DOE Hydrogen and Fuel Cells Program Record	
Record #: 15015	**Date:** September 30, 2015
Title: Fuel Cell System Cost - 2015	
Originator: Jason Marcinkoski, Jacob Spendelow, Adria Wilson, Dimitrios Papageorgopoulos	
Peer Reviewed By: Rajesh Ahluwalia (ANL), Brian James, Cassidy Houchins, Jennie Moton (SA, Inc.)	
Approved by: Sunita Satyapal	**Date:** October 22, 2015

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 \$60/kW_{net} at a volume of 100,000 units/year. One of the main changes in the FY2015 analysis that resulted in cost savings compared to FY2014 was the transition to a catalyst/electrode structure, which allowed optimization at a lower air flow and with a lower Pt loading than used previously. The expected cost of automotive PEM fuel cell systems based on current technology, planned for commercialization in the 2016 time frame, is approximately \$280/kW when manufactured at a volume of 20,000 units/year [1].

Rationale:

The DOE Fuel Cell Technologies Office (FCTO) supports projects that perform detailed analysis to estimate cost status of fuel cell systems, updated on an annual basis. In fiscal year 2015, Strategic Analysis, Inc. (SA) updated their 2014 cost analysis of an 80-kW_{net} direct hydrogen PEM automotive fuel cell system, based on 2015 technology and projected to a manufacturing volume of 500,000 units per year [2]. Results from the analysis were communicated to FCTO at the DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation [3] and at a meeting of the U.S. DRIVE Fuel Cell Technical Team (FCTT) [4]. The 2015 cost estimate of \$53/kW_{net} is based on Argonne National Laboratory's (ANL) projected stack performance for a Johnson-Matthey (JM) de-alloyed $PtNi_3$ catalyst (d-PtNi). Operating conditions and associated cost assumptions for the catalysts analyzed in 2015 are summarized in Table 1.

The SA cost analysis is based on beginning of life performance of membrane electrode assemblies (MEA) constructed with JM d-PtNi catalyst on 25.4 micron reinforced Nafion® membranes. As in past analyses, Pt commodity price is held fixed at \$1,500 per troy ounce to remove Pt price fluctuations from the analysis which may otherwise obscure improvements due to technology advancements. The cost estimate is based on materials price quotes obtained between 2012 and 2015. All calculations were performed using nominal year dollars.

[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.

In 2015, the following changes were made to the basis system for the cost analysis:

- Use of a d-PtNi dispersed catalyst applied via slot-die coating as opposed to the 2014 DOE record's nanostructured thin film (NSTF) PtCoMn cathode catalyst applied via a vacuum deposition process.
- Decrease in cell power density at rated power to 746 mW/cm^2 from the 2014 value of 834 mW/cm^2 based on optimized operating conditions and the d-PtNi dispersed catalyst system.
- Selection of the stack rated power operating conditions based on system performance modeled at Argonne National Laboratory, with stack modeling based on experimental single cell test data and imposition of a $Q/\Delta T < 1.45$ constraint as recommended by the FCTT.
- Decrease in the cell active-to-total-area ratio to 0.625 from 0.8 to reflect fuel cell stack design trends.
- Re-examination of machinery size and procedures at low production volume.
- Improved estimation of air humidifier sizing based on modeling from Argonne National Laboratory.

Key assumptions used in the 2015 cost analysis are summarized in Table 1 and are compared with cost breakdowns for the years 2010–2015 [5–9]. The net change in system cost from 2014 to 2015 was $1.85/kW. This reduction in cost may be primarily attributed to the use of the d-PtNi catalyst instead of the NSTF PtCoMn catalyst, as it permitted a reduction in the air stoichiometry of the system as well as a reduction in Pt loading. Overall, the use of the d-PtNi catalyst permits use of relatively less expensive catalyst application processes and offers a higher likelihood of achieving DOE catalyst lifetime targets.

Table 1. System design parameters and system cost from 2010 to 2015 evaluated at rated power.

