DOE Hydrogen and Fuel Cells Program Record	
Record #: 20005	**Date:** August 31, 2020
Title: Automotive Fuel Cell Targets and Status	
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Items:

To ensure the competitiveness of fuel cells for light-duty vehicle applications, the DOE ultimate targets have been updated for fuel cell system specific power, stack specific power, and stack power density, to 900 W_{net}/kg, 2,700 W_{gross}/kg, and 3,000 W_{gross}/L, respectively. The current specific power status for automotive fuel cell systems using state-of-the-art technology is estimated to be 860 W_{net}/kg, based on an industry-vetted fuel cell system model. The current status of several automotive fuel cell metrics has been updated based on assessment of the 2017 Toyota Mirai fuel cell vehicle, including a peak system efficiency of 64%, a stack specific power of 2,000 W_{gross}/kg, and a stack power density of 3,100 W_{gross}/L, with an estimated stack heat rejection metric of 2.4 kW/°C. While some individual targets have been met, the recorded status values were not all demonstrated simultaneously. Because there are tradeoffs between different fuel cell metrics, ultimately all fuel cell stack and system targets must be met simultaneously. DOE will continue to work with industry to update targets as needed.

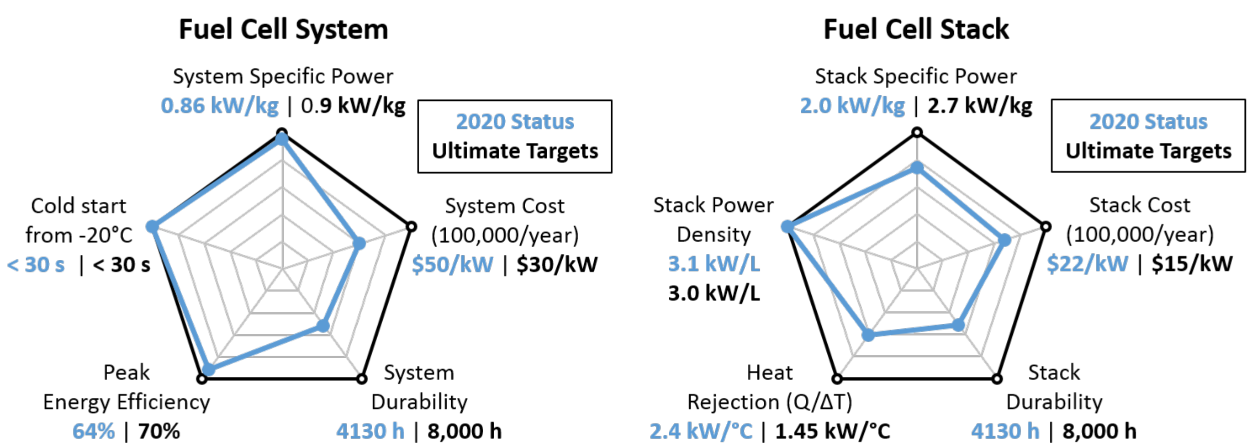

Figure 1: Diagrams illustrating current status of automotive fuel cell systems (left) and stacks (right) relative to ultimate subprogram targets in key areas.

Table 1: Transportation fuel cell system targets and status.

Technical Targets: 80-kW$_e$ (net) Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen [a]				
Characteristic	Units	Status	2025 Targets	Ultimate Targets
Peak energy efficiency[b]	%	64[c]	65	70
Power density	W / L	640[d]	650	850
Specific power	W / kg	860[e]	650	900
Cost[f]	\$ / kW$_{net}$	50[e]	40	30
Cold start-up time to 50% of rated power @–20°C ambient temperature @+20°C ambient temperature	 seconds seconds	 20[g] <10[g]	 30 5	 30 5
Unassisted start from low temperatures[h]	°C	–30[i]	–30	–30
Durability in automotive drive cycle[j]	hours	4,130[k]	5,000	8,000

[a] Target includes fuel cell stack, BOP, and thermal system. Target excludes hydrogen storage, battery, electric drive, and power electronics. Reported status values were not necessarily achieved by the same system. Further R&D is still needed to meet all targets simultaneously, including potentially in areas where the status exceeds current targets.

[b] Ratio of direct current (DC) output energy to the lower heating value (LHV) of the input fuel (hydrogen).

[c] "Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai," Argonne National Laboratory (2018), https://publications.anl.gov/anlpubs/2018/06/144774.pdf.

[d] J. Juriga, Hyundai Motor Group's Development of the Fuel Cell Electric Vehicle, May 10th, 2012, http://www.hydrogen.energy.gov/pdfs/htac_may2012_hyundai.pdf.

[e] Estimated specific power based on a 80 kW$_{net}$, 88 kW$_{gross}$ model fuel cell system derived from component masses. Brian D. James, Jennie M. Huya-Kouadio, Cassidy Houchins, Daniel A. DeSantis, "Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update," Strategic Analysis Inc., December 2018, https://www.energy.gov/sites/prod/files/2020/02/f71/fcto-sa-2018-transportation-fuel-cell-cost-analysis-2.pdf.

