DOE Hydrogen Program Record

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Title: Heavy-Duty Fuel Cell System Cost – 2023
Originator: Gregory Kleen and William Gibbons (DOE)
Peer Reviewed by:
Brian James (SA, Inc.), Jennie Huya-Kouadio (SA, Inc.), Cassidy Houchins (SA, Inc.), Rajesh Ahluwalia (ANL), Xiaohua Wang (ANL), Michael Ulsh (NREL), Craig Gittleman (GM), Anusorn Kongkanand (GM), Manish Sinha (GM), Md Azimur Rahman (GM), Mike Veenstra (Ford), Christian Appel (Nikola), Vivek Murthi (Nikola), Jeffrey Murawa (Daimler Truck), Darek Villeneuve (Daimler Truck), Jean St. Pierre (Accelera), Kyle Richardson (Accelera), and Gary Robb (Ionomr Innovations)
Approved by: Dimitrios Papageorgopoulos and Sunita Satyapal (DOE)
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Item:

The cost of a 275-kW$_{net}$ proton exchange membrane (PEM) fuel cell system for a Class 8 long-haul heavy-duty (HD) truck based on 2023-status next-generation laboratory technology[1] and operating on direct hydrogen is projected to be approximately \$170/kW$_{net}$ when manufactured at a volume of 50,000 units/year (~\$160/kW$_{net}$ when manufactured at a volume of 100,000 units/year). These costs include design aspects for enhanced durability projected to achieve one million miles (25,000 hours) of fuel cell system performance needed for long-haul trucks.[2] Durability assumptions include stack oversizing (allowing for fuel cell degradation), high Pt loading (0.45 mg Pt/cm^2 total), monometallic Pt cathode catalyst, 20-micron thick membrane, and balance-of plant (BOP) replacement costs.

Rationale:

The U.S. Department of Energy (DOE) Hydrogen and Fuel Cell Technologies Office (HFTO) within the office of Energy Efficiency and Renewable Energy (EERE) supports projects that conduct detailed analyses to estimate cost status of fuel cell systems on an annual basis. Strategic Analysis, Inc. (SA) conducted a cost analysis of a 275-kW$_{net}$ direct hydrogen PEM HD fuel cell system based on 2023 technology and manufacturing volume of up to 100,000 units per year. All costs reported in this record are in 2016 dollars unless otherwise noted to track the cost impact of technological improvements rather than the effects of inflation or volatility in material pricing. If reported in 2020 dollars, the projected total system cost would increase by ~\$4/kW if Pt is kept

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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 HFTO at the laboratory scale. Additional efforts would be needed for integration of components into a complete commercial vehicle system that meets durability requirements in real-world conditions.
[2] Marcinkoski, J., "Hydrogen Class 8 Long Haul Truck Targets", DOE Hydrogen Program Record# 19006, 2019. https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf

constant at its assumed value of $1,500 per troy ounce in nominal year dollars. The key contributors to cost reduction between 2022 and 2023 analysis are (1) an increase in power density from 606 to 642 mW/cm^2 due to lowering of the voltage clipping limit which reduces both degradation and the required stack active area oversizing, and (2) a reduction in the projected BOP replacement cost (from 40% to 35%) based on an improved BOP component lifetime evaluation.

SA and Argonne National Laboratory (ANL) worked together to establish a representative system design and realistic stack operating conditions, based on industry input, that was used as the basis of the HD Class 8 truck system. Power system cost projections are based on end of life (EOL) stack performance. EOL occurs when the system performance drops below the intended commercial application's requirements, although the power system could still be used for less demanding applications. Durability aspects have been reviewed by experts[3] and include the following:

- 53 m^2 of active area (total of two stacks) inclusive of 67% oversizing to account for MEA performance losses after 25,000 hours and targeted to achieve 275 kW_{net} at EOL
- Million Mile Fuel Cell Truck consortium (M2FCT) baseline catalyst: annealed Pt on high surface area carbon (a-Pt/HSC) cathode catalyst for enhanced durability compared to alloy catalysts[4]
- High Platinum Group Metal (PGM) loading (0.40 mg Pt/cm^2 on cathode, 0.05 mg Pt/cm^2 on anode) for enhanced durability[4]
- 20-micron thick ePTFE-supported perfluorosulfonic acid (PFSA) membrane for enhanced durability and reduced crossover[5]
- The fuel cell system is envisioned to operate in a Fuel Cell-Battery hybrid powertrain. Wherein the battery is sized to provide 75 kWh useable energy at EOL (70% depth of discharge, 10% power degradation over lifetime) and 140 kW_{net} of continuous power. Gradual improvements in battery technology are expected to facilitate enhanced fuel cell stack durability by enabling extended stack operation at conditions which minimize electrochemical surface area (ECSA) loss.
- A replacement cost (equal to 35% of balance of plant (BOP) component cost) for some fuel cell-specific components to achieve 25,000 hours of BOP system lifetime
- 10% cost contingency for supply chain uncertainties

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[3] System design based on input from the Million Mile Fuel Cell Truck consortium, the 21st Century Truck Partnership, and the U.S. DRIVE Fuel Cell Technical Team.

[4] R. Borup, A. Weber, et al, "M2FCT: Million Mile Fuel Cell Truck Consortium," presented at the U.S. DOE Hydrogen and Fuel Cells Program 2023 Annual Merit Review and Peer Evaluation Meeting, Arlington, Virginia, Jun. 2023. Accessed: February 29, 2024. [Online]. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/fc339_weber_2023_o-pdf.pdf

[5] Feedback from the fuel cell community is that membrane thickness in current commercial use is less than 20-microns, and thinner membranes should be considered for future analyses.

