DOE Hydrogen and Fuel Cells Program Record

Record #: 14014	**Date:** September 25, 2014
Title: Fuel Cell System Cost - 2014	
Update to: Record 14012	
Originator: Jacob Spendelow and Jason Marcinkoski	
Approved by: Sunita Satyapal	**Date:** October 6, 2014

Item:

The cost of an 80-kW$_{\text{net}}$ automotive polymer electrolyte membrane (PEM) fuel cell system based on next-generation laboratory technology[1] and operating on direct hydrogen is projected to be \$55/kW$_{\text{net}}$ when manufactured at a volume of 500,000 units/year. 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$_{\text{net}}$ when manufactured at a volume of 20,000 units/year.

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 [1]. In fiscal year 2014, Strategic Analysis, Inc. (SA) updated their 2013 cost analysis of an 80-kW$_{\text{net}}$ direct hydrogen PEM automotive fuel cell system, based on 2014 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 two meetings of the U.S. DRIVE Fuel Cell Technical Team (FCTT) [4,5], as well as through subsequent direct discussion between FCTO and SA. The initial 2014 cost estimate was \$57/kW$_{\text{net}}$; however, input from the FCTT indicated that the cell power density used in the cost analysis (641 mW/cm^2, provided by Argonne National Laboratory's (ANL) NSTF-based fuel cell system model) was low with respect to the state of the art systems. While the ANL model is a credible model, it represents only one of many possible fuel cell material and component combinations. SA revised their analysis, basing performance on available experimental data provided by 3M, and the FCTT indicated that the resulting power density of 834 mW/cm^2 at 0.672 V was still low, but close enough to the state-of-the-art to be used for cost-modeling purposes. The revised high-volume cost estimate of \$55/kW$_{\text{net}}$ was accepted by the FCTT as a reasonable estimate of the 2014 cost status. The SA estimate of \$55/kW$_{\text{net}}$ has been accepted as the FCTO 2014 cost status.

The SA cost analysis, which is based on performance at beginning of life, assumes 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 2014 analysis is consistent with the price used in 2013. The cost estimate is based on materials price quotes obtained between 2012 and

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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.

2014. Quoted prices were not adjusted for inflation after 2009. All calculations were performed using nominal dollars.

The parameters used in the 2010 through 2014 analyses, with the resulting cost estimates, are summarized in Table 1.

Table 1. System design parameters and system cost from the 2010 through 2014 cost analyses, evaluated at rated power.

Characteristic	**Units**	**2010**	**2011**	**2012**	**2013**	**2014**
Stack efficiency	%	55	55	55	57	54
Cell voltage	V	0.676	0.676	0.676	0.695[a]	0.672
Air stoichiometric ratio		2.5	1.5[a]	1.5	1.5[a]	2
Stack inlet pressure	atm	1.69	3[a]	2.5[a]	2.5[a]	2.5
Peak cell temperature	°C	90	95[a]	87[a]	97[a]	100
Total PGM loading	mg_{PGM}/cm^2	0.15	0.186[a]	0.196[a]	0.153[a]	0.153
MEA areal power density	mW/cm^2	833	1,110	984	692	834
Q/ΔT[b]	kW/°C	1.66	1.52	1.80	1.45	1.45
System cost	$\$/kW_{net}$	51	49	47	55	55

[a] Optimization parameter.

b Q/ΔT is a measure of heat rejection requirements 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)].

In previous years, the rated power operating point used in the cost analysis was selected based on an optimization of the ANL model in which parameters including cell voltage, air stoichiometric ratio, stack pressure, stack temperature, and PGM loading were varied to find the lowest cost point. In 2014, the use of actual experimental data from 3M instead of modeled results required a change in the optimization for lowest system cost. The values of the parameters were selected as follows:

- Peak cell temperature was set at the highest value deemed possible without significant loss in durability, 100°C. Performance data was unavailable at this temperature, but based on an observation that polarization data was roughly constant in the 85-95°C range,[2] it was assumed that a further 5°C increase would be possible without significant changes in performance.
- The selection of a relatively high peak cell temperature of 100°C, which provides a stack coolant outlet temperature of 95°C, enables good heat rejection capabilities, allowing reduction in the cell voltage to 0.672 V and increase in the cell power density to 834 mW/cm^2 while still meeting the DOE heat rejection target of $Q/\Delta T \leq 1.45$ [6]. Higher power density reduces stack cost.

