DOE Hydrogen Program Record	
Record #: 21001	**Date:** January 7, 2021
Title: Durability-Adjusted Fuel Cell System Cost	
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Item:

The 2020 estimated cost of an 80-kW$_{\text{net}}$ automotive polymer electrolyte membrane (PEM) fuel cell system is projected to be $\$76/\text{kW}_{\text{net}}$ when manufactured at a volume of 100,000 units/year [1]. These costs represent the power system cost to achieve 8,000 hours of on-road operation (the durability-adjusted cost), a system lifetime enabled through a combination of component design, operating methodology, and stack oversizing. The max fleet average on-road operational lifetime status (from 2016) of a fuel cell electric vehicle (FCEV) was over 4,100 hours [2]. The DOE Ultimate Target Durability of the fuel cell system is 8,000 hours [3].

Rationale:

The DOE Hydrogen and Fuel Cell Technologies Office (HFTO) supports projects that conduct annually updated detailed analyses to estimate the cost status of fuel cell systems. Additionally, HFTO supports projects that track the status of fuel cell durability, measured in hours of operation before 10% of the beginning of life rated power is lost [3]. Reported costs have previously been based on the performance of a fuel cell system at the beginning of life and partially considered the life of the stack or system, even though automotive fuel cell systems (FCSs) typically fall short of DOE durability targets. Consequently, there is interest from HFTO and the fuel cell community to incorporate durability into cost modeling efforts so as to project a durability-adjusted FCS cost. Such an assessment will allow cost and durability progress to be tracked jointly and will provide additional information for DOE to identify R&D focus needs.

To estimate the durability-adjusted cost, two different methods have been applied depending on the year of analysis and availability of modeling data. The first approach was to use fleet durability data to estimate a number of stack replacements to meet 8,000-hrs. The second approach was to use electrochemical surface area (ECSA) loss modeling to predict stack durability and extend operating hours via stack oversizing. Additionally, replacement costs for BOP components were considered for both approaches.

The first approach was used to adjust system cost for years prior to 2020. A durability multiplier (DM) was applied to the system cost [1] where DM is a ratio of the 8,000-hours (DOE Ultimate Target Durability) and the DOE Status Durability. This represents a stack replacement strategy wherein a new stack is purchased for the power plant so the total life may be extended to 8,000 hours. The DOE Status Durability is based on testing conducted at NREL's National Fuel Cell Technology Evaluation Center (NFCTEC) and adopts their values for on-road max fleet average durability hours [2] as this is judged to most closely represent the durability of fuel cell vehicles in the field. The durability-adjusted FCS cost equation is shown below where C_{stack} is the status stack cost (for a given year) and C_{BOP} is the status balance of plant (BOP) cost, all costs in $/kW$_{net}$. Stack cost is multiplied by the DM to represent the cost of the original stack plus any replacement stacks needed to achieve 8,000 hours of total operation. BOP cost is multiplied by 130% to represent the cost of the original BOP components (100%) plus the cost (30%) of BOP components that may not currently last 8,000 hours.[1] The cost portion of the BOP to be replaced is based on the cost of (1) valves and hoses that contain rubber or nylon, (2) the membrane air humidifier[2] (if used) whose ionomer membrane is subject to degradation under relative humidity (RH) cycling, freeze/thaw cycles, and exposure to high temperatures, (3) coolant pumps, thermostat valves, and other miscellaneous components that may be similar to ICEV components that require periodic replacement, and (4) installation cost of the replacement components. Installation cost is approximated as a value equal to the BOP replacement component cost (i.e., a 50%/50% split between labor and materials).[3] This approach has the advantages of being simple to apply and appropriately reflects the general trends as lifetime and cost are varied. Future efforts are anticipated to improve the cost estimation methodology and accuracy.

$$\text{Durability-Adjusted FCS Cost} = DM * (C_{stack}) + (1.3) * (C_{BOP})$$

In 2020, DOE-funded analyses projected the durability-adjusted cost of FCSs (using the second approach) through both material improvements and system design and operation. Argonne National Laboratory modeled operating protocols that allow the stacks to produce their targeted power levels but under stack conditions that minimize degradation.[4] These operating protocols, which primarily limit high cell voltages by controlling the relative humidity and air flow rate through the stack, are projected to reduce electrode degradation from ECSA loss and extend stack operation. The operating temperatures and RH were selected to be benign toward membrane stability, but further work is recommended to verify this conclusion. Argonne projected light duty vehicle fuel cell power system lifetime can be extended to 8,000 hours when coupled with an increase in total Pt loading ($0.175 mgPt/cm^2$), stack oversizing,[5] and other features.[6] Consequently, the system cost for 2020 does not employ a stack replacement strategy as used in past years, but rather a stack operation and

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[1] Industry feedback suggests BOP components may achieve the full 8,000 hours; estimates will be updated in future years.