To address durability and to design a system that meets the 25,000-hour power system lifetime requirement, a stack oversizing method was used rather than a stack replacement method.[6] ANL determined the beginning of life (BOL) and EOL operating conditions for estimated degradation based on the extent of ECSA loss after 25,000 hours over a Class 8 long-haul highway drive cycle. The system is sized to ensure 275 kW_{net} at EOL. Importantly, the modeled ECSA loss only affects the extent of stack oversizing and does not impact the other durability aspects built into the system cost. In the case of a greater degradation rate, the EOL power density decreases, and the system cost increases due to the required larger active area of the stack.

HD operating conditions for 2022, 2023, and 2025 systems[3] are listed in Table 1. Note that detailed definition of the HD vehicle (HDV) system is a more recent effort compared to the more extensively studied light-duty vehicle (LDV) system. Consequently, these HDV models are still evolving to fully capture real-world approaches and system designs. Key differences between the 2022 and 2023 systems are 1) reducing the upper potential limit from 0.835 to 0.820V increases the drive cycle power density (606 to 642 mW/cm^2 at EOL) and enables a reduction in total active area from 56 to 53 m^2 that contributed the most to cost reduction, 2) a reduction in the BOP replacement cost from 40% to 35%,[7] and 3) a reduction in radiator fan power from 28 kW to 26 kW[8] based on an increased radiator area from 1.08 m^2 to1.6 m^2.

ANL estimated that the 2023 HDV system could achieve 275 kW_{net} operating at 0.7 V/cell at EOL and would lose 50% of the ECSA over 25,000 hours of run time. ANL projects a 2023 BOL peak system efficiency of 64.5% compared to the DOE target of 68% in 2030.[9] The rate of ECSA loss over a long-haul truck drive cycle has not yet been verified by lab testing of the stack or validated through on-road testing. To account for uncertainty in durability, a 10% system cost contingency is added to the HD baseline cost to account for any non-enumerated costs associated with durability.

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[6] Feedback from the fuel cell community suggests that stack oversizing is a common method to extend the life of the fuel cell. Stack oversizing is a method to offset stack performance degradation by increasing stack active area above that necessary at beginning of life to achieve a targeted power production at end of life. In contrast, a replacement strategy would not oversize the stack (or at least not a full oversizing) but rather would replace the stack when power production fell to a threshold value.

[7] In 2022, two replacements of all FCS-specific replacement components were accounted for in the 40% of BOP replacement cost. In 2023, SA responded to feedback from industry that there should only be a single replacement in the near term and SA should consider a single replacement for the most expensive component ($820 for H_2 recirculation blower): implementing these suggested changes reduced the BOP replacement cost from 40% to 35% of BOP cost. Future work is planned to investigate the cost impact to the baseline and replacement costs for more durable components able to last >12k hours in the near term and 25k hours in the future.

[8] This difference in radiator fan power is a net change inclusive of the impacts of increasing the ambient temp from 27 to 40°C, which increases radiator fan power, and increasing the radiator area, which reduces the required radiator fan power.

[9] During operation, the vehicle will spend most of the time between peak system efficiency (which occurs at ~25% rated power) and the rated power efficiency (which occurs at full rated power). 68% stack efficiency remains the long-term DOE target to promote technological advancement towards more efficient FC stacks. Current technology requires a tradeoff between durability and efficiency, with higher stack voltages (efficiency) coming at the expense of catalyst durability. Present fuel cell systems emphasize durability over maximum efficiency.

Table 1: System design parameters at BOL and EOL for 2022[10], 2023[11], and projected 2025 HD fuel cell systems

Characteristic (all values at rated power unless otherwise indicated)	Units	2022 BOL[a]	2022 EOL	2023 BOL[a]	2023 EOL	2025 BOL[a]	2025 EOL
Net system power	kW$_{net}$	313	275	318	275	310	275
Gross stack power	kW$_{gross}$	380	342	369	338	362	336
Nominal System efficiency at rated power conditions[b] (at steady state)	%	51	45	56	50	55	50
Cell voltage[c]	V	0.78	0.70	0.77	0.70	0.76	0.70
Air stoichiometric ratio[c]		1.5	1.5	1.5	1.5	1.5	1.5
Stack inlet pressure[c]	atm	2.5	2.5	2.5	2.5	2.5	2.5
Stack exit coolant temp[c]	°C	90	90	90	90	90	90
Total PGM loading[c,d]	mg$_{PGM}$/cm^2	0.45	0.45	0.45	0.45	0.40	0.40
MEA areal power density	mW/cm^2	674	606	707	642	810	750
ECSA Loss after 25,000 hours	%	--	57	--	50	--	38
Active Area Oversizing	%	103	103	67	67	43	43
Total Active Area	m^2	56.4	56.4	52.6	52.6	44.8	44.8
Number of stacks/system	#	2	2	2	2	2	2
$Q/\Delta T$[e]	kW/°C	3.7	4.3	4.8	5.5	4.9	5.5
Ambient temp. (for radiator sizing)	°C	27	27	40	40	40	40
Fuel cell system cost @ 50k/y (2022/2023 status or 2025 target)[f]	2016\$/ kW$_{net}$		179		168		140

[a] Although the BOL stacks could produce a higher power with no ECSA loss, actual operation would be limited to 275kW$_{net}$ as the BOP components are sized for EOL gross power.

