DOE Hydrogen and Fuel Cells Program Record	
Record #: 16020	**Date:** September 30, 2016
Title: Fuel Cell System Cost - 2016	
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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 \$53/kW$_{net}$ when manufactured at a volume of 500,000 units/year and \$59/kW$_{net}$ at a volume of 100,000 units/year. Three main changes largely offset one-another to result in a nearly static cost when compared with the FY2015 analysis:

- Significant reduction in Pt loading on the anode,
- Higher bipolar plate forming and welding costs (per OEM feedback), and
- Modified gas diffusion layers (per OEM feedback).

The expected cost of automotive PEM fuel cell systems based on input from OEMs on current technology planned for commercialization in the 2016 time frame is approximately \$230/kW when manufactured at a volume of 1,000 units/year [1].

Rationale:

The DOE Fuel Cell Technologies Office (FCTO) supports projects that perform and update detailed analyses to estimate cost status of fuel cell systems on an annual basis. In fiscal year 2016, Strategic Analysis, Inc. (SA) updated their 2015 cost analysis [2] of an 80-kW$_{net}$ direct hydrogen PEM automotive fuel cell system based on 2016 technology and projected to a maximum manufacturing volume of 500,000 units per year [1]. Results from the analysis were communicated to FCTO 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 Technical Team (FCTT) [4], and in a detailed written report [1]. The 2016 cost estimate of \$53/kW$_{net}$ is based on Argonne National Laboratory's (ANL) projected system performance for Johnson-Matthey Fuel Cell's (JMFC) de-alloyed $PtNi_3/C$ cathode catalyst (referred to as d-PtNi/C).[2] Operating conditions and associated cost assumptions for the catalysts analyzed in 2016 are summarized in Table 1.

The SA cost analysis is based on beginning of life performance of membrane electrode assemblies (MEA) made with the JMFC d-PtNi/C cathode catalyst and a Pt/C anode catalyst on 17 micron reinforced Nafion® membranes. As in past analyses, the Pt commodity price was fixed

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[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] $PtNi_3$ refers to the catalyst material prior to de-alloying. After de-alloying, the material has a material composition containing less nickel.

at $1,500 per troy ounce to remove 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 2016. All calculations were performed using nominal year dollars.

In 2016, the following specific changes were made to the baseline system for the cost analysis:

- Reduced total Pt loading (from 0.142 to 0.134 $\mathrm{mg_{Pt}/cm^2}$) and air stoichiometry (from 1.5 to 1.4) while slightly increasing power density (from 746 to 749 $\mathrm{mW/cm^2}$).
- Re-examined state of the art in bipolar plate design and the required stamping force needed to form fine flow-field features. This resulted in a substantial increase in press tonnage (from 115 to 1,800 tons), a corresponding increase in stamping process line capital cost (from $530k to $2.1M), and a decrease in stamping rate (from 60 to 24 strokes/min). Additionally, the estimated tooling cost increased (from $100k to $660k/die).
- Updated hydrogen sensor cost based on quotations from FiS Inc. (a Nissha Company) for sensor model FH2-HY04.
- Re-evaluated the extent of bipolar plate laser welding used in commercial systems to allow proper electrical conduction between plates (increased total weld length from 1.5 m to 1.8 m).
- Updated bipolar plate anti-corrosion coating to Treadstone's second generation material, resulting in reduced material costs and simplified processing.
- Updated catalyst synthesis parameters based on industry input. Main operational steps remained the same but batch sizes, thermal cycle times, and markup rates were adjusted.
- Added acid washing of the catalyst coated membrane (CCM) as a component of the state of the art MEA fabrication process.
- Completed a ground-up cost evaluation of the GDL manufacturing process (compared to the use of price quotes, as was done for the 2015 analysis).

Key assumptions used in the 2016 cost analysis are summarized in Table 1 and are compared with cost breakdowns for the years 2011 – 2015 [5, 6, 7, 8, 9]. The results of the current year cost analysis are graphically compared with prior year results in Figure 1. There is no net change in projected system cost at 500,000 units per year between 2015 and 2016.

Table 1: System design parameters and system cost evaluated at rated power from 2011 to 2016.