[2] Based on ANL modeling, the 2020 system does not include a humidifier. W. B. Johnson, "Materials and Modules for Low Cost, High Performance Fuel Cell Humidifiers," Final Report, DE-EE0000465, 2015.

[3] If a H_2 recirculation pump were used, an additional 30% of BOP cost would be included as a replacement BOP cost. All system cost results presented here do not include a H_2 recirculation pump. Air compressors are assumed to last the full 8,000 hour life of the vehicle.

[4] R. K. Ahluwalia, X. Wang, J-K Peng, V. Konduru, S. Arisetty, N. Ramaswamy, and S. Kumaraguru, "Achieving 5,000-h and 8,000-h Low-PGM Electrode Durability on Automotive Drive Cycles," Submitted for publication in Journal of Electrochemical Society, Dec. 2019.

[5] Stack oversizing refers to use of a physically larger stack so that power degradation only lowers system power to the acceptable level (i.e., only a 10% reduction below beginning of life rated power). 2020 stack oversizing is estimated to be 23% of total active area.

[6] A variety of features are postulated for the system to meet 8,000 hours without a stack replacement: voltage monitoring system, dummy cells at each end of the stack, and 10% system cost contingency to account for non-enumerated system changes for durability.

oversizing strategy to achieve 8,000 hours. This type of oversizing or end-of-life based analysis is similar to the battery electric vehicle cost analysis conducted by Argonne. An additional 30% of BOP replacement costs were also included for the 2020 system, as detailed in the previous paragraph.

The unadjusted cost (initial system purchase cost), durability hours, corresponding DM, and durability-adjusted cost for each year at 500k and 100k units per year manufacturing rate are listed in Table 1.

Year	Unadjusted Cost at 500k units/yr ($/kW)	Unadjusted Cost at 100k units/yr ($/kW)	Stack Durability (hrs)[7, 8]	Durability Multiplier	Durability-Adjusted Cost at 500k units/yr ($/kW)	Durability-Adjusted Cost at 100k units/yr ($/kW)	Strategy to Achieve 8,000 hours
2006*	140	165	**2000**	4.0	409	481	Stack Replacement
2007	118	138	2170	3.7	301	353	Stack Replacement
2008	84	104	2340	3.4	200	248	Stack Replacement
2009*	76	96	**2500**	3.2	163	207	Stack Replacement
2010	63	82	2730	2.9	134	175	Stack Replacement
2011	57	72	2960	2.7	113	142	Stack Replacement
2012	55	67	3190	2.5	101	122	Stack Replacement
2013	54	66	3420	2.3	98	119	Stack Replacement
2014	53	63	3650	2.2	90	107	Stack Replacement
2015	52	59	3880	2.1	87	99	Stack Replacement
2016*	53	60	**4100**	2.0	86	99	Stack Replacement
2017	44	49	4100	2.0	70	78	Stack Replacement
2018	45	50	4100	2.0	70	79	Stack Replacement
2019	45	50	4100	2.0	70	79	Stack Replacement
2020[9]	46	52	8000	NA	68	76	Stack Operation/Oversize

Table 1. Unadjusted and adjusted cost, stack durability in hours, and durability multiplier for each year. *Represents a year in which status hours were documented in the DOE 2016 Durability Record [2]. Years without an asterisk and prior to 2016 use extrapolation between recorded status years. In years 2017 to 2019, the status hours for 2016 are repeated due to limited data after 2016.

The durability-adjusted cost for each year at 100,000 units per year is shown in Figure 1. The DOE Ultimate Cost Target of $30/kW is logically assumed to meet the 8,000 hour DOE target lifetime. Error bars are shown for each projected system for the years in which cost uncertainty analysis was conducted. The uncertainty bars represent the middle-90% confidence band in durability-adjusted cost and were determined by combining the unadjusted-cost uncertainty with the durability multiplier uncertainty. Cost uncertainty was estimated using Monte Carlo analysis.[10] Durability uncertainty was

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[7] Note that the increase in values each year was not due to technological changes, but in fact more data allowing higher projections with a reasonable certainty.

[8] Hours of operation to reach 10% voltage degradation.

