| DOE Hydrogen Program Record | |
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| **Record #:** 23002 | **Date:** 05/23/2023 |
| **Title:** Heavy-Duty Fuel Cell System Cost – 2022 | |
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| **Approved by:** Dimitrios Papageorgopoulos and Sunita Satyapal (DOE) | **Date:** 05/30/2023 |

## 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 next-generation laboratory technology[1] and operating on direct hydrogen is projected to be \$179/$kW_{net}$ when manufactured at a volume of 50,000 units/year (\$170/$kW_{net}$ 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 2022 technology and manufacturing volume of up to 100,000 units per year.

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

[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

demanding applications. Durability aspects have been reviewed by experts[3] and include the following:

- 56 $m^2$ of active area (total of two stacks) inclusive of oversizing to account for approximately 57% electrochemical surface area (ECSA) loss after 25,000 hours and targeted to achieve 275 $kW_{net}$ at EOL
- Million Mile Fuel Cell Tuck 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[5]
- 20-micron thick ePTFE-supported perfluorosulfonic acid (PFSA) membrane for enhanced durability
- The fuel cell system is envisioned to operate in a Fuel Cell-Battery hybrid powertrain. Although not included in the cost estimates, ANL models the battery to be 26 kWh usable (70% depth of discharge) and 112 kW continuous power.
- A replacement cost (equal to 40% 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 unaccounted durability adjustments.

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 2021, 2022, and 2025 systems 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

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

[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 2022 Annual Merit Review and Peer Evaluation Meeting, Washington D.C., Jun. 2022. [Online]. https://www.hydrogen.energy.gov/pdfs/review22/fc339_weber_borup_2022_o.pdf

[5] R. K. Ahluwalia and X. Wang, "Fuel Cell System Modeling and Analysis," presented at the U.S. DOE Hydrogen and Fuel Cells Program 2019 Annual Merit Review and Peer Evaluation Meeting, Washington D.C., Apr. 2019. Accessed: May 11, 2021. [Online]. https://www.hydrogen.energy.gov/pdfs/review19/fc017_ahluwalia_2019_o.pdf

[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.

2021 and 2022 systems are 1) an increase in power density (440 to 606 $mW/cm^2$ at EOL (reducing total active area from 78 to 56 $m^2$) that contributed the most to cost reduction, 2) a reduction in the number of stacks (from 4 to 2), and 3) an increase in total Pt loading (from 0.4 to 0.45 mg $Pt/cm^2$).

ANL estimated that both the 2022 and 2025 systems could achieve 275 $kW_{net}$ operating at 0.7 V/cell at EOL and would lose 57% of the ECSA over 25,000 hours of run time. 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.

***Table 1: System design parameters at BOL and EOL for 2021,[7] 2022, and 2025 HD fuel cell systems***

| Characteristic (all values at rated power unless otherwise indicated) | Units | 2021 BOL[a] | 2021 EOL | 2022 BOL[a] | 2022 EOL | 2025 BOL[a] | 2025 EOL |
|---|---|---|---|---|---|---|---|
| Net system power (rated power) | $kW_{net}$ | 314 | 275 | 313 | 275 | 313 | 275 |
| Gross stack power | $kW_{gross}$ | 374 | 345 | 380 | 342 | 377 | 338 |
| System efficiency | % | 51 | 45 | 51 | 45 | 52 | 45 |
| Cell voltage[b] | V | 0.753 | 0.7 | 0.778 | 0.7 | 0.778 | 0.7 |
| Air stoichiometric ratio[b] | | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| Stack inlet pressure[b] | atm | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| Stack exit coolant temp[b] | °C | 88 | 88 | 90 | 90 | 90 | 90 |
| Total PGM loading[b,c] | $mg_{PGM}/cm^2$ | 0.4 | 0.4 | 0.45 | 0.45 | 0.35 | 0.35 |
| MEA areal power density | $mW/cm^2$ | 476 | 440 | 674 | 606 | 808 | 726 |
| ECSA Loss after 25,000 hours | % | 60 | 60 | 57 | 57 | 57 | 57 |
| Active Area Oversizing | % | 67 | 67 | 103 | 103 | 103 | 103 |
| Total Active Area | $m^2$ | 78.5 | 78.5 | 56.4 | 56.4 | 46.6 | 46.6 |
| Number of stacks/system | # | 4 | 4 | 2 | 2 | 2 | 2 |
| $Q/\Delta T$[d] | kW/°C | 3.9 | 4.3 | 3.7 | 4.3 | 3.6 | 4.2 |
| Ambient temp. (for radiator sizing) | °C | 25 | 25 | 27 | 27 | 27 | 27 |

[a] Although the BOL stacks could produce a higher power with no ECSA loss, actual operation would be limited to 275$kW_{net}$ as the BOP components are sized for EOL gross power.
[b] Optimization parameter.
[c] Modeling based on experimental test data for 0.3 mg $Pt/cm^2$ total Pt loading.
[d] $Q/\Delta T$ 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)].