Characteristic	Units	2010	2011	2012	2013	2014	2015
Gross stack power	kW_{gross}	87.9	89.25	88.2	89.4	92.8	88.2
Stack efficiency	%	55	55	55	57	55	53
Cell voltage	V	0.676	0.676	0.676	0.695[a]	0.672[a]	0.661[a]
Air stoichiometric ratio		2.5	1.5[a]	1.5	1.5[a]	2	1.5[a]
Stack inlet pressure	atm	1.69	3[a]	2.5[a]	2.5[a]	2.5[a]	2.5[a]
Stack exit coolant temperature	°C	85	90[a]	82[a]	92[a]	95[a]	94.1[a]
Total PGM loading	mg_{PGM}/cm^2	0.15	0.186[a]	0.196[a]	0.153[a]	0.153[a]	0.142[a]
MEA areal power density	mW/cm^2	833	1,110	984	692	834	746
$Q/\Delta T$[b]	kW/°C	1.66	1.52	1.78	1.37[c]	1.45	1.45
System cost	$\$/kW_{net}$	51	49	47	55	55	53

[a] Optimization parameter.

[b] $Q/\Delta T$ is a measure of radiator size and is defined as [Stack Gross Power x (1.25V – Cell Voltage at Rated Power) / (Cell Voltage at Rated Power)] / [(Stack Coolant Exit Temperature (°C) – ambient temperature (40°C)].

[c] In 2013, the heat of condensation was accounted for in the $Q/\Delta T$ calculation resulting in an operating point satisfying $Q/\Delta T$ with a higher cell voltage than would be calculated using the definition in footnote b above. System cost analyses from 2012 and earlier have not been corrected to reflect the change in the $Q/\Delta T$ requirements. Additionally, they used a lower Pt price of $1100/oz and used more favorable assumptions about compressor and expander performance, all of which contribute to lower cost estimates that cannot be directly compared to the estimates from 2013 and later. For more details, see the 2013 Fuel Cells cost record: http://www.hydrogen.energy.gov/pdfs/14012_fuel_cell_system_cost_2013.pdf.

The results of the current year cost analysis are compared with prior year results in Figure 1.

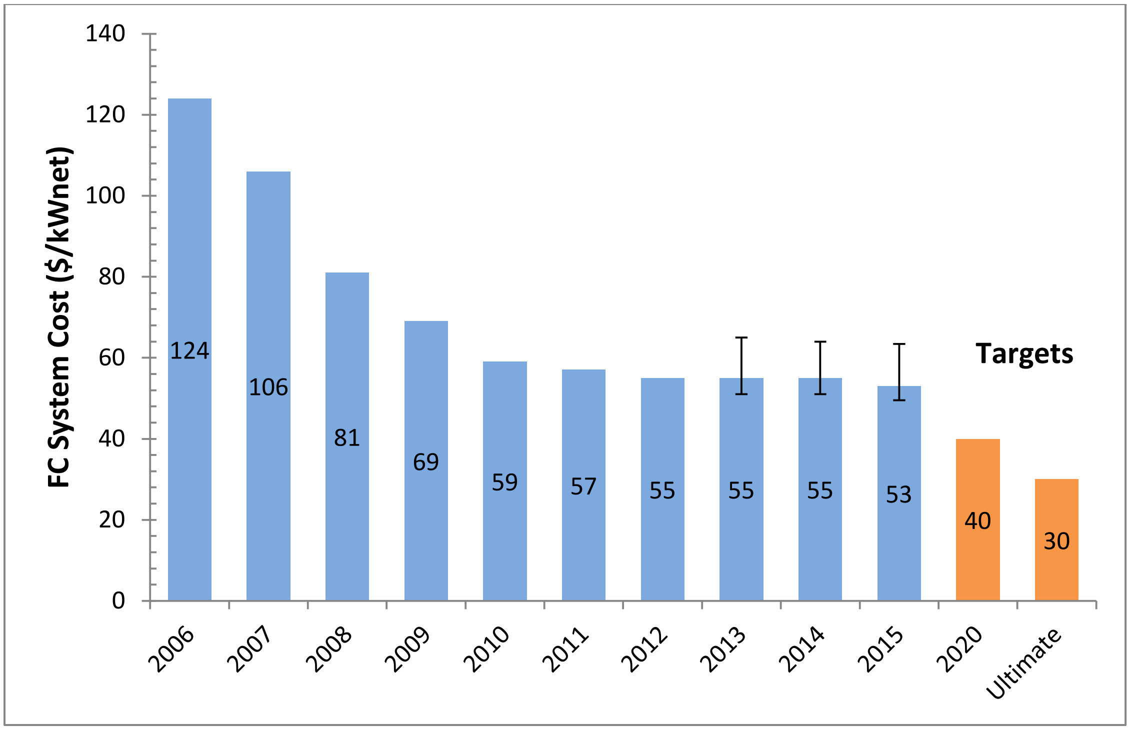

Figure 1. Modeled cost of an 80-kW_{net} PEM fuel cell system based on projection to high-volume manufacturing (500,000 units/year). Reported values from 2012 and earlier were adjusted to account for the higher platinum price, the realigned compressor and expander efficiencies, and the Q/ΔT requirement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

