DOE Fuel Cell Technologies Office Record	
Record #: 13012	**Date:** September 18, 2013
Title: Fuel Cell System Cost - 2013	
Update to: Record 12020	
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Approved by: Sunita Satyapal	**Date:** October 16, 2013

Item:

The cost of an 80-kW_{net} automotive polymer electrolyte membrane (PEM) fuel cell system based on 2013 technology[1] and operating on direct hydrogen is projected to be $67/kW when manufactured at a volume of 100,000 units/year, and $55/kW at 500,000 units/year.

Rationale:

The DOE Fuel Cell Technologies (FCT) Office supports projects that perform detailed analysis to estimate cost status of fuel cell systems, updated on an annual basis [1]. In fiscal year 2013, Strategic Analysis, Inc. (SA) updated their 2012 cost analysis of an 80-kW_{net} direct hydrogen PEM automotive fuel cell system, based on 2013 technology and projected to a manufacturing volume of 500,000 units per year [2]. Results from the analysis were communicated to the FCT Office 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 (the Tech Team) [4], as well as through subsequent direct discussion between FCT and SA. The initial 2013 cost estimate was $47/kW; however, SA was asked to revise their analysis with new requirements to meet the DOE heat rejection target and to update the platinum price to reflect recent market levels. The revised high-volume cost estimate of $55/kW was accepted by the Tech Team as a reasonable estimate of the 2013 cost status. The SA estimate of $55/kW has been accepted as the FCT 2013 cost status.

The SA cost analysis, which is based on performance at beginning of life, uses a fuel cell model developed at Argonne National Laboratory (ANL) [5] to predict system performance as a function of operating conditions. The 2013 analysis used an updated 2013 polarization curve from ANL with revised stack humidity assumptions. The ANL and SA analyses assume use of membrane electrode assemblies (MEAs) containing state-of-the-art 3M nanostructured thin film (NSTF) ternary platinum-alloy catalyst layers on 25 micron reinforced Nafion® membranes. The Pt commodity price of $1,500 per troy ounce for the 2013 analysis represents an increase from the price of $1,100 per troy ounce that was used in the 2006-2012 estimates. The cost estimate is based on capital equipment price quotes or estimates obtained between 2010 and 2013, and materials price quotes obtained between 2012 and 2013. Quoted prices were not adjusted for inflation. All calculations were performed using nominal dollars.

ANL performed an optimization study in fiscal year 2013 in which five system design parameters (cathode catalyst loading, peak operating temperature, peak stack inlet pressure, oxygen

[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.

stoichiometric ratio, and cell voltage) were varied to minimize system cost. The parameters used in the 2010 through 2013 analyses, with the resulting cost estimates, are summarized in Table 1.

Table 1: System design parameters and system cost from the 2010 through 2013 cost analyses, evaluated at rated power.

Characteristic	Units	2010	2011	2012	2013
Stack efficiency	%	55	55	55	57
Cell voltage	V	0.676	0.676	0.676	0.695[a]
Oxygen stoichiometric ratio		2.5	1.5[a]	1.5	1.5[a]
Stack inlet pressure	atm	1.69	3[a]	2.5[a]	2.5[a]
Stack temperature	°C	90	95[a]	87[a]	97[a]
Total PGM loading	mg_{PGM}/cm^2	0.15	0.186[a]	0.196[a]	0.153[a]
MEA areal power density	mW/cm^2	833	1,110	984	692
System cost	$\$/kW_{net}$	51	49	47	55

[a] Optimization parameter.

In their optimization analysis, ANL investigated oxygen stoichiometric ratios ranging from 1.5 to 2.5, peak inlet pressures from 1.5 to 2.5 atm, peak temperatures from 75 to 100°C, total PGM loadings from 0.10 to 0.24 mg/cm^2, and cell voltages from 0.67 to 0.80 V.

The current status of $55/kW at 500,000 units/year ($67/kW at 100,000 units/year) represents a new baseline for the DOE automotive fuel cell cost status, and is not directly comparable to reported cost status values from previous years due to changes in the assumptions and methodology introduced in 2013. The principal assumption change introduced in 2013 was the platinum price increase to $1,500 per troy ounce. The price of platinum used in the 2006 through 2012 analyses had remained constant at $1,100 per troy ounce, enabling the cost analyses to examine changes in technological status that would otherwise be overshadowed by variations in platinum price, which in one year ranged from under $800 to over $2,200 per troy ounce (Figure 1). However, with Pt prices consistently above $1,100 per troy ounce for more than four years, an increase in the price used in the cost analysis was deemed necessary. The new price of $1,500 per troy ounce was selected because it approximates the average monthly platinum price between 2006 and 2013, and is also quite close to current prices (Figure 1).