Characteristic	**Units**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Net system power	kW_{net}	80	80	80	80	80	80
Gross stack power	kW_{gross}	89.25	88.2	89.4	92.8	88.2	87.7
Stack efficiency	%	55	55	57	55	53	52
Cell voltage	V	0.676	0.676	0.695[a]	0.672[a]	0.661[a]	0.659[a]
Air stoichiometric ratio		1.5[a]	1.5	1.5[a]	2	1.5[a]	1.4[a]
Stack inlet pressure	atm	3[a]	2.5[a]	2.5[a]	2.5[a]	2.5[a]	2.5[a]
Stack exit coolant temperature	°C	90[a]	82[a]	92[a]	95[a]	94.1[a]	94[a]
Total PGM[b] loading	mg_{PGM}/cm^2	0.186[a]	0.196[a]	0.153[a]	0.153[a]	0.142[a]	0.134[a]
MEA areal power density	mW/cm^2	1,110	984	692	834	746	749
Q/ΔT[c]	kW/°C	1.52	1.78	1.37[d]	1.45	1.45	1.45
System cost	$\$/kW_{net}$	49	47	55	55	53	53

[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 b above.

Experimental data for two cathode catalyst systems[3] were considered in 2016: JMFC's d-PtNi/C and 3M's d-Pt_3Ni_7 nanostructured thin film catalyst (labeled 3M d-PtNi NSTF). The data used were all from small (~12.5 cm^2 – 5 cm^2) single cell measurements of differential cells, at conditions similar, but not identical, to those later found to be cost optimal. These data were used within a first principles ANL model to predict stack and system performance for both catalyst systems. Operating conditions were parametrically varied to determine the cost optimized conditions at rated power. Optimized system cost was based on a simplified model supplied to ANL by SA based on SA's 2015 detailed Design for Manufacture and Assembly (DFMA®) cost analysis. Although the 3M d-PtNi NSTF catalyst system was projected to result in a substantially lower stack and system cost, it was not selected as part of the 2016 baseline system due to concerns about the lack of adequate robustness data to support its selection. Therefore, the JMFC d-PtNi/C catalyst was selected for the 2016 update, resulting in a final estimate of $\$53/kW_{net}$ under the system cost optimized conditions of an O_2 stoichiometric ratio of 1.4, cell voltage of 659 mV/cell, and power density of 749 mW/cm^2. Results for both catalyst systems are summarized in Table 2.

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[3] JM d-PtNi/C cathode catalyst system contained dispersed Pt/C on the anode while the 3M d-PtNi NSTF cathode catalyst system contained 3M PtCoMn NSTF on the anode.