[b] The steady state efficiency at 275kW (rated power). Note that stack conditions in the table correspond to the conditions used to size the system for peak power and differ from conditions experienced during nominal system operation for 2023 and 2025. Additionally, the 2025 system efficiency declines slightly compared to 2023 due to an assumed lower degradation rate and the resulting lower stack oversizing.

[c] Optimization parameter.

[d] Modeling based on experimental test data for 0.3 mg Pt/cm^2 total Pt loading.

[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 (°C)].

[f] See Figure 2 for additional system cost, status, and target information

HDV fuel cell systems, originally based on upscaled LDV components, are trending toward HD-specific designs. Stakeholder feedback indicates manufacturers are moving toward larger size cells (currently in the range of 500-600 cm^2 and in the future up to 700-800 cm^2/cell). To limit the number of cells per stack ($\leq$500 cells/stack for structural reasons), keep the active area per cell a reasonable size (considering the amount of membrane area per stack), and enable flexibility in operation, SA chose to have 2 stacks[12] electrically connected in series. Stacks are arranged with gas and coolant connections manifolded in parallel and contain stack shut-off

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[10] Assumptions and results for the 2022 system are documented in SA's 2022 Final Report: "Mass Production Cost Estimation of Direct H$_2$ PEM Fuel Cell Systems for Transportation Applications: 2022 Update on Heavy and Light-Duty Vehicles," Brian D. James, Jennie M. Huya-Kouadio, Cassidy Houchins, and Kevin R. McNamara, Strategic Analysis, Inc., September 2022.

[11] Assumptions and results for the 2023 and 2025 systems are documented in SA's 2023 Final Report: "Mass Production Cost Estimation of Direct H$_2$ PEM Fuel Cell Systems for Transportation Applications: 2023 Update on Heavy and Medium-Duty Vehicles," Brian D. James, Jennie M. Huya-Kouadio, Cassidy Houchins, Mark J. Jensen, and Kevin R. McNamara, Strategic Analysis, Inc., September 2023.

[12] In 2022, SA received feedback from multiple companies that the number of stacks should be limited to 2 stacks per HDV system.

valves to enable stack isolation, as seen in the system diagram in Figure 1. The air system includes a centrifugal air compressor with expander (without motor air-bleed recycle), an air precooler, and membrane humidifiers (one for each stack for 2023 and a single humidifier for 2025). The hydrogen loop contains a combination of hydrogen blower (for recirculation) and injector (for flow control) to achieve superior control compared to an injector/ejector design.

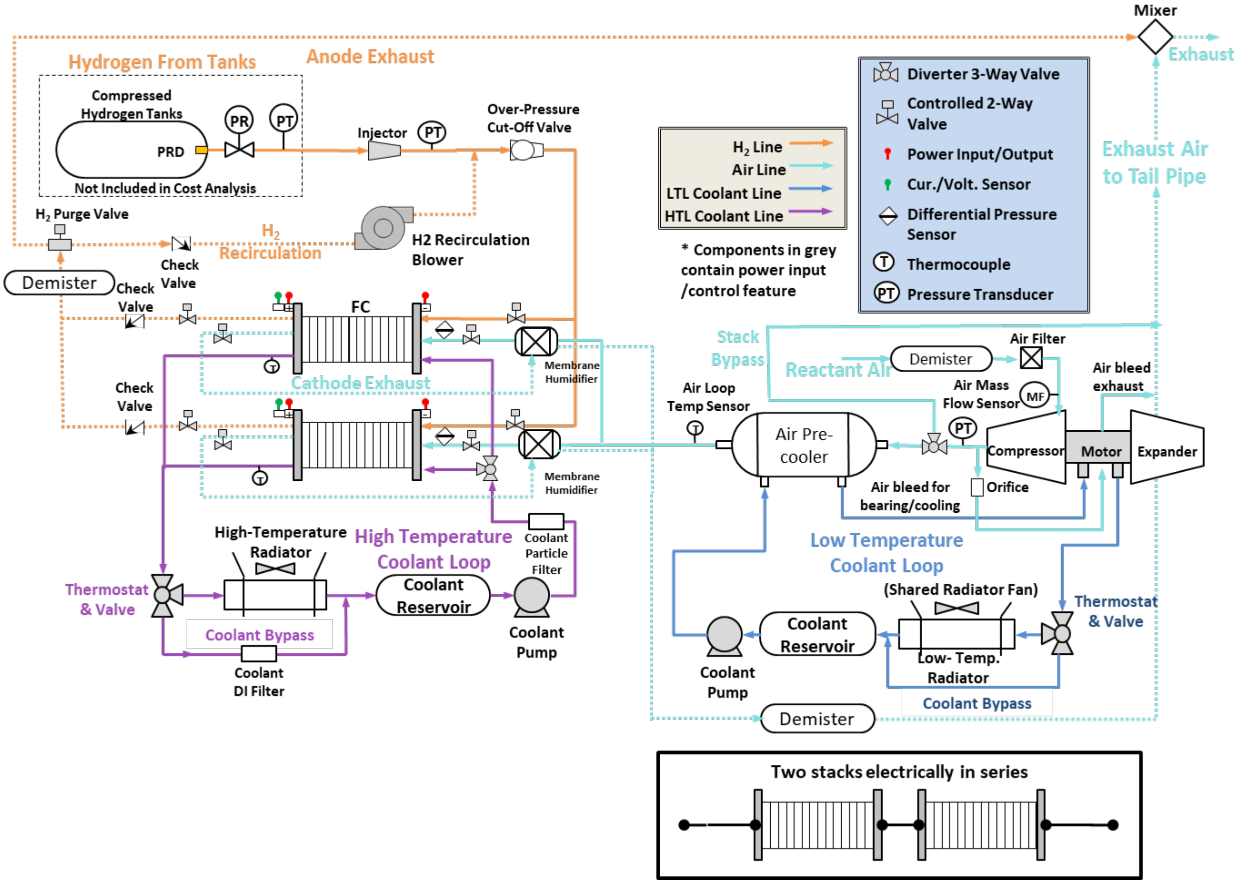

Figure 1. 2023 Class 8 long-haul truck fuel cell system diagram[13]