Experimental data for three catalysts were considered in 2015: JM dispersed d-$PtNi_3$, 3M d-Pt_3Ni_7 NSTF, and 3M PtCoMn NSTF. The data were all from small (~12.5 cm^2–50 cm^2) single cell measurements from Best of Class (BOC) cells, at conditions similar, but not identical, to those later found to be cost optimal. These data were used within a first principles ANL computer model to predict stack and system performance for the 3M ternary NSTF and the JM binary catalyst systems. Operating parameters 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 2013 detailed DFMA cost analysis. Performance estimation of the 3M binary NSTF catalyst at the stack level was based on SA adjustment of the 3M single cell data per the procedure established in the 2014 record [9]. Adjustments were made to account for stack losses (using stack data provided by 3M) and for lower O_2 stoichiometric ratio. Based on FCTT input, the JM d-PtNi was selected for the 2015 update, resulting in an SA estimate of \$53/kW_{net} under the system cost optimized conditions of an O_2 stoichiometric ratio of 1.5, cell voltage of 661 mV/cell, and power density of 746 mW/cm^2. This is comparable to the cost calculated for 2014 using the 3M PtCoMn catalyst technology. Results for the two ANL-optimized catalyst systems are summarized in Table 2.

Table 2. Catalysts and operating conditions analyzed in 2015.

	Units	d-PtNi (JM) (ANL Optimized Conditions)	d-PtNi (JM) (O_2 Stoich of 2)	PtCoMn NSTF (3M) (ANL Optimized Conditions)
Pressure	atm	2.5	2.5	2.5
O_2 Stoich	--	1.5	2	1.5
Stack Coolant Exit Temperature	°C	94	94	94
Total PGM	mg_{PGM}/cm^2	0.142	0.142	0.150
Voltage	mV	661	671	662
Power Density	mW/cm^2	746	766	753
Stack Cost	$\$/kW_{net}$	$25.60	$25.62	$25.41
System Cost	$\$/kW_{net}$	$52.99	$55.47	$52.76

Lower volume cost estimates were prepared by SA for manufacturing volumes of 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 the parameter value distributions listed in Table 3. Estimates of the total 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 $50/kW and $63/kW (Figure 4). These cost uncertainty levels only include uncertainty associated with modeling assumptions and parameter values listed in Table 3 and do not include uncertainty associated with other modeling assumptions.