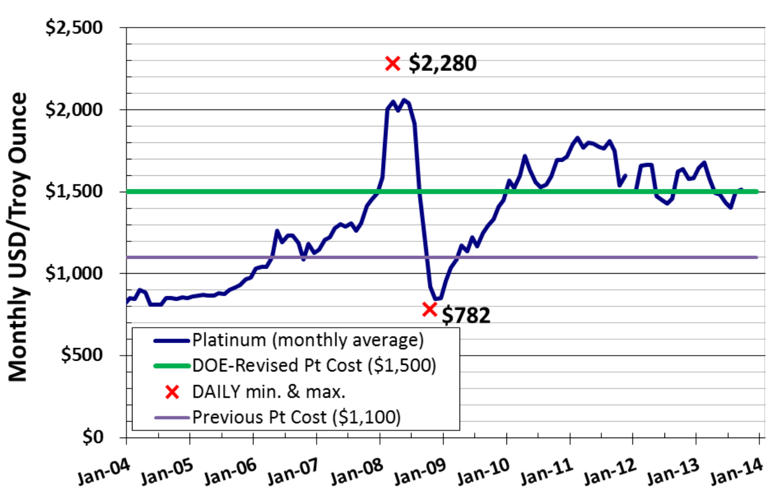

Figure 1. Monthly average platinum prices, 2004 to 2013.

The principal change in the methodology in 2013 was the introduction of a requirement to meet the DOE heat rejection target, $Q/\Delta T \leq 1.45$ [6]. Achievement of this target is required due to the constraints on the radiator size inherent in automotive applications. To meet this target, the system design parameters were modified to decrease waste heat generation by operating at a higher rated power stack efficiency (57%, vs. 55% in 2012), and the heat rejection driving force was increased through operation of the stack at a higher peak temperature (97°C, vs. 87°C in 2012). The addition of the $Q/\Delta T$ requirement, as well as the availability of new NSTF performance data from 3M, necessitated re-optimization of the system design parameters to minimize cost. These changes in the system design parameters and performance model resulted in a net increase in cost over the 2012 estimate (+$3/kW). Additional significant changes in system cost resulting from the 2013 analysis occurred as a result of the increased platinum price (+$3/kW), and as a result of a realignment of compressor and expander efficiencies to match the values used by SA with those used in the ANL analysis (+$2/kW). Key assumptions of the 2013 cost analysis are summarized in Table 2, along with a cost breakdown for the years 2007 – 2012 [7-12].

Table 2: Key Assumptions of Cost Analyses and Resulting Cost

Characteristic	**Units**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Stack power	kW_{gross}	90	90	88	88	89	88	89
System power	kW_{net}	80	80	80	80	80	80	80
Cell power density	mW_{gross}/cm^2	583	715	833	833	1,110	984	692
Peak stack temperature	°C	70-90	80	80	90	95	87	97
PGM loading	mg/cm^2	0.35	0.25	0.15	0.15	0.19	0.20	0.15
PGM total content	g/kW_{gross}	0.6	0.35	0.18	0.18	0.17	0.20	0.23
PGM total content	g/kW_{net}	0.68	0.39	0.20	0.20	0.19	0.22	0.25
Pt cost	$/troz.	1,100	1,100	1,100	1,100	1,100	1,100	1,500
Stack cost	$\$/kW_{net}$	50	34	27	25	22	20	27
Balance of plant cost	$\$/kW_{net}$	42	37	33	25	26	26	27
Sys. Assy. and Testing	$\$/kW_{net}$	2	2	1	1	1	1	1
System cost	$\$/kW_{net}$	94	73	61	51	49	47	55