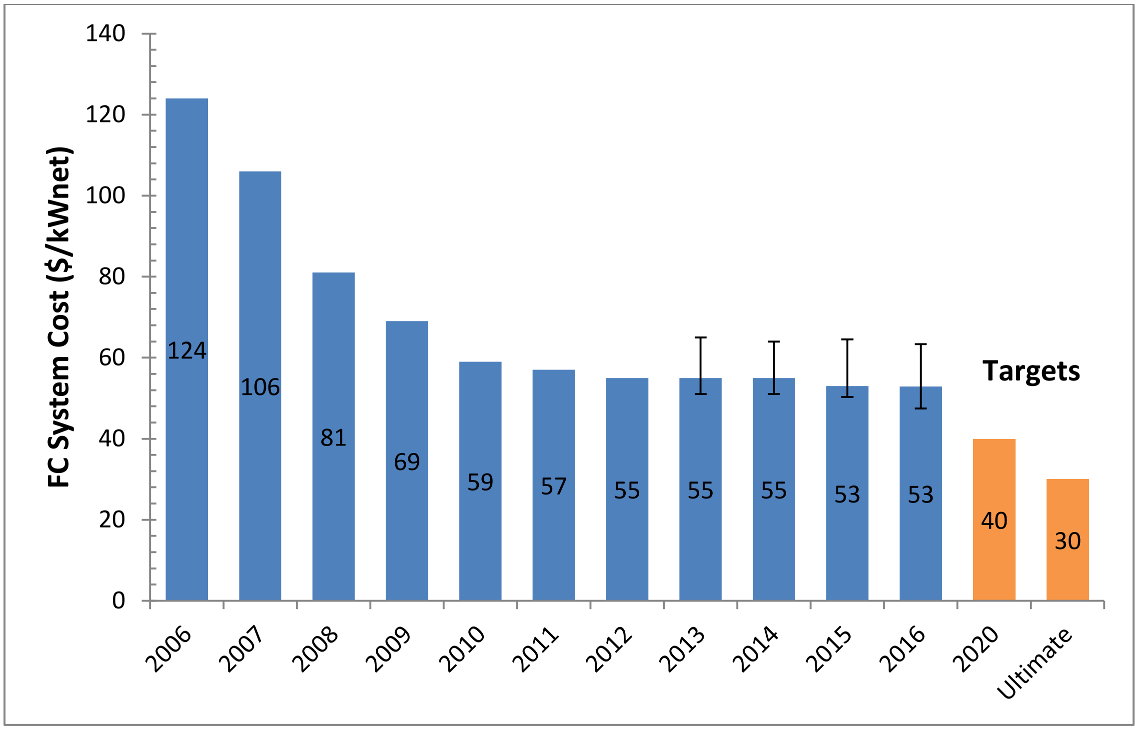
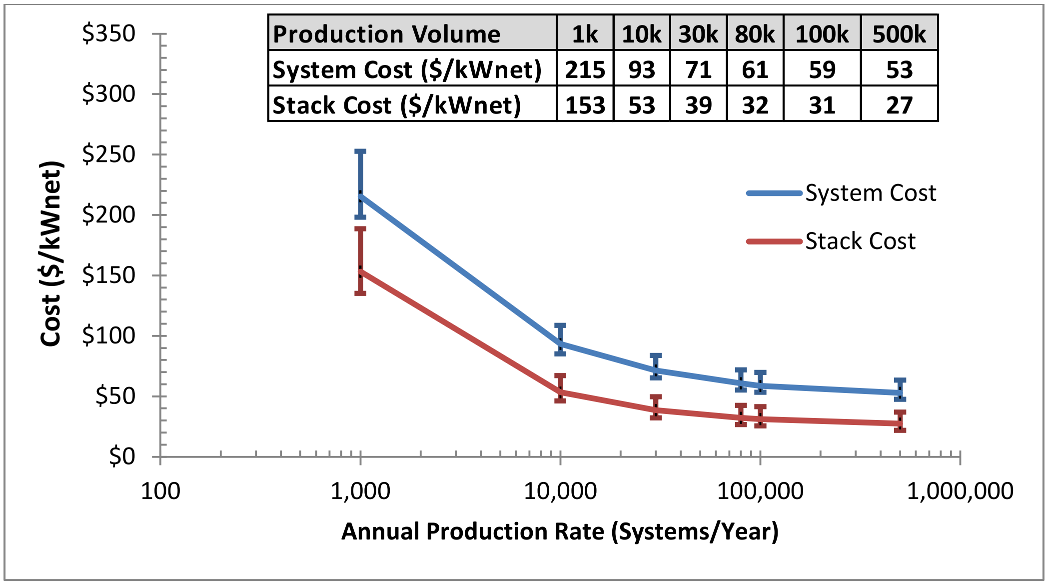


Figure 1. Modeled cost of an 80-kW_{net} PEM fuel cell system based on projection to high-volume manufacturing (500,000 units/year). Reported values from 2012 and earlier were adjusted to account for higher platinum price, realigned compressor and expander efficiencies, and the Q/ΔT requirement introduced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

Table 2: Catalysts and operating conditions analyzed by ANL in 2016.

Cathode Catalyst	**Units**	**d-PtNi/C (JM)**	**d-PtNi NSTF (3M)**
Anode Catalyst	--	Dispersed Pt/C	PtCoMn NSTF
Cathode Interlayer	--	NA	Dispersed Pt/C
Pressure	atm	2.5	2.5
O_2 Stoich	--	1.4	1.5
Stack Coolant Exit Temperature	°C	94	95
Total PGM	mg_{PGM}/cm^2	0.134	0.131
Voltage	mV	659	664
Power Density	mW/cm^2	749	941
Stack Cost	$\$/kW_{net}$	$27	$22
System Cost	$\$/kW_{net}$	$53	$47

Lower manufacturing volume cost estimates also were prepared by SA at 1,000, 10,000, 30,000, 80,000, and 100,000 units per year. The projected effect of manufacturing volume on cost is depicted in Figure 2. Sensitivity of the system cost to individual parameter values, as shown in Figure 3, was evaluated using a majority of the parameter value distributions listed in Table 3.[4] Estimates of the total system cost uncertainty due to uncertainty in the individual parameter values were evaluated through a Monte Carlo analysis. Based on the Monte Carlo results, the system cost at 500,000 units/year is projected with 90% certainty to be between $49/kW and $63/kW (Figure 4). These cost uncertainty levels only include uncertainty associated with the modeling assumptions and parameter values listed in Table 3 and do not include uncertainty associated with other modeling assumptions.