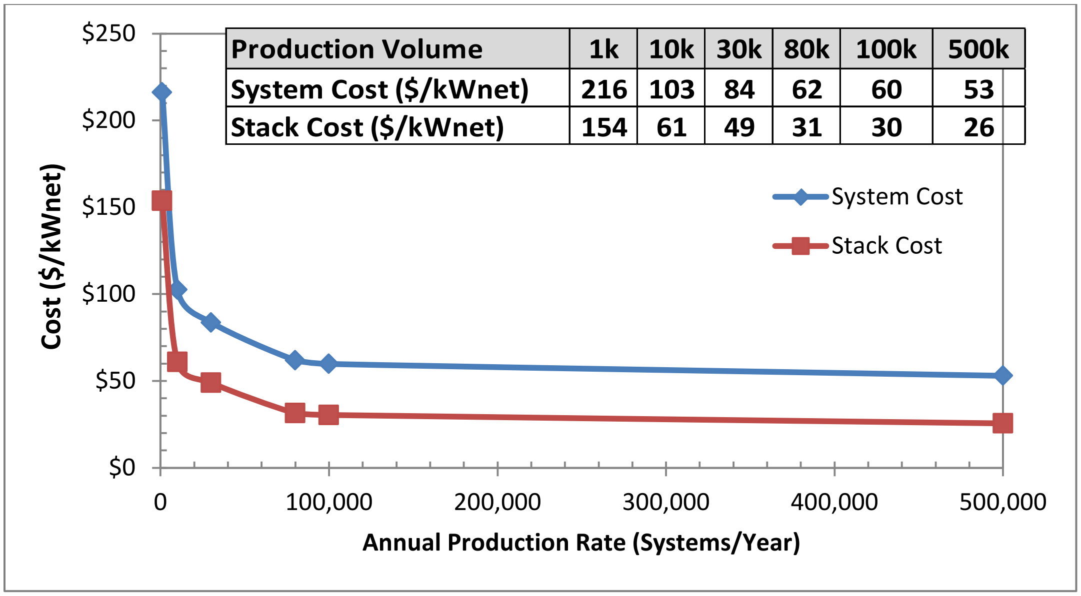

Figure 2. Projected cost of 2015 80-kW$_{net}$ transportation fuel cell stacks and systems at 1,000, 10,000, 30,000, 80,000, 100,000, and 500,000 units/year.

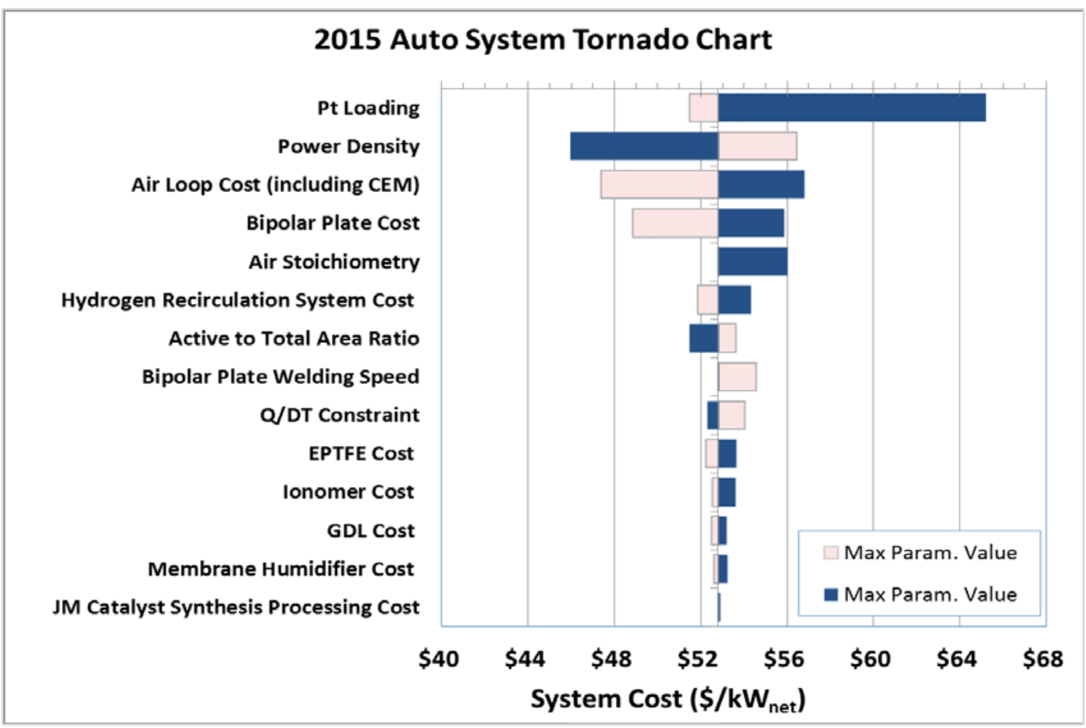

Figure 3. Tornado chart of single variable sensitivity analysis of system cost at 500,000 systems per year.