Cost Results:

The cost of the HD fuel cell system described and depicted above in Figure 1 was modeled at a rate of 50,000 systems per year to provide the current 2023 cost status. The interim target in 2025 is also at 50,000 systems per year while the 2030 and ultimate targets are presented at an increased manufacturing volume of 100,000 systems per year. The 2022 status[10], current 2023 status[11], and interim target in 2025, as well as the future 2030 and ultimate targets are presented in Figure 2. The 2023 status of $168/kW at 50,000 systems per year is 6% less than the 2022 status of $179/kW at the same production rate. Notably, many medium-duty (MD) and HD fuel cell stack developers are producing modular stack systems that would allow multiple vehicular applications to share a common platform design (e.g., stack and BOP) leading to greater economies of scale. 2023 MD and HD diesel truck sales in the US are 240,525 trucks/year and

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[13] The modeled fuel cell system does not currently include a DC/DC converter. Although power electronics can impact the truck powertrain cost, this analysis focuses only on the FC system.

266,752 trucks/year, respectively.[14] Consequently, future high-volume production from a single fuel cell manufacturer of 50,000 to 100,000 per year is reasonable, particularly if a high degree of stack commonality is achieved that would additionally benefit other applications. The 2025 interim, 2030, and ultimate targets are $140/kW$_{net}$, $80/kW$_{net}$, and $60/kW$_{net}$ respectively. Future cost reductions are based on anticipated technology improvements and increased manufacturing volumes.

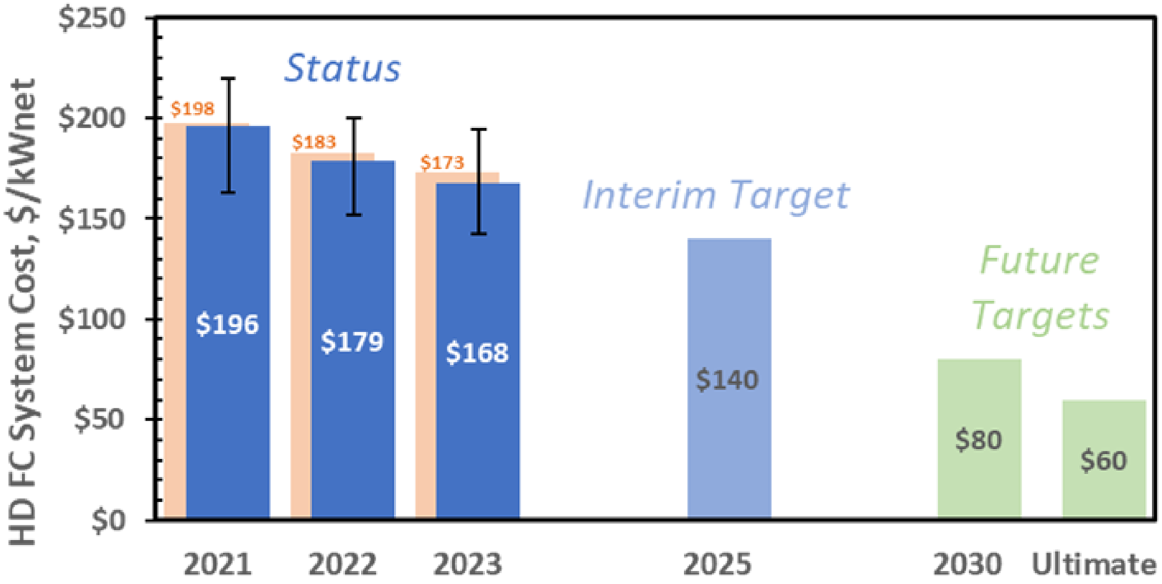

Figure 2: Modeled HD Fuel Cell System Cost Status (2021, 2022, 2023) in 2016$ (blue bars) and 2020$ (orange bars) compared to the Interim Target (2025) for a manufacturing volume of 50,000 systems per year. Future (2030, $80/kW), and ultimate ($60/kW) targets at 100,000 systems per year.[15]