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[2] 3M provided data at a quoted temperature of up to 90°C with temperature measured on the back of the graphite bipolar plate within a reactant gas cooled single cell apparatus. It is believed that this temperature could be increased to 95°C with no discernable impact on performance or durability. The modeled stack system is based on liquid cooled stacks and it is expected that the temperature on the back of the bipolar plate would closely match the temperature of the coolant. Furthermore, modeling at ANL suggests that the expected temperature difference between the stack coolant liquid and the MEA surface is approximately 5°C. Thus for a peak coolant exit temperature of 95°C, the peak cell temperature is expected to be ~100°C.

- Most experimental data provided by 3M represented operation at an air stoichiometric ratio of 2, but a few data sets at values ranging from 1.5 to 5 were included. The data indicate that cell performance levels increased slightly when increasing the air stoichiometric ratio from 1.5 to 2, but further increase did not result in additional gains. Air stoichiometric ratios of either 1.5 or 2 give approximately the same modeled system cost, since reductions in stack cost at the higher ratio are offset by increases in air compressor cost and increase in cell performance is offset by additional power required for air compression. An air stoichiometric ratio of 2 was selected for the cost model because it resulted in approximately the same system cost as a ratio of 1.5, but with improved performance stability.
- FCTT input has indicated that peak stack pressures of 2.5 atm are reasonable. All experimental data provided by 3M was collected at 2.5 atm. Therefore, 2.5 atm was used as the stack pressure in the cost model.

Key assumptions of the 2014 cost analysis are summarized in Table 2, and compared with cost breakdowns for the years 2007 – 2013 [7-13]. The modified polarization curve and different operating conditions selected in 2014 resulted in a \$0.37/kW decrease from the 2013 system cost, while modified efficiency calculations and other miscellaneous changes resulted in a \$0.39/kW increase. Therefore, the net change in system cost from 2013 to 2014 was \$0.02/kW. The small change in cost in 2014 is understandable given that the technologies used in the 2014 model are essentially the same as used in the 2013 model, and the polarization data used to calculate expected stack performance dates from 2012. All cost analyses since 2009 have used essentially the same 3M ternary NSTF catalysts, explaining the relatively small change in system cost since 2009. Examination of more advanced catalyst technology, including de-alloyed PtNi catalysts, is planned for future year analyses.

Table 2. Key assumptions of cost analyses and resulting cost.

Characteristic	**Units**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Stack power	kW_{gross}	90	90	88	88	89	88	89	93
System power	kW_{net}	80	80	80	80	80	80	80	80
Cell power density	mW_{gross}/cm^2	583	715	833	833	1,110	984	692	834
Peak cell temp.	°C	70-90	80	80	90	95	87	97	100
PGM loading	mg/cm^2	0.35	0.25	0.15	0.15	0.19	0.20	0.15	0.15
PGM total content	g/kW_{gross}	0.6	0.35	0.18	0.18	0.17	0.20	0.23	0.18
PGM total content	g/kW_{net}	0.68	0.39	0.20	0.20	0.19	0.22	0.25	0.21
Pt cost	\$/troz.	1,100	1,100	1,100	1,100	1,100	1,100	1,500	1,500
Stack cost	$\$/kW_{net}$	50	34	27	25	22	20	27	24
BOP cost	$\$/kW_{net}$	42	37	33	25	26	26	27	29
Assy. and testing	$\$/kW_{net}$	2	2	1	1	1	1	1	1
System cost	$\$/kW_{net}$	94	73	61	51	49	47	55	55
Sys. cost adjusted[3]	$\$/kW_{net}$	106	81	69	59	57	55	55	55

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

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[3] Cost analyses performed prior to 2013 used different assumptions and were subject to different system requirements, preventing direct comparison with more recent cost analyses. Therefore, adjusted cost status numbers from 2012 and earlier are provided to be more comparable to the results from 2013 and later. See 2013 cost record for additional details of the adjustment procedure.