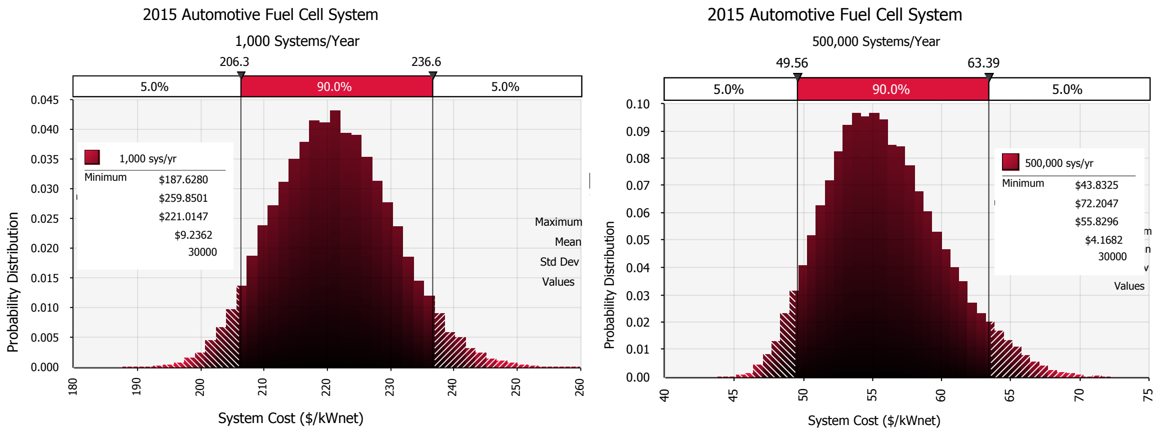

Figure 4. Monte Carlo analyses of system cost probability at 1,000 and 500,000 systems per year.

Table 3. 2015 technology tornado and Monte Carlo analysis, 500k sys/year

Parameter	Unit	Minimum Value	Likeliest Value	Maximum Value	Bounds Rationale
Power Density[a]	**mW/cm^2**	634	**746**	1119	Same % variation (-15%/+50%) as recommended by 2012 FCTT at 500k/yr.
Pt Loading[a]	**$mgPt/cm^2$**	0.125	**0.142**	0.3	Low value from DOE target, high value from FCTT guidance.
Ionomer Cost	**$/kg**	$48.99	**$81.64**	$163.28	Same % variation (-40%/+100%) as recommended by 2012 FCTT at 500k/yr.
Gas Diffusion Layer (GDL) Cost	**$\$/m^2$**	$2.98	**$4.08**	$5.30	Same % variation (-27%/+30%) as recommended by 2012 FCTT at 500k/yr.
Bipolar Plate Cost	**$\$/kW_{net}$**	$3.00	**$6.98**	$10.00	Low Value: DOE 2020 target for BPP cost. High value 2011 status of $\$10/kW_{net}$.
Bipolar Plate Welding Speed	**m/min**	2.5	**15**	15	Max. Value = Baseline Treadstone coating with high speed laser welding (15m/min). Min. Value = Au Nanoclad plates with slower laser welding (2.5m/min)
Air Stoichiometry[a]		1.5	**1.5**	2	Expected range based on experimental results from 3M. High End: Reasonable system operating condition.

Parameter	Unit	Minimum Value	Likeliest Value	Maximum Value	Bounds Rationale
Membrane Humidifier Cost	**$/system**	$60.84	**$81.12**	$121.69	Min. Value = 25% decrease Max. Value = 50% increase (30% due to extra degradation allowance, 20% other cost increase)
Compressor Efficiency[a]	**%**	69%	**71%**	75%	Min. Value = 97% of likeliest value in each of the three component efficiencies. Max. Value = DOE 2020 Targets
Expander Efficiency[a]	**%**	71%	**73%**	80%	
Motor/Controller Efficiency[a]	**%**	78%	**80%**	90%	
Air Compressor Cost Multiplier		0.8	**1**	1.2	Min. Value = 80% of calculated cost. Max. Value = 120% of calculated cost.
Balance of Air Compressor Cost	**$/system**	$122.06	**$183**	$274.49	Min. Value = 66% of calculated cost. Max. Value = 150% of calculated cost.
Hydrogen Recirculation System Cost	**$/system**	$158.48	**$237.59**	$359.39	Min. Value = 66% of calculated cost. Max. Value = 150% of calculated cost.
EPTFE Cost	**$/m^2**	$3.00	**$6.00**	$10.20	Industry quotes
JM Catalyst Processing Cost	**$/system**	$3.01	**$4.01**	$8.02	Min Value = 75% of calculated cost. Max. Value = 200% of calculated cost.

[a] The Monte Carlo analysis treats each parameter as an independent variable with respect to power density. Additionally, the Q/ΔT <1.45 constraint is relaxed.