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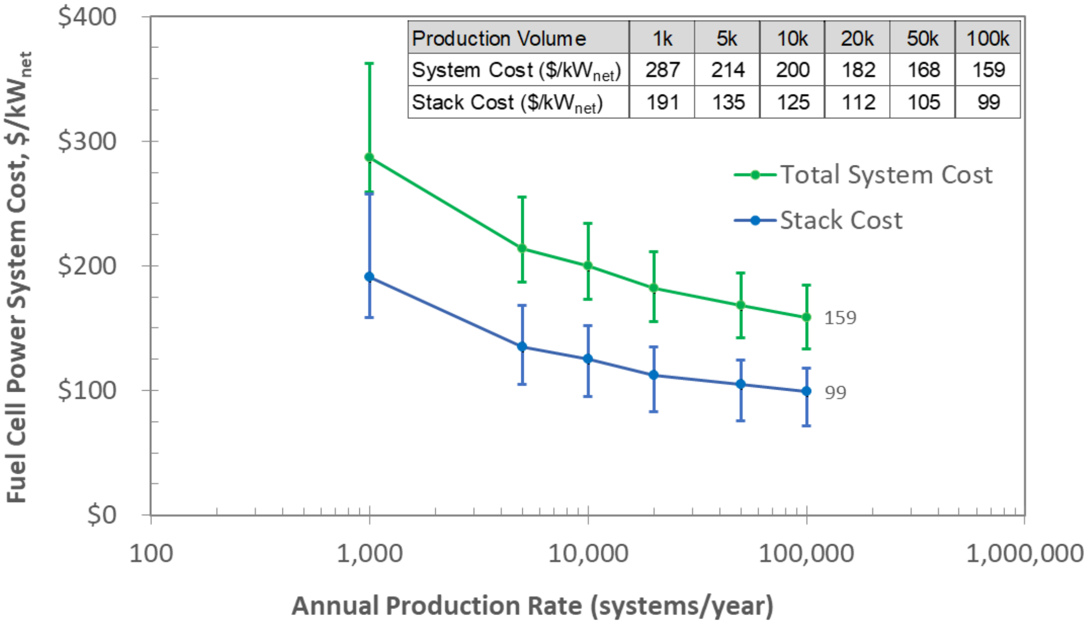
[14] 2023 US truck sales from American Truck Dealers (ATD) Truck Beat. (https://www.nada.org/atd/atd-insider/atd-truck-beat-2023-commercial-truck-sales-reach-half-million-first-time-2019)

[15] While the cost results, particularly the $/kW results, are presented to three significant figures, this should not be construed to indicate that level of accuracy in all cases. Rather, results are presented to a high level of monetary discretization to allow discernment of the direction and approximate magnitude of cost changes. Those minor impacts might otherwise be lost to the reader due to rounding and rigid adherence to rules for significant digits or might be misconstrued as an error or as having no impact.

To assess the impact of manufacturing volumes on overall system costs, the system cost is projected at manufacturing rates from 1,000 to 100,000 per year, as shown in Figure 3. The projected cost of the truck fuel cell system at a production rate of 50,000 units/year is \$168/kW_{net} using 2023 technology. Error/Uncertainty bars are added to the data points based on Monte Carlo analysis and represent the range of cost results containing the true cost with 90% confidence.



Production Volume	1k	5k	10k	20k	50k	100k
System Cost (\$/kW_{net})	287	214	200	182	168	159
Stack Cost (\$/kW_{net})	191	135	125	112	105	99

Figure 3. Modeled cost of a 275-kW_{net} PEM fuel cell system in 2016\$ based on projection to high-volume manufacturing (100,000 units per year) for 2023 technology years. Error bars represent the 90% confidence interval from a stochastic uncertainty analysis and reflect manufacturing uncertainty in the modeled system.

The system cost may be separated into component costs as shown in Figure 4 and Figure 5. Notably, the stack cost represents the majority, circa 63%, of the total 2023 HD fuel cell system cost. The large active area and high Pt loading (0.45 mg Pt/cm^2 total) result in the catalyst cost being more than half the stack cost at high production volume. The BOP cost is driven by the air loop, BOP replacement cost[16], and high temperature coolant loop; combined, they make up 70% of the BOP cost as seen in the pie chart in Figure 5. The percentage for each BOP component loop changes very little between low (1,000 systems per year) and high (100,000 systems per year) production volumes. Unlike the fuel cell stack, the BOP components are not oversized to meet the 25,000-hour vehicle lifetime. BOP component replacement costs are included in the estimates to track progress in both durability and performance of BOP components. While the BOP replacement currently assumes a mix of one and two replacements of components, evaluation of more robust components requiring no or only a single replacement is planned for future analysis.

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[16] BOP replacements over the 25,000 hours vehicle service life include air bearings for the air compressor (single replacement), the H_2 recirculation pump (single replacement), air humidifier (two replacements), and radiator fan (two replacements). Additionally, an installation labor cost is included in the BOP replacements cost and is estimated to be 100% of the replaced components cost.