[9] As the 2020 system does not require a stack replacement, the durability adjusted cost equation does not apply to the 2020 system. Instead, as mentioned in the body of the document, the durability adjusted cost contains four main categories summing to $24/kW at 100k sys/yr: (1) cell voltage monitor and dummy cells, $2/kW, (2) durability adjusted operating conditions and oversizing, $6/kW, (3) 10% system cost contingency for durability, $6/kW, and (4) 30% BOP replacement, $10/kW. Note that $52/kW (at 100k sys/yr) includes adjustments from previous studies, such as an increase in ionomer cost.

[10] Monte Carlo analysis results for each year are reported in the corresponding year's DOE Cost Record. Each analysis stochastically varies approximately 17 fuel cell stack and system parameters to project the probability distribution of FCS cost.

estimated from the NFCTEC on-road stack durability data.[11] Note that the uncertainty in stack durability is largely due to sparseness of data and is the predominant cause of the large error bars from 2014 to 2019. In contrast, the 2020 projection is not based on the stack durability data as it uses stack oversizing to achieve full lifetime. Instead, the durability uncertainty is represented by a +/-20% variation in stack oversizing based on the anticipated uncertainty in the stack degradation rate. Overall, the 2020 total system error bars are narrower as they are predominantly determined by cost projection uncertainty, rather than stack oversizing uncertainty. Note that the current analysis focused on the primary mechanisms for performance loss—degradation of the cathode electrode due to Pt dissolution, leaching of transition metal, ECSA loss by Pt dissolution/migration/growth, and rearrangement of catalyst particles within the pores of the catalyst support. Other life-limiting degradation mechanisms responsible for carbon corrosion and membrane instability may also need to be considered in the future as more information becomes available.

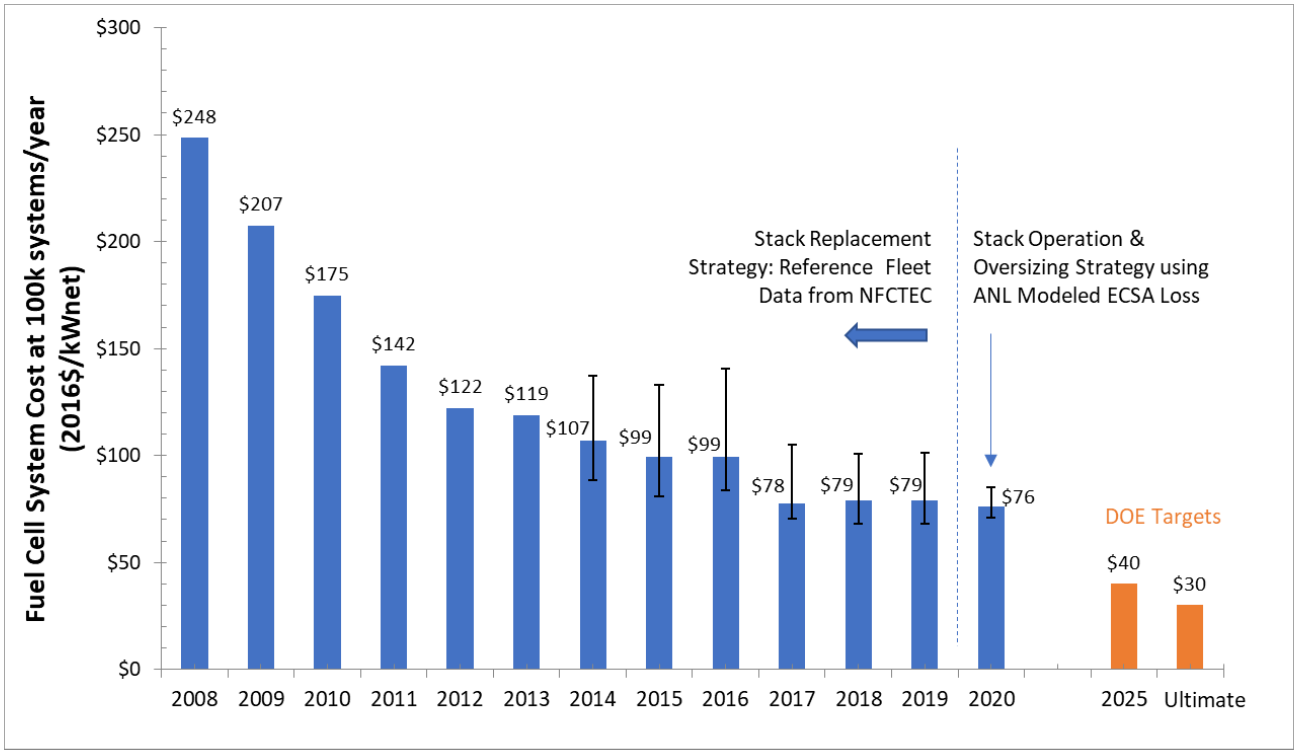

Figure 1. Durability-adjusted cost of an 80-kW$_{\text{net}}$ PEM fuel cell system based on projection to high-volume manufacturing at 100,000 units/year, reported in 2016$.