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[8] electrically connected in series. Stacks are

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[7] Assumptions and results for the 2021 system are documented in SA's 2021 Final Report: "Mass Production Cost Estimation of Direct $H_2$ PEM Fuel Cell Systems for Transportation Applications: 2021 Update on Medium and Heavy-Duty Vehicles," Brian D. James, Jennie M. Huya-Kouadio, Brian M. Murphy, Cassidy Houchins, Maria E. Gomez, and Kevin R. McNamara, Strategic Analysis, Inc., September 2022.
[8] In 2022, SA received feedback from multiple companies that the number of stacks should be limited to 2 stacks per HDV system.

arranged with gas and coolant connections manifolded in parallel and contain stack shut-off 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). 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.

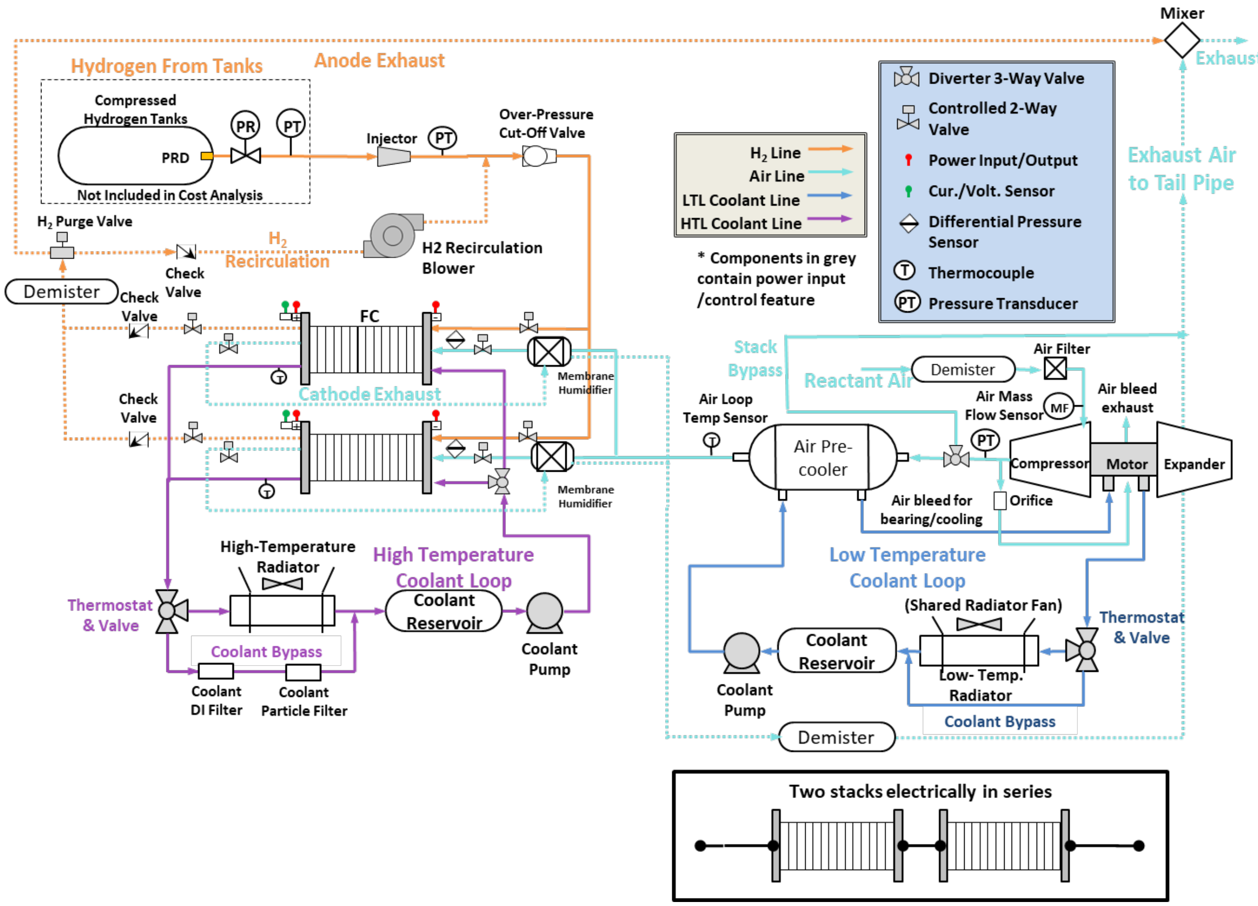


*Figure 1. 2022 and projected 2025 Class 8 long-haul truck fuel cell system diagram*[9]

