baseline cost reported above. Based on conversations with automotive fuel cell experts and an internet resource stating 30 g Pt per vehicle [12], SA assumed a higher Pt loading in the commercial vehicle to ensure a ten-year lifetime and to reflect a design freeze for technology that was state-of-the-art in approximately 2014. SA modeled bipolar plates based on Toyota reports that the Mirai uses titanium bipolar plates with an amorphous carbon coating [13] to provide excellent corrosion resistance compared to lower-cost stainless steel material (and coating) used in the state-of-the-art system. The Mirai requires a hydrogen recirculation pump to recirculate hydrogen and water [14] through the anode of the fuel cell stack while the state-of-the-art system uses low-cost hydrogen ejectors. There are numerous additional differences between these systems and the reader is referred to SA's 2017 Final Report [1] for further detail.

SA also performed cost analyses of assumed system advances achievable in 2020 and 2025. The 2020 system is based on modest improvements to the current 2017 system, such as the assumption that current catalyst projects will meet their targets. The 2025 system parameters assume aggressive or optimistic technology advances; that is, advances that are achievable if there was a focused and well-funded effort (or possibly in a later year if development efforts are not focused or well-funded). A list of the changes and their respective reduction in cost between years 2017, 2020, and 2025 are shown in waterfall form in Figure 6. Not surprisingly, the greatest contributors to cost reduction between years are increases in power density and reduction in Pt catalyst loading. The projection for 2020 falls short of the DOE 2020 Target of $\$40/kW_{net}$, set for cost at high volume (that is, 500,000 units/year, where all components are at scale). If the 2020 system were to meet the DOE 2020 air compressor component target of $500/CEM, the overall system DOE 2020 Target of $\$40/kW_{net}$ would be achieved. Additionally, if the $\$3/kW_{net}$ bipolar plate DOE 2020 Target was also met, it would reduce the system cost to $\$38/kW_{net}$, below the 2020 DOE Target for cost at high volume. Likewise, the projection for 2025 does not meet DOE's Ultimate Target of $\$30/kW_{net}$, suggesting that more time and further technology improvement are required to achieve that goal.



A: Increase of power density from 1,095 to 1,165 mW/cm^2.
B: Switched from SS316 to SS304 for BPP base material and switched from TreadStone DOTS -R to TIOX coating.
C: Reduction in membrane thickness from 14 to 10 microns thick.
D: Switch from Dual Ejector System to Pulsed Ejector with Bypass for hydrogen recirculation system.
E: Increase of power density from 1,165 to 1,500 mW/cm^2 and reduced Pt loading from 0.125 mg/cm^2 to 0.088 mg/cm^2.
F: Switched from TreadStone TIOX to no coating on BPPs.
G: Switched from ePTFE-supported membrane to Giner DSM supported membrane.
H: Switched to more advanced CEM design.
I: Moved from 2 h to 1 h of stack conditioning time.
J: Increase in active to total area from 0.625 to 0.65.
*Additional information regarding each change can be found in SA's 2017 report [1].

Figure 6. Waterfall chart showing magnitude of each change between 2017, 2020, and 2025 system analyses.

This record was reviewed by Brian D. James, Jennie M. Huya-Kouadio, and Cassidy Houchins (Strategic Analysis, Inc.), and Rajesh Ahluwalia (Argonne National Laboratory).

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