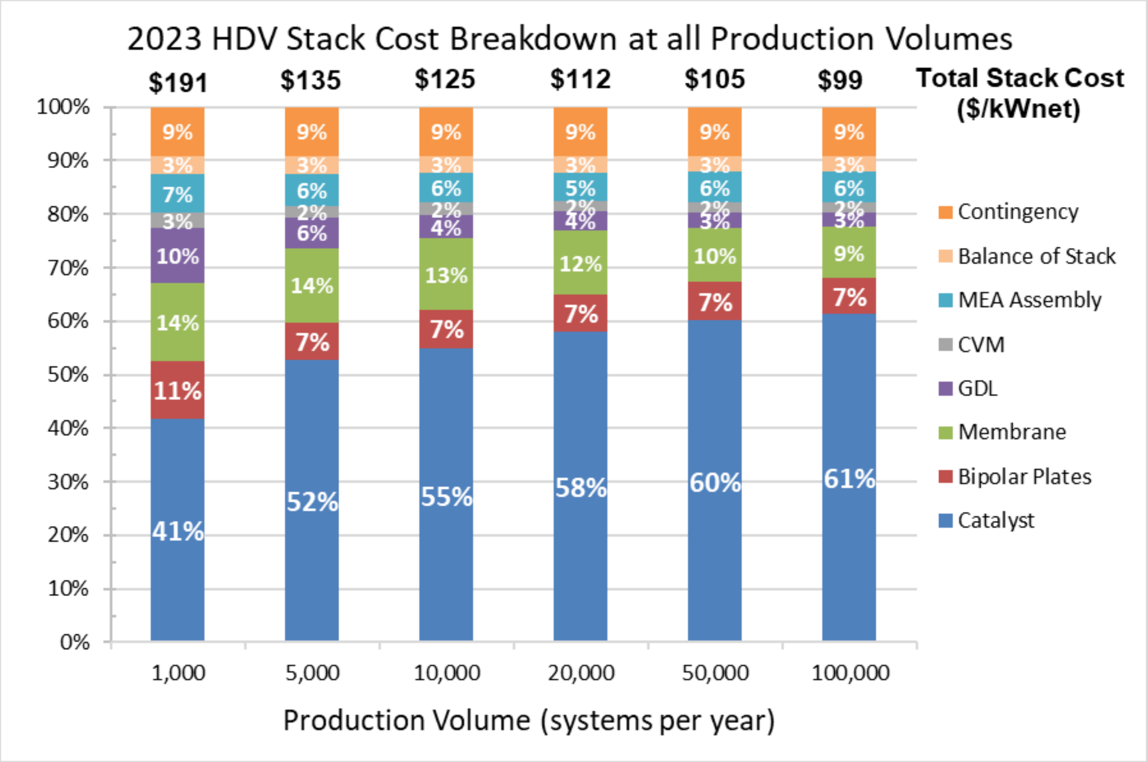

Figure 4. 2023 HDV stack component cost breakdown at all modeled production volumes (CVM: cell voltage monitor)

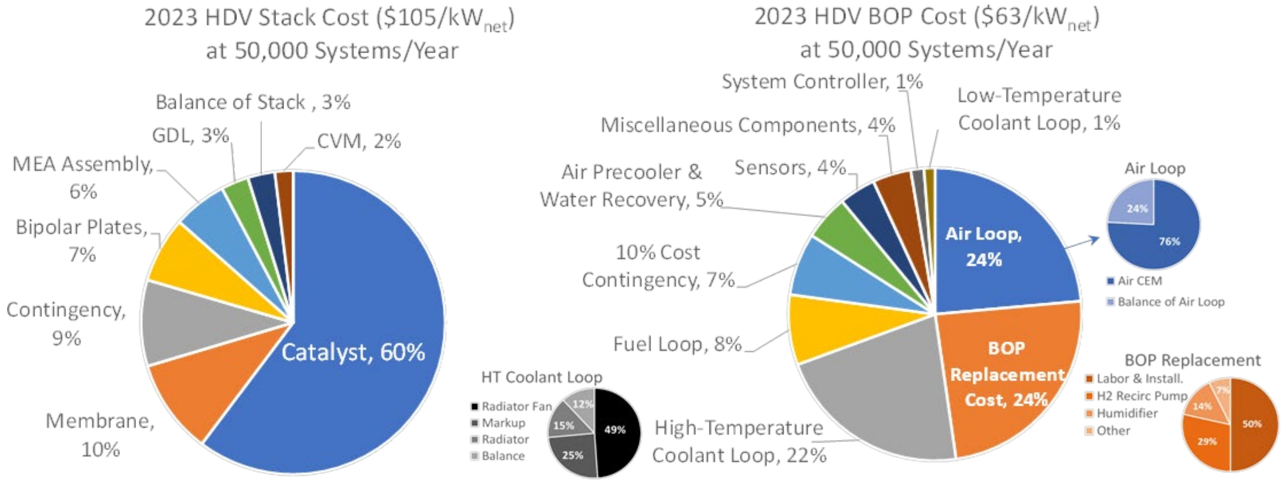

Figure 5. 2023 Cost breakdown for stack (left) and balance of plant (right) components at 50,000 systems per year

Sensitivity Analysis:

A single variable sensitivity analysis at 50,000 systems per year is shown in Figure 6 and indicates the system cost impact from a change in a single variable. The uncertainty parameters are summarized in Table 2.[17] Two new parameters were added for 2023, including the membrane humidifier cost and sub-gasket material cost. The multi-variable Monte Carlo sensitivity analysis estimates uncertainty in the total system cost due to multiple variables changing simultaneously. From the Monte Carlo results, the 2023 system cost at 50,000 units per year is projected to be between \$142/kW and \$195/kW (Figure 8) with 90% confidence. Uncertainty in power density reflects the range of possible test data for a-Pt/HSC cathode catalyst at 0.7V at EOL. The EOL power density influences the amount of oversizing of the active area, however, there is a separate active area oversizing uncertainty parameter incorporated within the Monte Carlo analysis to reflect uncertainty in the ECSA loss experienced over the stack lifetime.[18]