The results of the current year cost analysis are compared with prior year results in Figure 2. Cost analyses from previous years were reexamined and updated to reflect the changes made in the 2013 analysis. In this updating process, the change in platinum price from $1,100 to $1,500 per troy ounce resulted in the largest effect on cost status, ranging from $3/kW in 2009-2012 (years in which the platinum total content was stable at around 0.2 g/kW_{net}) to $13/kW in 2006, when the platinum content was much higher at 1 g/kW_{net}. The change due to the compressor and expander efficiency realignment was smaller, ranging from $0/kW in 2006-2008 (years in which the lower efficiencies used were deemed appropriate) to $2/kW in 2009-2012 (years in which the high efficiencies used were deemed overly optimistic). A uniform $3/kW was added to all analyses to account for the new heat rejection requirement, under the assumption that the cost change resulting from introducing this requirement in the previous years would have been roughly comparable to the change in 2013. Estimates of the cost values that would have resulted from adopting these changes in prior years are included in Figure 2. In years in which Monte Carlo error analysis was performed (2010-2013), the resulting 90% confidence intervals are shown in the error bars. The error analysis was not revisited in the updated cost estimates for years prior to 2013, so only the error bars on the original estimates are shown. In 2013, error analysis had not yet been performed at the time when SA and ANL were asked to revise their analyses. Therefore, error bars are only shown on the updated 2013 analysis.

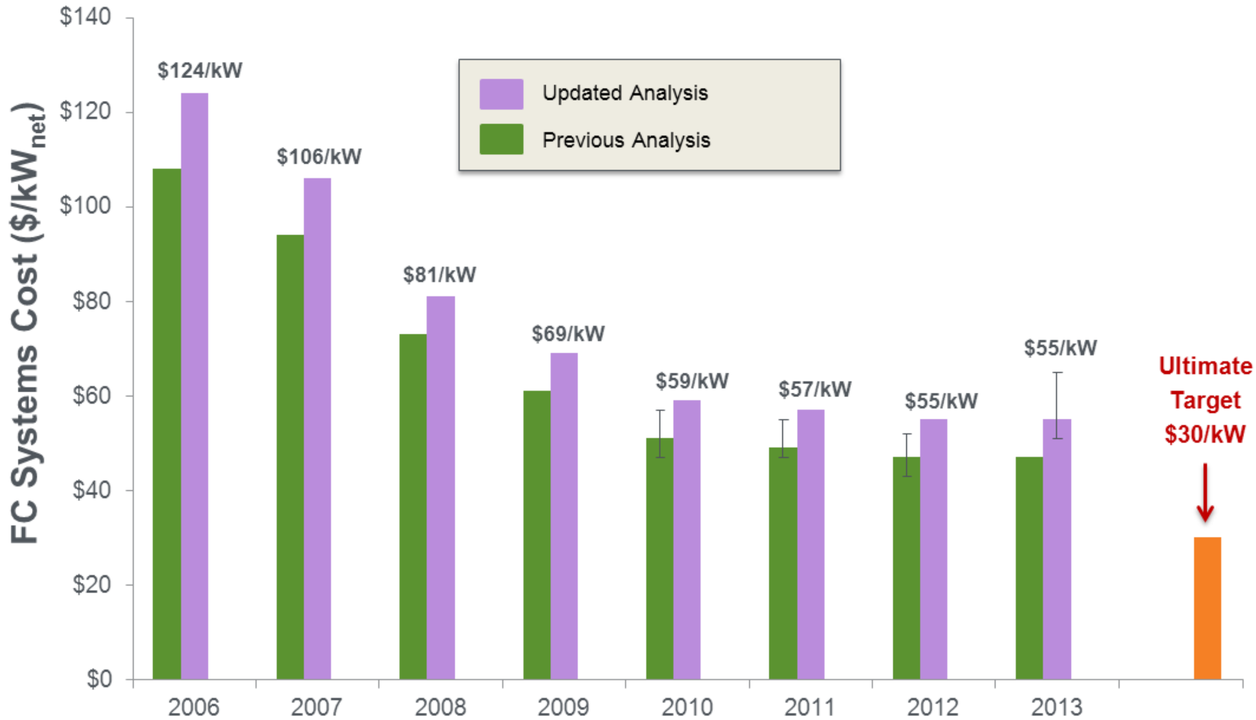

Figure 2. Modeled cost of an 80-kW_{net} PEM fuel cell system based on projection to high-volume manufacturing (500,000 units/year). Reported values from prior year cost estimates were adjusted to account for the higher platinum price, the realigned compressor and expander efficiencies, and the $Q/\Delta T$ requirement introduced in 2013.

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 3.