## 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 2022 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 2021 status[10], current 2022 status, and interim target in 2025, as well as the future 2030 and ultimate targets are presented in Figure 2. The 2022 status of $179/kW at 50,000 systems per year is 8% less than the 2021 status of $196/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

[9] The modeled fuel cell system does not currently include a DC/DC converter.
[10] B. James, J. Huya-Kouadio, et al., Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2021 Update.

applications to share a common platform design (e.g., stack and BOP) leading to greater economies at scale. 2020 MD and HD diesel truck sales in the US are 167,000 trucks/year and 243,000 trucks/year, respectively.[11] 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. The 2025 interim target is $140/kW$_{net}$ with anticipated technology improvements, while the 2030 and ultimate targets are $80/kW$_{net}$ and $60/kW$_{net}$ respectively.

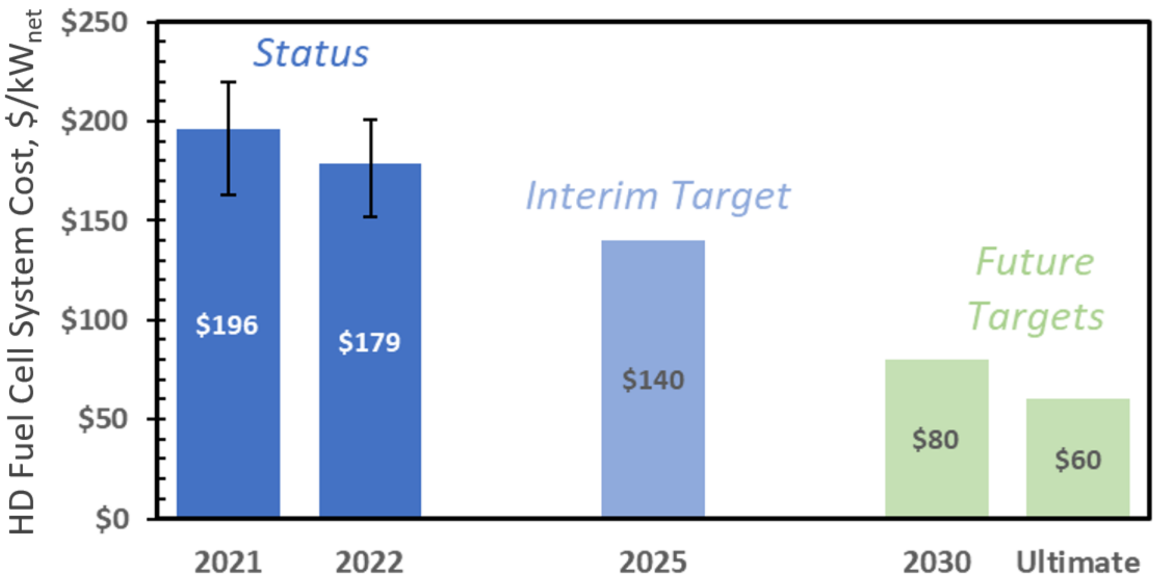


***Figure 2: Modeled HD Fuel Cell System Cost Status (2021, 2022) and Interim Target (2025) for a manufacturing volume of 50,000 systems per year. Future (2030, $80/kW), and ultimate ($60/kW) targets at 100,000 systems per year.[12]***

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 $179/kW$_{net}$ using 2022 projected 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.

[11] 2020 US truck sales where MD is the sum of Class 4-6 and HD is sum of Class 7 and 8. (https://www.statista.com/statistics/261416/class-3-8-truck-sales-in-the-united-states/)

[12] 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.