[f] Cost projected to high-volume production (100,000 systems per year).

[g] Based on average of status values reported at 2010 SAE World Congress (W. Sung, Y-I. Song, K-H Yu, T.W. Lim, SAE-2-10-01-1089). These systems do not necessarily meet other system-level targets.

[h] Eight-hour soak at stated temperature must not impact subsequent achievement of targets.

[i] Press Release: Honda Demonstrates the FCX Concept Vehicle, Sept. 25, 2006, http://world.honda.com/news/2006/4060925FCXConcept/; Associated Press, Toyota Develops a New Fuel Cell Hybrid, June 6, 2008, http://www.nbcnews.com/id/25004758/.

[j] Defined as time to 10% voltage degradation at rated power.

[k] Average projected time to 10% voltage degradation for the fleet with the highest durability, as reported in J. Kurtz et al., "Fuel Cell Electric Vehicle Evaluation," 2015 Annual Merit Review, http://www.hydrogen.energy.gov/pdfs/review15/tv001_kurtz_2015_o.pdf (slide 9). Testing reflects real-world driving, not a simulated drive cycle. Catalyst loading was not reported and did not necessarily match the target value of 0.125 mg_{PGM}/cm^2.

Table 2: Transportation fuel cell stack targets and status.

Technical Targets: 80-kW_e (net) Transportation Fuel Cell Stacks Operating on Direct Hydrogen[a]				
Characteristic	Units	Status	2025 Targets	Ultimate Targets
Stack power density[b]	W / L	3,100[c]	3,000	3,000
Stack specific power[m]	W / kg	2,000[n]	2,700	2,700
Heat Rejection ($Q/\Delta T_i$)[d]	kW / °C	2.4[e]	1.45	1.45
Cost[f]	$ / kW_{net}	22[g]	20	15
Durability in automotive drive cycle[h]	hours	4,100[i]	5,000	8,000

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[a] Excludes hydrogen storage, power electronics, electric drive, and fuel cell ancillaries: thermal, water, and air management systems. Reported status values were not necessarily achieved by the same stack. Further R&D is still needed to meet all targets simultaneously, including potentially in areas where the status exceeds current targets.

[b] Stack power refers to gross power. Volume is "box" volume, including dead space in the stack enclosure.

[c] Based on the Toyota Mirai fuel cell stack, which has a PGM loading of ~0.3 g/kW. N. Konno, S. Mizuno, H. Nakaji, and Y. Ishikawa, "Development of Compact and High-Performance Fuel Cell Stack," *SAE Int. J. Alt. Power* 4, no. 1 (2015), doi:10.4271/2015-01-1175.

[d] The heat rejection metric $Q/\Delta T_i$ indicates the amount of waste heat that must be removed from the fuel cell and should be below the target value. This metric is estimated with the formula: $Q/\Delta T_i$ = [stack power (90 kW) × (1.25 V – voltage at rated power)/(voltage at rated power)]/[(stack coolant out temp (°C) – ambient temp (40°C)]. Target assumes 90 kW stack gross power required for 80 kW net power.

[e] Based on a 90 kW stack gross power with voltage of 0.6 V and stack coolant outlet temperature of 80°C. The voltage and temperature assumptions are based on assessment of the Toyota Mirai stack, as reported in "Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai," Argonne National Laboratory (2018), https://publications.anl.gov/anlpubs/2018/06/144774.pdf.

[f] Guideline based on 2016 dollars, Pt cost of $1,500/troy ounce, and cost projected to high-volume production (100,000 fuel cell stacks per year).

[g] Brian D. James, Jennie M. Huya-Kouadio, Cassidy Houchins, Daniel A. DeSantis, "Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update," Strategic Analysis Inc., December 2018, https://www.energy.gov/sites/prod/files/2020/02/f71/fcto-sa-2018-transportation-fuel-cell-cost-analysis-2.pdf.

[h] Defined as time to 10% voltage degradation at rated power.

[i] Average projected time to 10% voltage degradation for the fleet with the highest durability, as reported in J. Kurtz et al., "Fuel Cell Electric Vehicle Evaluation," 2015 Annual Merit Review, http://www.hydrogen.energy.gov/pdfs/review15/tv001_kurtz_2015_o.pdf (slide 9).

Supporting information:

Fuel Cell System Specific Power and Power Density

The specific power of incumbent combustion engine technologies and other advanced alternative technologies is continually increasing.[1] To ensure the competitiveness of transportation fuel cells, and based on industry input, the DOE Hydrogen and Fuel Cell Technologies Office has increased the ultimate target for fuel cell system specific power from 650 W_{net}/kg to 900 W_{net}/kg.