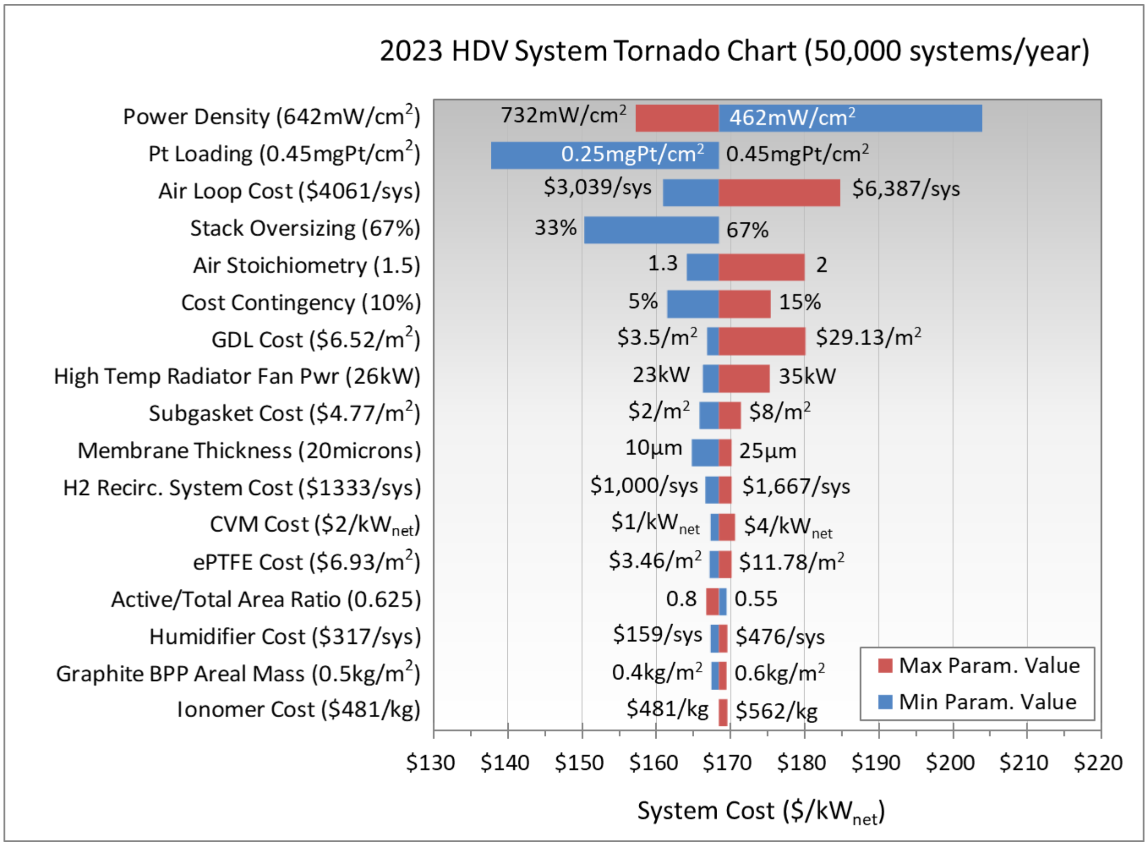

Figure 6. Tornado chart of single variable sensitivity analysis of HDV system cost at 50,000 systems per year.[19]

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[17] The range in parameter values for the single variable sensitivity analysis are the same as the multi-variable sensitivity analysis parameter values. The air loop cost in the Tornado chart includes the combined variations in the air compressor cost, compressor-expander-motor (CEM) efficiencies, and balance of air compressor cost variation.

[18] Oversizing percentage values are calculated: (active area to reach EOL conditions) / (active area for a system with 0% ECSA loss) - 1.

[19] Acronyms: gas diffusion layer (GDL), cell voltage monitor (CVM), expanded polytetrafluoroethylene (ePTFE), bipolar plate (BPP)

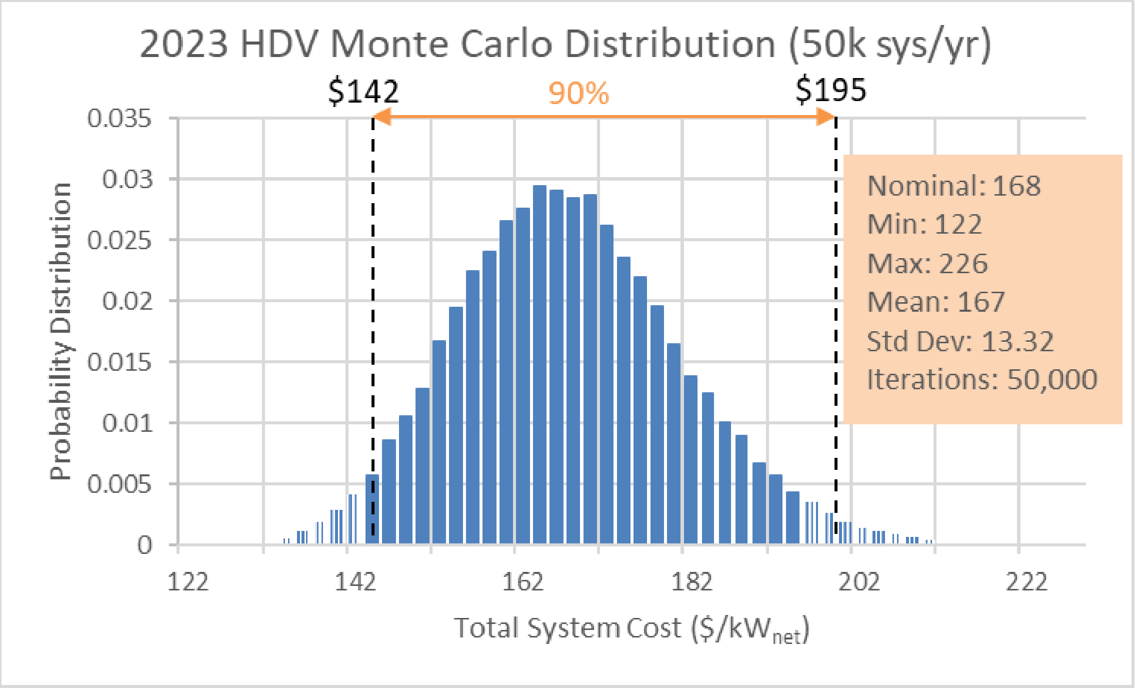

Figure 7. Monte Carlo analysis of system cost probability at 50,000 systems per year.