The SA analysis indicates that the fuel cell stack would account for 71% and 48% 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 stem more from 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 from 28% and 20% of system cost at 1,000 systems per year to 10% and 5% of system cost at 500,000 systems per year, respectively, while the catalyst and bipolar plate cost elements increase from 20% and 13% to 45% and 27% of total stack cost, respectively.

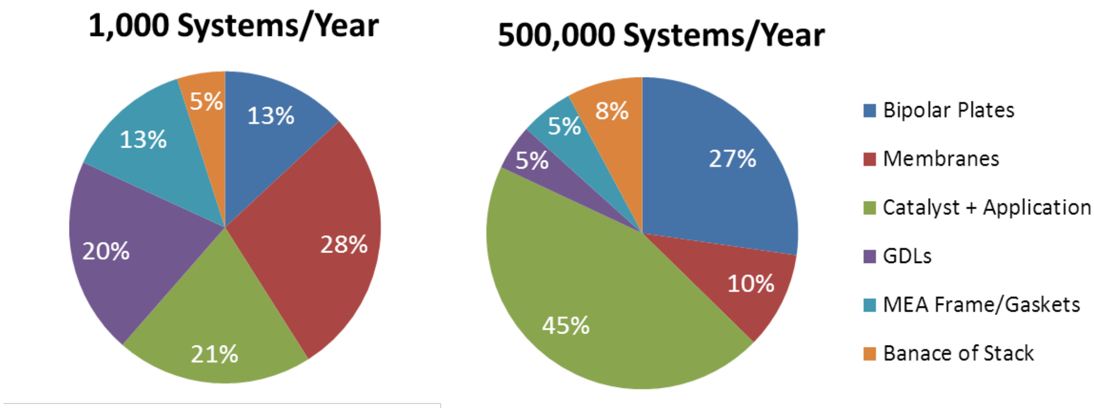

Figure 5. Breakdown of the 2015 projected fuel cell stack cost at 1,000 and 500,000 systems per year.

Costs are further broken down by category in Table 4. Each row in Table 4 corresponds to a cost target in the Multi-Year Research, Development, and Demonstration Plan. This table is provided for the purpose of tracking status with respect to each target.

Table 4. Projected cost status at 500,000 systems per year compared with 2020 cost targets.

Component	**Cost Status**	**2020 Cost Target**
System	$53/kW_{net}$	$40/kW_{net}$
Stack	$26/kW_{net}$	$20/kW_{net}$
MEA[a]	$17/kW_{net}$	$14/kW_{net}$
Fuel cell membrane	$17/m^{2,b}$	$20/m^2$
Bipolar plates[c]	$7/kW_{net}$	$3/kW_{net}$
Air compressor (CEM)[d]	$750/system[e]	$500/system[e]
Humidifier system	$81/system[f]	$100/system[f]
Humidifier membrane[g]	$20/m^2	$10/m^2

[a] Includes membrane, catalyst, GDL, gaskets, hot pressing, and cutting/slitting into cells.
[b] Based on 11.8 m^2 of active area per stack, which does not include cost of membrane lost in stack fabrication or membrane that is outside the cell active area. Equivalent to \$2.60/kW_{net}.
[c] Includes the plates and the coating.
[d] Includes the compressor/expander/motor (CEM) unit and CEM controller.
[e] Equivalent to \$9.40/kW_{net}.
[f] Equivalent to \$1.00/kW_{net}.
[g] The humidifier uses 1.48 m^2 of membrane, so the humidifier membrane cost is \$30/system or \$0.37/kW_{net}.

The Toyota Mirai is the world's first serially produced fuel cell vehicle to be offered for sale to the public and thus offers a unique opportunity for cost validation. The Mirai was released for sale in 2015 with a retail price of $58,325 [10] which equates to approximately $512/kW for the entire vehicle. This stands in contrast to the SA projected cost of $216/kW for the fuel cell power system at 1,000 systems/year. However, this comparison is imperfect as the Mirai value is a price rather than a cost and is for the entire vehicle rather than just the fuel cell power system. Nonetheless, this imperfect comparison is of some value in demonstrating that the cost projections are not inconsistent with the only serially produced fuel cell vehicle to date. Additional cost validation is planned for future years.

This record was reviewed by Brian James, Cassidy Houchins, and Jennie Moton (Strategic Analysis, Inc.) and Rajesh Ahluwalia (Argonne National Laboratory).

References Cited

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