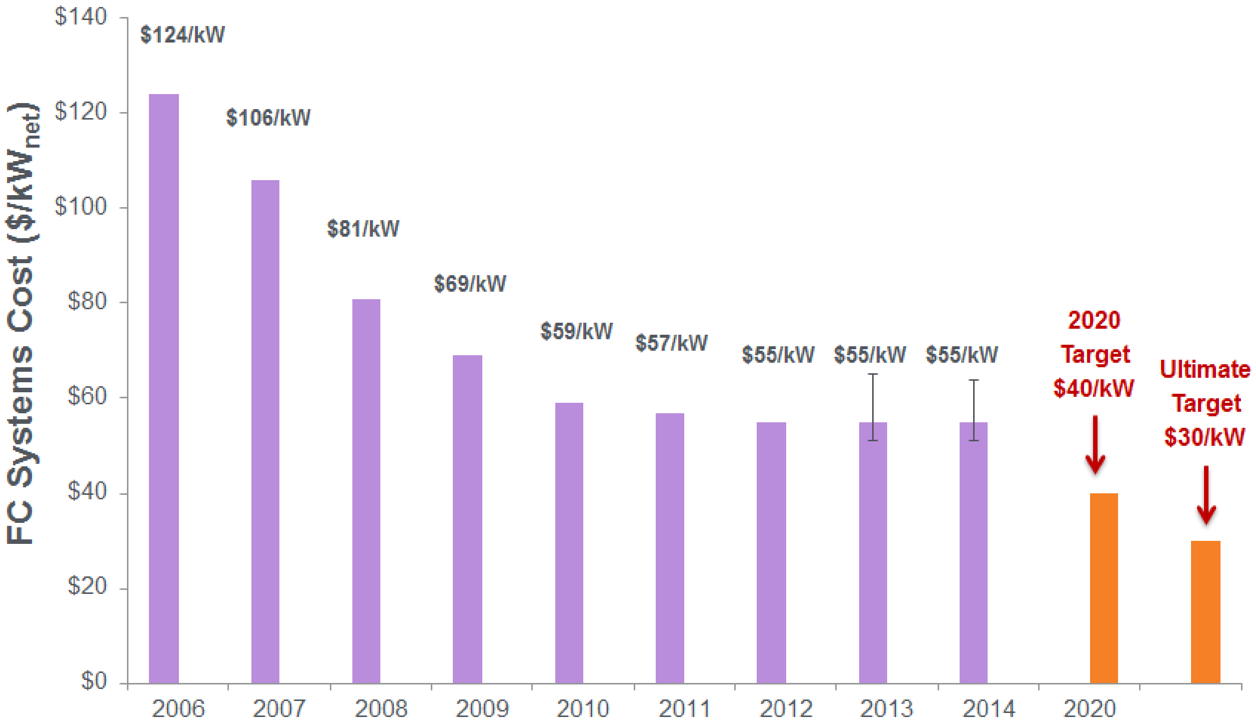

Figure 1. Modeled cost of an 80-kW$_{net}$ PEM fuel cell system based on projection to high-volume manufacturing (500,000 units/year). Reported values from 2012 and earlier were adjusted to account for the higher platinum price, the realigned compressor and expander efficiencies, and the Q/ΔT requirement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

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.

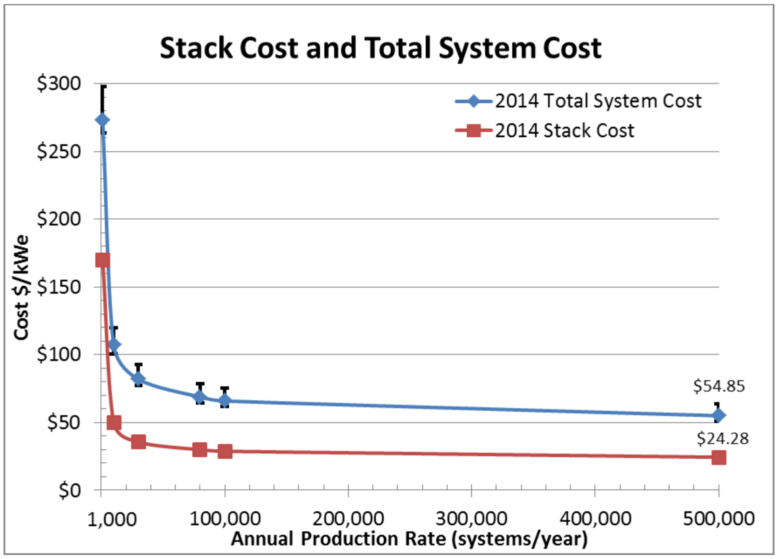

Figure 2. Projected cost of 2014 80-kW$_{net}$ transportation fuel cell stacks and systems at 1,000, 10,000, 30,000, 80,000, 100,000, and 500,000 units/year.

Error estimates shown in Figure 2 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 $64/kW (Figure 3). 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.