Table 2: 2023 HDV Technology Tornado and Monte Carlo Analysis at 50,000 systems per year

Parameter	Unit	Minimum Value	Likeliest Value[c]	Maximum Value	Bounds Rationale
			(50,000 systems/year value)		
Power Density [a, b]	**mW/cm^2**	462	**642**	732	-28%/+14% High end based on possible range in data for annealed Pt/HSC catalyst
Pt Loading [a]	**mg Pt/cm^2**	0.25	**0.45**	0.450	0.25mg Pt/cm^2 at low end based on amount needed for durability
Ionomer Cost[d]	**$/kg**	$481	**$481**	$563	Min Value: Same as Baseline Value Max Value: from extrapolation of quoted ionomer cost of $563/kg at 127 tons/year or 50,000 HDV systems/year
Gas Diffusion Layer (GDL) Cost	**$/m^2**	$3.00	**$6.52**	$25.00	Min Value: Lower bound of reported GDL Costs ($3/m^2) Max Value: $25/m^2 (estimated)[20]
Graphite Bipolar Plate (BPP) Areal Mass	**kg/m^2**	0.4	**0.5**	0.6	+/- 0.1 kg/m^2
Air Stoichiometry[a, b]		1.3	**1.5**	2	Min. Value = HD fuel cell system integrators recommendation Max. Value = Reasonable system operating condition
Compressor Efficiency [a, b]	**%**	65%	**72%**	75%	Using ANL's assumptions for range in compressor/expander/motor/controller efficiencies: Compressor Efficiency: 65% min (72% baseline) to 75% max Expander Efficiency: 71% min (75% baseline) to 80% max Motor Efficiency: 89.5% min (89.5% baseline) to 95% max Controller Efficiency: 89.5% min (95% baseline) to 95% max Combined Motor/Controller Efficiency: 80% min (84% baseline) to 90% max
Expander Efficiency [a, b]	**%**	71%	**75%**	80%	
Motor/Controller Efficiency [a, b]	**%**	80%	**84%**	90%	
Air Compressor Cost	**$/system**	$2,771	**$3,079**	$3,695	Min. Value = 90% of calculated cost Max. Value = 120% of calculated cost
Balance of Air Compressor Cost	**$/system**	$655	**$982**	$1,669	Min. Value = 66% of calculated cost Max. Value = 170% of calculated cost (170% = 1.5x base value with added 20% more for four $50 components possibly included: gas-capture filter, resonator, and shut-off valve)
Hydrogen Recirculation System Cost	**$/system**	$1,000	**$1,333**	$1,666	Min Value: 75% of calculated cost Max Value: 125% of calculated cost
Expanded polytetrafluoroethylene (ePTFE) Cost	**$/m^2**	$3.47	**$6.93**	$11.78	Range of industry quotes

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[20] Multiple OEMs suggested that current GDL cost may be higher than $16/m^2 at high volume.

Active to Total Area Ratio		0.55	**0.625**	0.8	Min Value = Based on discussions with vendors Max Value = Based on value used in previous years studies
Membrane Thickness	**µm**	10	**20**	25	Range based on feedback from HD fuel cell system integrators and OEMs
HTL Radiator Fan Power	**kW**	23	**26**	35	Min Value = 23 kW based on EMP fan power for Class 8 HD fuel cell truck Max Value= 35 kW based ANL range at 0.7 V
Stack Oversizing	**%**	50%	**67%**	67%	Min Value: 50% based on feedback of limit on active area of stack Max Value: No change from likeliest value
Cost Contingency	**%**	5%	**10%**	15%	+/- 50% on the computed likeliest value
CVM Cost	**$/kW**	$1.00	**$2.00**	$4.00	+100% on the computed likeliest value - 50% on the computed likeliest value
Humidifier Cost	**$/system**	$159	**$317**	$476	+/- 50% on the computed likeliest value
Sub-gasket Material Cost	**$/m^2**	$2.00	**$4.77**	$8.00	Min Value: $2/m^2 if use similar PET cost Max Value: $8/m^2 if up to 4x the cost of PET

[a] The Monte Carlo analysis treats each parameter as an independent variable with respect to power density. Thus, changes to operating conditions (such as catalyst loading, pressure, etc.) do not alter the power density for purposes of the Monte Carlo analysis.

[b] Variation of some parameters (such as air stoichiometry, compressor efficiency, etc.) may affect the system Q/ΔT value causing a change in the value of Q/ΔT within the Monte Carlo analysis.

[c] For all parameters, the "likeliest value" is set to the 2023 cost analysis baseline value for that parameter.

[d] Ionomer cost here is represented by both the ionomer in the catalyst ink and the ionomer in the membrane. The range in cost affects both the catalyst ink cost and the membrane material cost.

Fuel Cell System Improvement Opportunities:

With the increased focus on HDV fuel cell systems, there is still rapid learning occurring. Multiple pathways are being pursued to improve fuel cell stack and BOP components, along with alternative system architecture designs.

For the fuel cell stack, improvement opportunities include increasing the EOL power density, decreasing cathode catalyst loading, reducing membrane thickness, manufacturing improvements, and increasing stack operating temperature. Fuel cell stack advancements will result in smaller cells and fewer cells per stack. BOP cost reductions can be achieved by reducing the number of BOP components, such as using only a single cathode humidifier, and reducing and/or eliminating BOP replacements.

As commercial adoption accelerates, and the cumulative deployment of HDV fuel cell systems grows in the coming years, significant component and system level improvement opportunities are expected. Continued refinements and incorporation of improvements, including those listed above, are likely to shift the ultimate configuration of HDV systems. Future cost records will be updated to both track progress and reflect changes to the modeled HDV systems.