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[11] Stack durability for each year was varied by +/-30%. Reported NREL durability values varied considerably year to year. This durability uncertainty value is to be further investigated in the future.

Characteristic	**Units**	**2016**	**2017**	**2018**	**2019**[a]	**2020**
Net system power	kW_{net}	80	80	80	80	80
Gross stack power	kW_{gross}	87.7	87.9	88.4	88.4	88.8
Stack rated power efficiency	%	52	52	52	52	54
Cell voltage at rated power[b]	V	0.659	0.663	0.657	0.657	0.677
Air stoichiometric ratio[b]		1.4	1.5	1.5	1.5	1.5
Stack inlet pressure[b]	atm	2.5	2.5	2.5	2.5	2.5
Stack exit maximum coolant temperature[b]	°C	94	94	95	95	92
Total PGM[c] loading[b]	mg_{PGM}/cm^2	0.134	0.125	0.125	0.125	0.175
Total Pt usage over life	g	31	20	19	19	15
MEA areal power density	mW/cm^2	749	1,095	1,183	1,183	1,240[d]
Active area oversizing	%	0	0	0	0	23%
$Q/\Delta T$[e]	kW/°C	1.45	1.45	1.45	1.45	1.45
Unadjusted system cost (100k sys/yr)	$\$/kW_{net}$	60	49	50	50	52
Adjusted system cost (100k sys/yr)	$\$/kW_{net}$	99	78	79	79	76

[a] The LDV system cost model was not updated in 2019, therefore all characteristic values are the same as in 2018.

[b] Optimization parameter.

[c] PGM: platinum group metal.

[d] 2020 power density is a design point prior to accounting for oversizing the active area. Operational power density would be around 1,006 mW/cm^2.

[e] $Q/\Delta T$ 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)].

Table 2. System design parameters and system cost evaluated at rated power from 2016 to 2020.

While the fuel cell system costs (prior to durability adjustment) are based on a series of annual cost records [4], from 2007 to 2017, they require further adjustment to enable a fair comparison across the years. As described in the 2013 Cost Record #14012, cost values from 2012 and earlier were adjusted to account for higher platinum price, realigned compressor and expander efficiencies, and the $Q/\Delta T$ requirement introduced in 2013. Furthermore, all costs were adjusted to 2016$ (as they had been previously reported in nominal year dollars).

One point of note in the current method of durability-adjusted cost estimation is that the cost values for each year are for state-of-the-art fuel cell catalysts and systems that do not exactly match up with the on-road durability-tested FCEVs in that same year. For example, a FCEV on the road likely has an older technology catalyst and higher Pt loading than what is assumed for a state-of-the-art (lab tested) system in the same year. However, without long term, real-world durability data on current state-of-the-art fuel cell systems, the only available independently validated durability data based on real-world operation of FCEVs was used in this analysis.

References

[1] B. D. James, J. M. Huya-Kouadio, and C. Houchins, "Final Report: Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications 2020," Strategic Analysis Inc., Arlington, VA (United States), [**Preprint**] (January 2021).

[2] A. Wilson, J. Marcinkoski, and D. Papageorgopoulos, "On-Road Fuel Cell Stack Durability - 2016," U.S. DOE Fuel Cell Technologies Office, Record # 16019 (2016). https://www.hydrogen.energy.gov/pdfs/16019_fuel_cell_stack_durability_2016.pdf

[3] "Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan - Section 3.4 Fuel Cells." U.S. DOE Fuel Cell Technologies Office (2017). https://www.energy.gov/sites/prod/files/2017/05/f34/fcto_myrdd_fuel_cells.pdf

[4] "Fuel Cell System Cost," U.S. DOE Fuel Cell Technologies Office, Records # 8002, 8019, 9012, 10004, 10004, 11012, 12020, 14012, 15015, 16020, 17007 (2007–2017). https://www.hydrogen.energy.gov/program_records.html#fuel_cells