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

2014 Technology Monte Carlo Analysis, 500k sys/year					
Parameter	**Unit**	**Minimum Value**	**Likeliest Value**	**Maximum Value**	**Bounds Rationale**
Power Density	**mW/cm^2**	709	**834**	1251	Same % variation (-15%/+50%) as recommended by 2012 FCTT at 500k/yr.
Pt Loading	**mgPt/cm^2**	0.15	**0.153**	0.3	FCTT guidance.
Ionomer Cost	**$/kg**	$47.57	**$79.28**	$158.55	Same % variation (-40%/+100%) as recommended by 2012 FCTT at 500k/yr.
Gas Diffusion Layer (GDL) Cost	**$/m2**	$3.02	**$4.14**	$5.38	Same % variation (-27%/+30%) as recommended by 2012 FCTT at 500k/yr.
Bipolar Plate & Coating Cost Multiplier		1	**1**	1.5	Min. Value = Baseline Treadstone coating with high speed laser welding (15m/min). Max. Value = Au Nanoclad plates with slower laser welding (2.5m/min)
Air Stoichiometry		1.5	**2**	2.5	Expected range based on experimental results from 3M
Membrane Humidifier Cost	**$/system**	$82.25	**$109.67**	$164.50	Min. Value = 25% decrease Max. Value = 50% increase (30% due to degradation allowance, 15% other cost increase)
Compressor Effic.	**%**	69%	**71%**	75%	Min. Value = 97% of likeliest value in each of the three component efficiencies. Max. Value = DOE Targets
Expander Effic.	**%**	71%	**73%**	80%	
Motor/Controller Efficiency	***%***	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**	$103.25	**$154.80**	$232.20	Min. Value = 66% of calculated cost. Max. Value = 150% of calculated cost.
Hydrogen Recirculation System Cost	**$/system**	$160.95	**$241.30**	$361.96	Min. Value = 66% of calculated cost. Max. Value = 150% of calculated cost.
EPTFE Cost	**$/m^2**	$3	**$6**	$10	Industry quotes

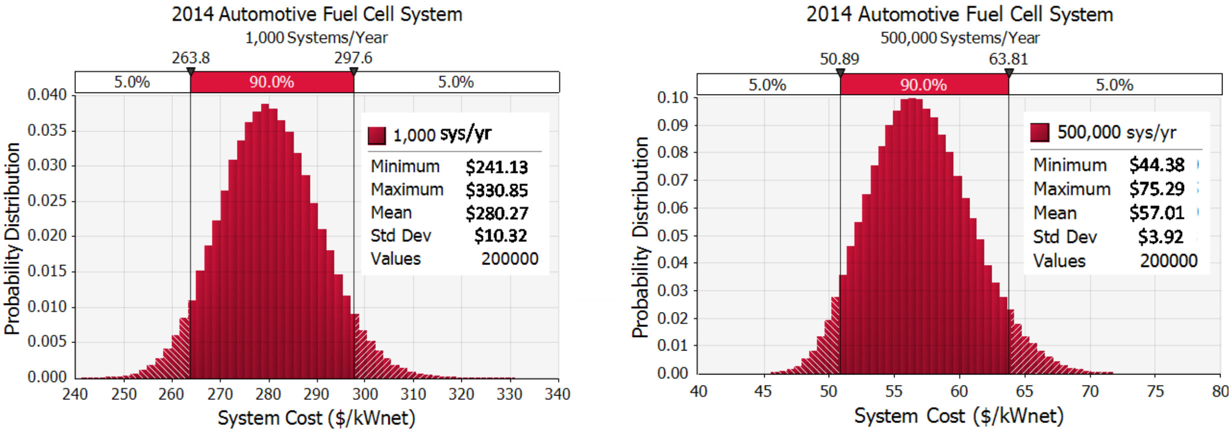

Figure 3. Monte Carlo analyses of system cost probability at 1,000 and 500,000 systems per year.