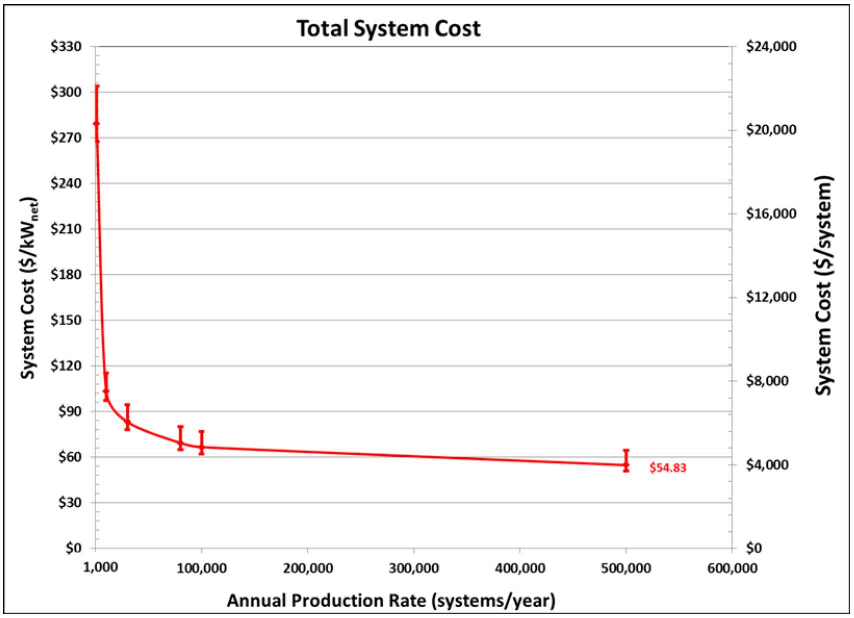

Figure 3. Projected cost of 2013 80-kW_{net} transportation fuel cell systems at 1,000, 10,000, 30,000, 80,000, 100,000, and 500,000 units/year.

Error estimates shown in Figure 3 were evaluated through a Monte Carlo analysis using estimated parameter value distributions listed in Table 3. Based on the Monte Carlo results, the system cost at 500,000 units/year is projected with 90% certainty to be between $51/kW and $65/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.

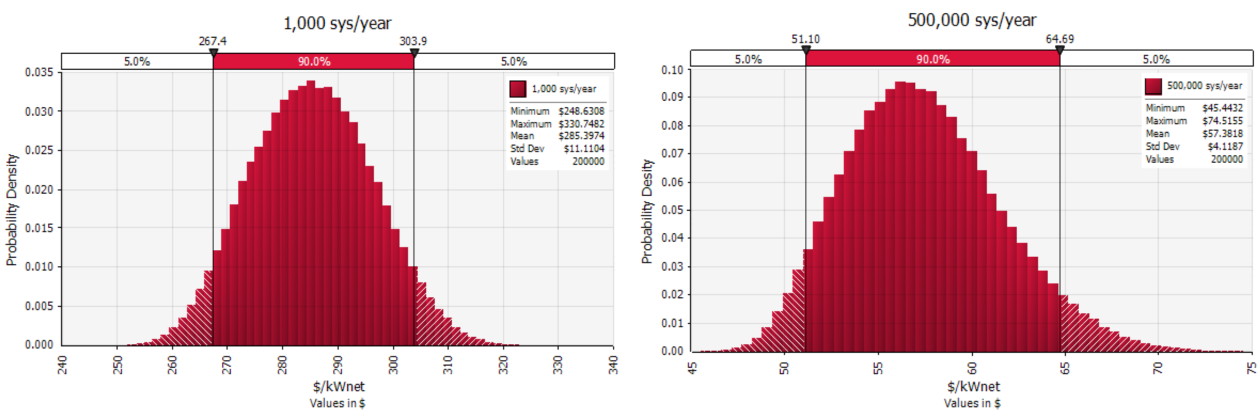

Figure 4. Monte Carlo analyses of system cost probability at 1,000 and 500,000 systems per year.

Table 3. Parameter values for system cost Monte Carlo simulations.