Production Volume	1k	10k	30k	80k	100k	500k
System Cost ($/kWnet)	215	93	71	61	59	53
Stack Cost ($/kWnet)	153	53	39	32	31	27

Figure 2. Projected cost of 2016 80-kW$_{net}$ transportation fuel cell stacks and systems at 1,000, 10,000, 30,000, 80,000, 100,000, and 500,000 units/year.

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[4] 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/ΔT parameter which only occurs in single variable analysis. The Q/ΔT 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.

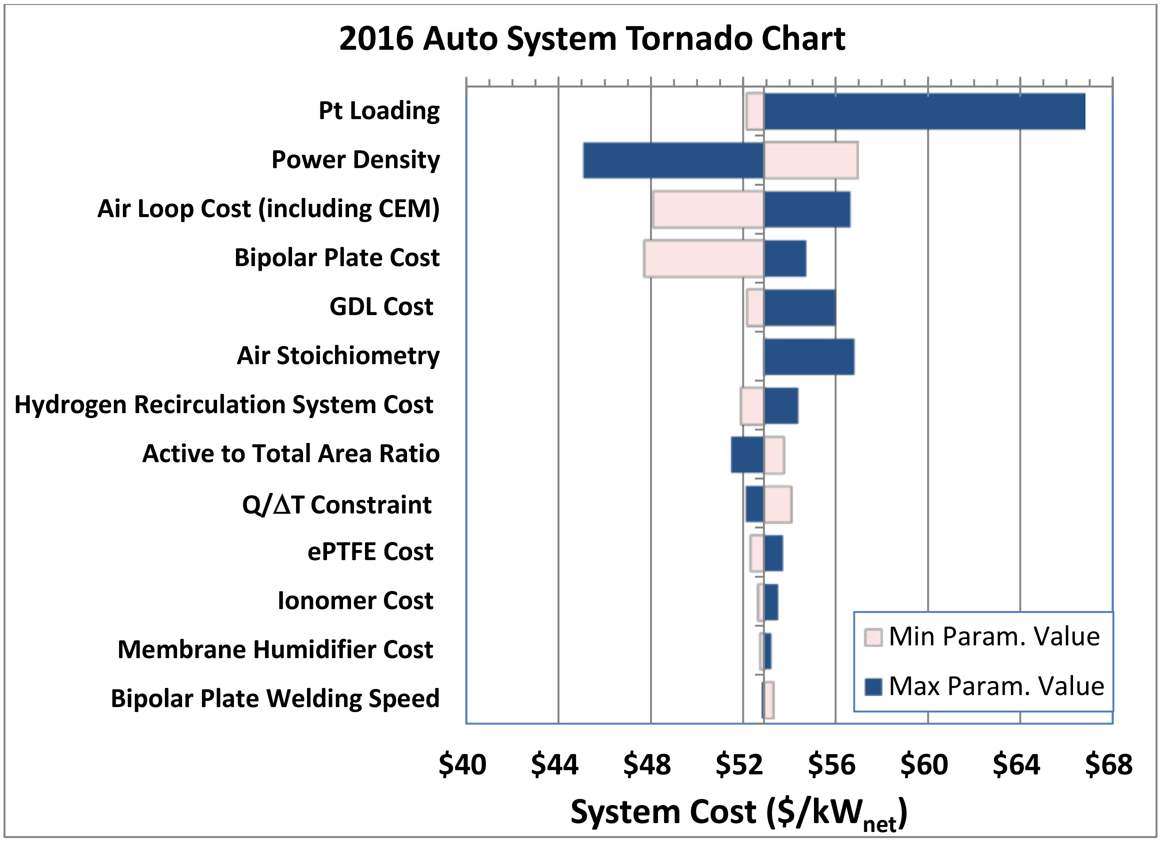

Figure 3. Tornado chart of single variable sensitivity analysis of system cost at 500,000 systems per year. "CEM" refers to "compressor expander module".