Specific power and power density values for state-of-the-art transportation fuel cell systems are rarely reported, and available numbers commonly have inconsistent system definitions and assumptions. Strategic Analysis, Inc. (SA) and Argonne National Laboratory have developed a fuel cell system model using industry input through the U.S. DRIVE Fuel Cell Tech Team.[2] This system model, which has been used to benchmark fuel cell costs, can also be used to estimate the power density of fuel cell systems using state-of-the-art technology. In 2018, SA estimated the overall system specific power using the mass of the individual components, reporting 960 W_{gross}/kg for the 88.4 kW_{gross}, 80 kW_{net} fuel cell system, equivalent to 860 W_{net}/kg for the overall system specific power.[2] Due to limited publicly available information on automotive fuel cell system packaging, a similar model-based estimate of the system volumetric power density cannot be made accurately.

Fuel Cell System Efficiency

Argonne National Laboratory conducted an assessment of the commercially available 2017 Toyota Mirai fuel cell vehicle, including an evaluation of the energy efficiency of the fuel cell system.[3] The hydrogen fuel consumption and output power of the 114 kW_{gross} fuel cell system were measured during steady vehicle operation at different power levels.[4] This assessment determined that the peak efficiency of the fuel cell system was approximately 64% and occurred at a power output under 10 kW.

Fuel Cell Stack Specific Power, Power Density, and Heat Rejection

To ensure the competitiveness of automotive fuel cells, and based on industry input, the DOE Hydrogen and Fuel Cell Technologies Office has updated the ultimate targets for fuel cell stack specific power and power density to 2,700 W/kg and 3,000 W/L, respectively. The steady state

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[1] For example, see Curt Bennick, "The Trend Toward Higher Power Densities," OEM Off-Highway (2013). https://www.oemoffhighway.com/engines/article/11078357/the-trend-toward-higher-power-densities, accessed September 22, 2020.

[2] Brian D. James, Jennie M. Huya-Kouadio, Cassidy Houchins, Daniel A. DeSantis, "Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update," Strategic Analysis Inc., December 2018, https://www.energy.gov/sites/prod/files/2020/02/f71/fcto-sa-2018-transportation-fuel-cell-cost-analysis-2.pdf.

[3] Henning Lohse-Busch, Michael Duoba, Kevin Stutenberg, Simeon Iliev, Mike Kern, Brad Richards, Martha Christenson, Aaron Loiselle-Lapointe, "Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai," Argonne National Laboratory (2018), https://publications.anl.gov/anlpubs/2018/06/144774.pdf.

[4] For assessing the efficiency, the fuel cell system was defined to include the fuel cell stack and supporting balance of plant components, including the air compressor, coolant water pumps, hydrogen pumps, and the fuel cell boost converter.

power output of transportation fuel cell stacks is limited by heat rejection constraints, as vehicle packaging limits the capacity of the radiator and thermal management system to remove waste heat, especially at elevated ambient temperature.[5] Ideally, stack power output and heat rejection should be reported together for assessment of the technology status, although this has not been common practice and information on stack heat rejection is rarely publicly available.

Sufficient information has been collected through assessment of the Toyota Mirai[3] to align the reported power density and specific power with a corresponding heat rejection estimate. The Toyota Mirai fuel cell stack is reported to have a gross power of 114 kW, with a volume of 37 L and mass of 56 kg, corresponding to a (gross) power density of 3,100 W/L and specific power of 2,000 W/kg.[6] The assessment of the Toyota Mirai fuel cell system conducted by Argonne National Laboratory indicated that the fuel cell stack reached a cell voltage of approximately 0.6 V and a coolant outlet temperature of 80°C at rated power conditions.[3] For benchmarking purposes, it is preferable to calculate the stack heat rejection (Q/ΔT) using a standardized formula[7] depending only on the cell voltage and coolant outlet temperature at rated power conditions (at a standardized power thereby eliminating dependence on the system size). This approach leads to an estimated heat rejection of 2.4 kW/°C based on the rated power conditions of the Toyota Mirai fuel cell stack, a gross power of 90 kW, and 40°C ambient temperature. While the power density and specific power of the Toyota Mirai stack individually meet the 2025 targets of 2,250 W/L and 2,000 W/kg, they do not concurrently meet the heat rejection target of less than 1.45 kW/°C.

The status values reported here for automotive fuel cell cost, performance, and durability were not concurrently demonstrated on the same system, and some values, such as cost, are projected based on system models assuming state-of-the-art technology rather than demonstrated in on-road vehicles. Additional research and development effort is required to concurrently meet all targets for fuel cell stacks and systems.

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[5] Rajesh K. Ahluwalia, Xiaohua Wang, Andrew J. Steinbach, "Performance of Advanced Automotive Fuel Cell Systems with Heat Rejection Constraint," *Journal of Power Sources* 309 (2016): 178–191. https://dx.doi.org/10.1016/j.jpowsour.2016.01.060.

[6] N. Konno, S. Mizuno, H. Nakaji, and Y. Ishikawa, "Development of Compact and High-Performance Fuel Cell Stack," *SAE Int. J. Alt. Power* 4, no. 1 (2015). https://dx.doi.org/10.4271/2015-01-1175.

[7] $Q/\Delta T_i$ = [stack power (90 kW) × (1.25 V – voltage at rated power)/(voltage at rated power)]/[(stack coolant out temp (°C) – ambient temp (40°C)]. Target assumes 90 kW stack gross power required for 80 kW net power.