2013 Technology Monte Carlo Analysis, 500k sys/year					
Parameter	**Unit**	**Minimum Value**	**Likeliest Value**	**Maximum Value**	**Bounds Rationale**
Power Density	**mW/cm2**	588	**692**	1038	Approx. same % range recommended by 2012 FCTT at 500k/yr.
Pt Loading	**mgPt/cm2**	0.15	**0.153**	0.3	FCTT guidance.
Ionomer Cost	**$/kg**	$46.63	**$77.71**	$155.43	Approx. same % range recommended by 2012 FCTT at 500k/yr.
GDL Cost	**$/m2**	$2.79	**$3.82**	$4.97	Approx. same % range recommended by 2012 FCTT at 500k/yr.
Bipolar Plate & Coating Cost Multiplier		1	**1**	1.5	Low = Baseline Treadstone coating with high speed laser welding (15m/min). High = Au Nanoclad plates with slower laser welding (2.5m/min)
Membrane Humidifier Cost	**$/system**	$70.77	**$94.36**	$141.53	Low = 25% decrease. High = 50% increase (30% due to degradation allowance, 15% other cost increase)
Compressor Effic. Expander Effic. *Motor/Controller Effic.*	**%** **%** ***%***	69% 71% 78%	**71%** **73%** **80%**	75% 80% 90%	Low End: 97% of baseline in each of three component efficiencies. High End: DOE Targets
Air Compressor Cost Multiplier		0.8	**1**	1.2	Low end is 20% reduction of calculated cost. High end is 20% increase of calculated cost
Balance of Air Compressor Cost	**$/system**	$99.92	**$149.81**	$224.71	2/3 of value at low end, 1.5x at high
Hydrogen Recirculation System Cost	**$/system**	$160.96	**$241.32**	$361.98	2/3 of value at low end, 1.5x at high
EPTFE Cost	**$/m^2**	$3.00	**$6.00**	$10.20	Industry quotes with min of half the cost and a max of 1.7x

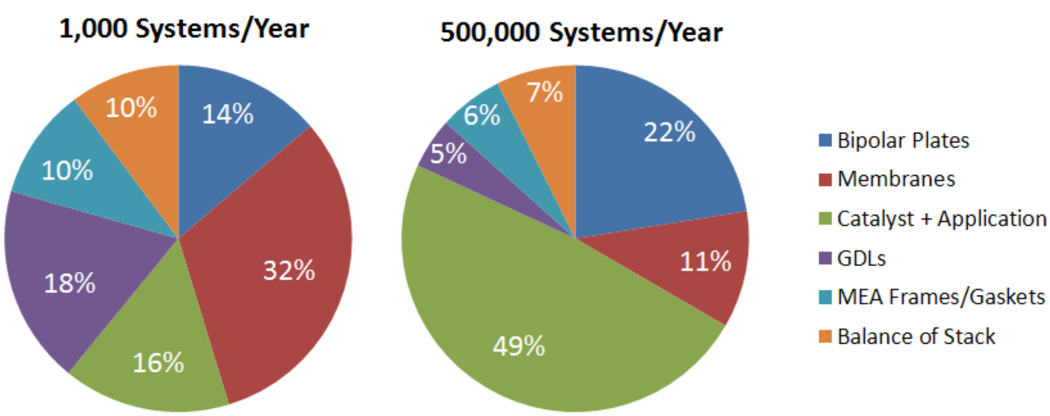

Figure 5. Breakdown of the 2013 projected fuel cell stack cost at 1,000 and 500,000 systems per year.

The SA analysis indicates that the fuel cell stack would account for 64% and 49% 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 (stainless steel and platinum, respectively), which are revlatively 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 volume causes the membrane and GDL cost elements to decrease from 32% and 18% of system cost at 1,000 systems per year to 11% and 5% of system cost at 500,000 systems per year, respectively, while the catalyst and bipolar plate cost elements increase from 16% and 14% to 49% and 22% of total system cost, respectively.

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

References

[1] J. Marcinkoski et al., "Manufacturing process assumptions used in fuel cell system cost analyses," J. Power Sources 196 (2011) 5282-5292.

[2] B. James et al., "Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications: 2013 Update," report to the DOE Fuel Cell Technologies Program, in preparation.

[3] B. James et al., "Fuel Cell Transportation Cost Analysis," presentation at the 2013 U.S. DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation. http://www.hydrogen.energy.gov/pdfs/review13/fc018_james_2013_o.pdf

[4] B. James, presentation at the July 17, 2013 meeting of the U.S. Drive Fuel Cell Technical Team.

[5] R. Ahluwalia et al., "Fuel Cells Systems Analysis," presentation at the 2013 U.S. DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation. http://www.hydrogen.energy.gov/pdfs/review13/fc017_ahluwalia_2013_o.pdf

[6] Fuel Cell Technologies Office Multi-Year Research, Development and Demonstration Plan, 2012 Update, pp. 3.4-28. http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf

[7] U.S. Department of Energy (Hydrogen Program), "Record 8002: Fuel Cell System Cost - 2007," http://www.hydrogen.energy.gov/program_records.html

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