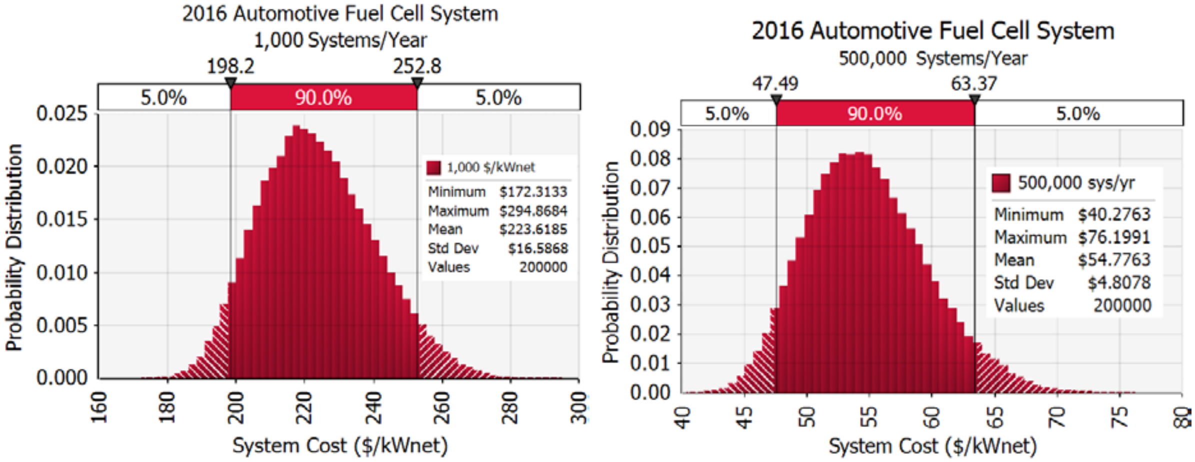

Figure 4. Monte Carlo analyses of system cost probability at 1,000 and 500,000 systems per year.

Table 3: 2016 Technology Tornado and Monte Carlo Analysis, 500,000 systems per year

Parameter	Unit	Minimum Value	Likeliest Value	Maximum Value	Bounds Rationale
Power Density [a, b]	**mW/cm^2**	637	**749**	1,124	Same % variation (-15%/+50%) as previously recommended by FCTT at 500k/yr.
Pt Loading [a]	**mgPt/cm^2**	0.125	**0.134**	0.3	Low value from DOE target, high value from FCTT guidance.
Ionomer Cost	**$/kg**	$53.14	**$88.57**	$177.14	Same % variation (-40%/+100%) as previously recommended by FCTT at 500k/yr.
Gas Diffusion Layer (GDL) Cost	**$/m^2**	$3.00	**$5.50**	$16.00	Range of 2016 Reported GDL Prices.
Bipolar Plate Welding Speed	**m/min**	2.5	**7.5**	15	Min. Value = Lower bound of vendor recommendations. Max. Value = Double the baseline value.
Air Stoichiometry[a, b]		1.4	**1.4**	2	Min. Value = experimental results from JM. Max. Value = Reasonable system operating condition.
Membrane Humidifier Cost	**$/system**	$38.73	**$51.64**	$77.46	Min. Value = 25% decrease. Max. Value = 50% increase (30% due to extra degradation allowance, 20% other cost increase).
Compressor Efficiency [a, b]	**%**	69%	**71%**	75%	Min. Value = 97% of likeliest value in each of the three component efficiencies. Max. Value = DOE 2020 Targets.
Expander Efficiency [a, b]	**%**	71%	**73%**	80%	
Motor/Controller Efficiency [a, b]	**%**	78%	**80%**	90%	
Air Compressor Cost	**$/system**	$500	**$707.56**	$849.07	Min. Value = DOE 2020 target. Max. Value = 120% of calculated cost.
Balance of Air Compressor Cost	**$/system**	$122.06	**$183.00**	$274.49	Min. Value = 66% of calculated cost. Max. Value = 150% of calculated cost.
Hydrogen Recirculation System Cost	**$/system**	$158.48	**$237.59**	$356.39	Min. Value = 66% of calculated cost. Max. Value = 150% of calculated cost.
Expanded polytetrafluoroethylene (ePTFE) Cost	**$/m^2**	$3.00	**$6.00**	$10.20	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 Cost [c]	**$\$/\text{kW}_{\text{net}}$**	\$3.00	**\$8.17**	\$10.00	Min Value= DOE 2020 Target. Max. Value= 2011 status.

[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 $Q/\Delta T$ value causing a violation of the $Q/\Delta T < 1.45$ constraint within the Monte Carlo analysis.

[c] Bipolar plate cost includes forming and coating, but not laser welding.

The SA analysis indicates that the fuel cell stack would account for 71% and 52% 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 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.