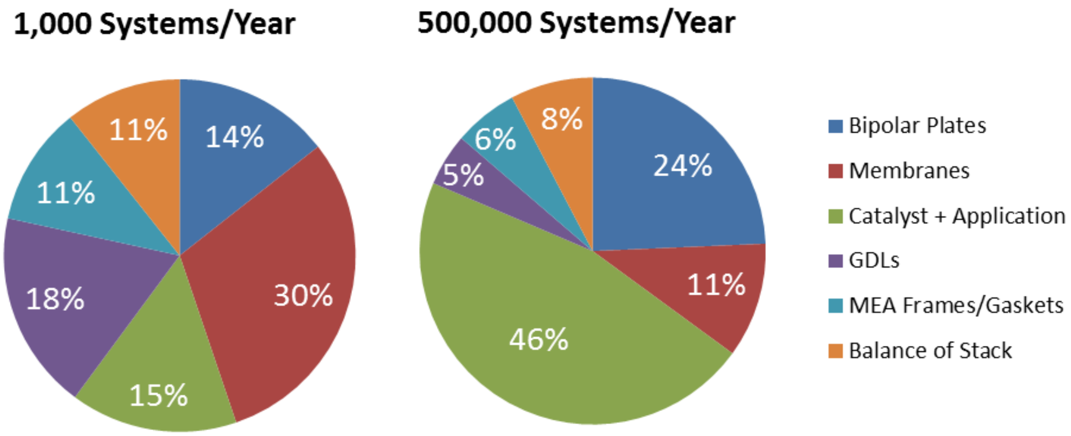

Figure 4. Breakdown of the 2014 projected fuel cell stack cost at 1,000 and 500,000 systems per year.

The SA analysis indicates that the fuel cell stack would account for 62% and 44% 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 4. 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 volume causes the membrane and gas diffusion layer (GDL) cost elements to decrease from 30% 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 15% and 14% to 46% and 24% of total system cost, respectively.

The SA analysis is based on the next-generation components currently being developed and tested at the laboratory scale through DOE funded activities. The cost of currently available integrated systems is significantly higher. A 2013 analysis by Oak Ridge National Laboratory [14], which included an examination of published information as well as interviews with OEM representatives, determined that initial commercialization of fuel cell vehicles in the 2016 time frame will likely occur with fuel cell system cost on the order of $24,000 for an 85 kW system, or $280/kW. This analysis assumes a likely manufacturing volume of 20,000 systems/year. Higher volume production, which is likely to reach 200,000 systems/year by 2020, is expected to lead to a fuel cell system cost of around $90/kW (with technological breakthroughs) to $160/kW (assuming only incremental progress).

A number of factors may contribute to the difference in the high-volume cost estimates between the ORNL analysis and the SA analysis. Notably, the ORNL analysis takes a top-down approach based on interviews with industry experts and application of heuristic adjustments to predict cost at high volume, in contrast to the bottom-up analysis starting with individual component manufacturing costs performed by SA. Furthermore, the ORNL analysis takes currently integrated systems as its starting point, whereas the SA analysis starts with the highest performing components identified to date and combines them into a complete system, with the assumption that the components can be integrated together without loss of performance and with sufficient durability for commercial deployment. The differences between the analysis techniques and assumptions results in high volume cost estimates that are not directly comparable, but both methods of cost estimation may be useful in attempting to determine or predict the cost of fuel cell systems during high-volume commercial production.

This record was reviewed by Brian James and Jennie Moton (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: 2014 Update,” report to the DOE Fuel Cell Technologies Office, in preparation.

[3] B. James et al., “Fuel Cell Transportation Cost Analysis,” presentation at the 2014 U.S. DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation. http://www.hydrogen.energy.gov/pdfs/review14/fc018_james_2014_o.pdf

[4] B. James, presentation at the July 16, 2014 meeting of the U.S. Drive Fuel Cell Technical Team.

[5] B. James, presentation at the September 10, 2014 meeting of the U.S. Drive Fuel Cell Technical Team.

[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 and Fuel Cells Program), "Record 8002: Fuel Cell System Cost - 2007," http://www.hydrogen.energy.gov/program_records.html

[8] U.S. Department of Energy (Hydrogen and Fuel Cells Program), "Record 8019: Fuel Cell System Cost - 2008," http://www.hydrogen.energy.gov/program_records.html

[9] U.S. Department of Energy (Hydrogen and Fuel Cells Program), "Record 9012: Fuel Cell System Cost - 2009," http://www.hydrogen.energy.gov/program_records.html

[10] U.S. Department of Energy (Hydrogen and Fuel Cells Program), "Record 10004: Fuel Cell System Cost - 2010," http://www.hydrogen.energy.gov/program_records.html

[11] 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

[12] 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

[13] 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

[14] D. Greene et al., "Status and Prospects of the Global Automotive Fuel Cell Industry and Plans for Deployment of Fuel Cell Vehicles and Hydrogen Refueling Infrastructure," http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fcev_status_prospects_july2013.pdf