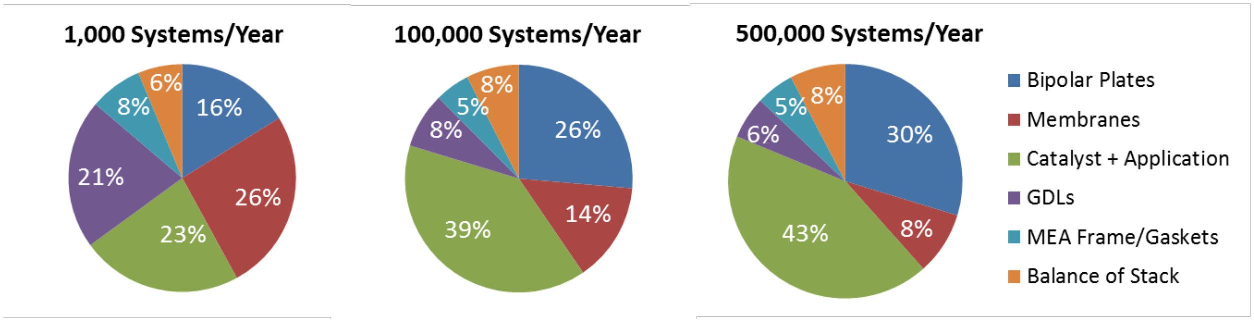

Figure 5. Breakdown of the 2016 projected fuel cell stack cost at 1,000, 100,000, and 500,000 systems per year.

The expected cost of a ~90kW$_{\text{net}}$ automotive PEM fuel cell system based on technology currently ready for commercialization is approximately \$230/kW when manufactured at a volume of 1,000 units/year [1]. This cost estimate is based on the inputs of several auto manufacturers and on resources that describe the design of commercially available light-duty vehicles. The difference in projected cost of a commercially available fuel cell system (\$230/kW at 1,000 systems/year) and the reported 2016 status system (\$197/kW$_{\text{net}}$ when the analysis is extrapolated to a comparable 90kW$_{\text{net}}$ system at 1,000 units/year) is that the 2016 status system is based on next generation lab-demonstrated components while commercially available systems prioritize durability and near-term robustness over cost. Thus, the commercially available technology design uses coated titanium plates rather than coated stainless steel plates, higher catalyst loading (0.3 vs. 0.134 mgPt/cm^2), and manufacturing methods appropriate for early market introduction.

In contrast, the 2016 status system assumes the use of design and fabrication methods based on state-of-the-art technologies, largely demonstrated in the lab or with modeling, but not yet proven in a relevant manufacturing environment. Additionally, the 2016 status system is designed to achieve initial system performance and may not have the same levels of durability as the commercially available system.

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

References Cited

[1] B. D. James, J. M. Huya-Kouadio and C. Houchins, "Mass Production Cost Estimation for Direct Hydrogen PEM Fuel Cell Systems for Automotive Applications: 2016 Update," Report to the DOE Fuel Cell Technologies Office, 2016.

[2] B. D. James, J. M. Moton and C. Houchins, "Mass Production Cost Estimation for Direct Hydrogen PEM Fuel Cell Systems for Automotive Applications: 2015 Update," Report to the DOE Fuel Cell Technologies Office, 2015.

[3] B. D. James, "Fuel Cell Transportation Cost Analysis," in *2016 U.S. DOE Hydrogen and Fuel Cell Annual Merit and Peer Review*, Washington D. C., 2016.

[4] B. James, *presentation to the U.S. Drive Fuel Cell Technical Team,* Southfield, 2016.

[5] "U.S. Department of Energy (Hydrogen and Fuel Cells Program), “Record 11012: Fuel Cell System Cost - 2011" http://www.hydrogen.energy.gov/program_records.html," 2011.

[6] "U.S. Department of Energy (Hydrogen and Fuel Cells Program), “Record 12020: Fuel Cell System Cost - 2012" http://www.hydrogen.energy.gov/program_records.html," 2012.

[7] "U.S. Department of Energy (Hydrogen and Fuel Cells Program), “Record 14012: Fuel Cell System Cost - 2013" http://www.hydrogen.energy.gov/program_records.html," 2013.

[8] "U.S. Department of Energy (Hydrogen and Fuel Cells Program), “Record 14014: Fuel Cell System Cost - 2014" http://www.hydrogen.energy.gov/program_records.html," 2014.

[9] "U.S. Department of Energy (Hydrogen and Fuel Cells Program), “Record 15015: Fuel Cell System Cost - 2015" http://www.hydrogen.energy.gov/program_records.html," 2015.