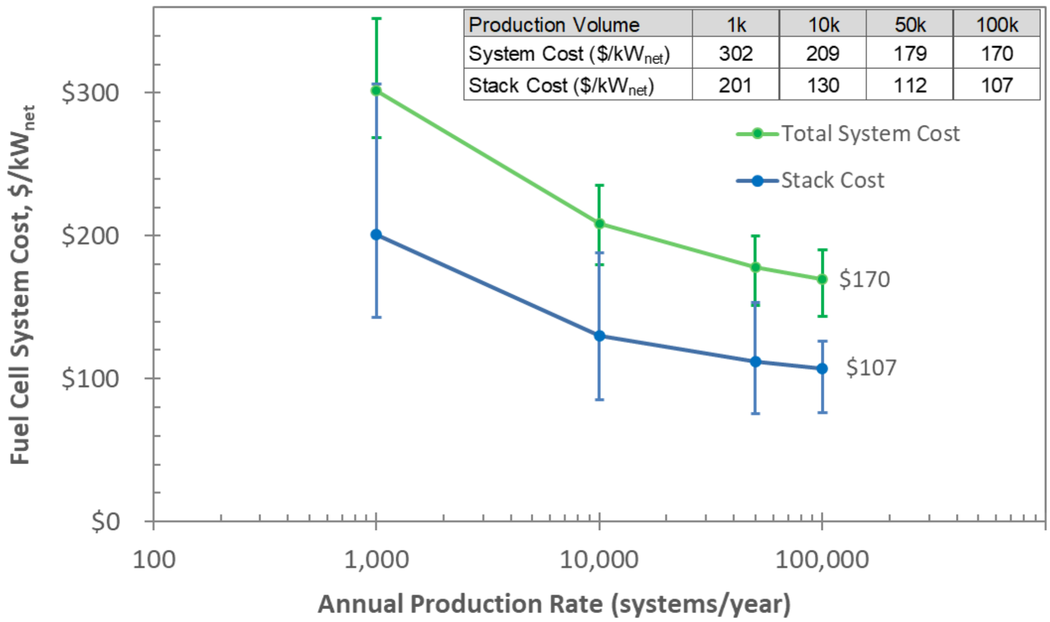


***Figure 3. Modeled cost of a 275-kW$_{net}$ PEM fuel cell system based on projection to high-volume manufacturing (100,000 units per year) for 2022 technology years.[13] Error bars represent the 90% confidence interval from a stochastic uncertainty analysis and reflect manufacturing uncertainty in 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 75%, of the total 2022 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 and BOP replacement cost[14]; combined, they make up half the BOP cost as seen in the pie chart in Figure 5. The percentage for each BOP component loop changes very little between low (200 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.

[13] To align with other reported costs for related projects (for example onboard hydrogen storage), values for the fuel cell system are reported here in 2016-year dollars.

[14] BOP replacements include two component replacements over 25,000 hours (air bearings for the air compressor, the $H_2$ recirculation pump, air humidifier, and radiator fan) and labor and installation (estimated to be 100% of the replaced components).

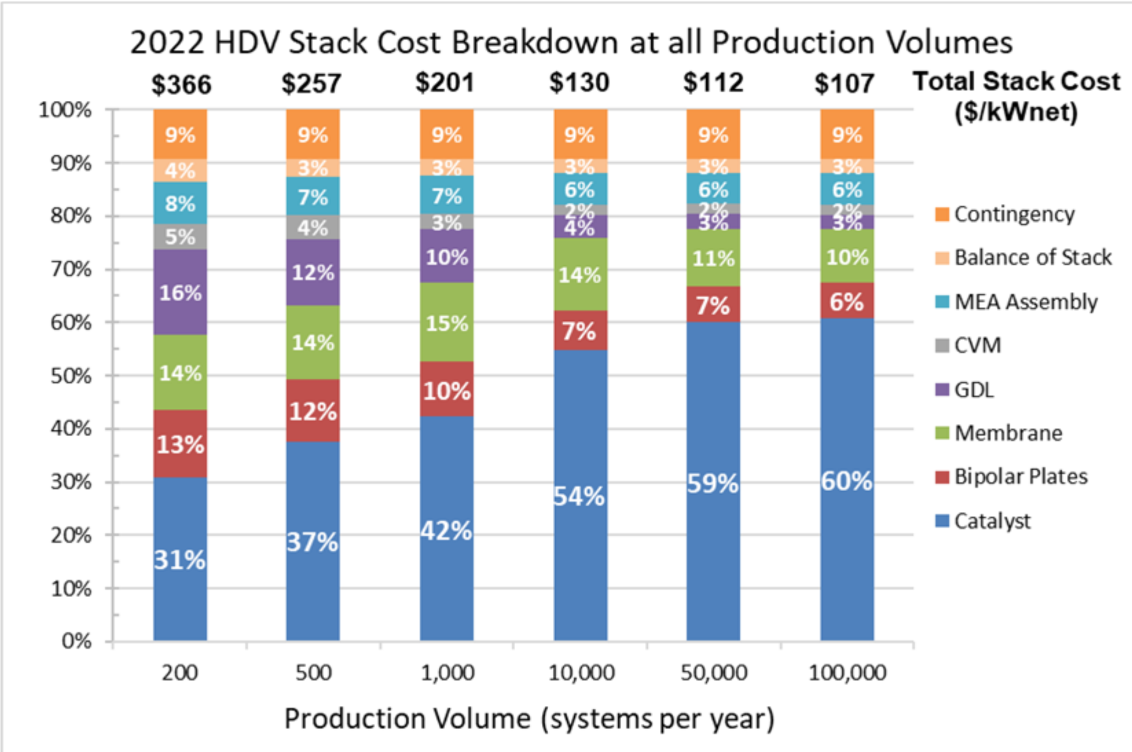


*Figure 4. 2022 HDV stack component cost breakdown at all modeled production volumes (CVM: cell voltage monitor)*

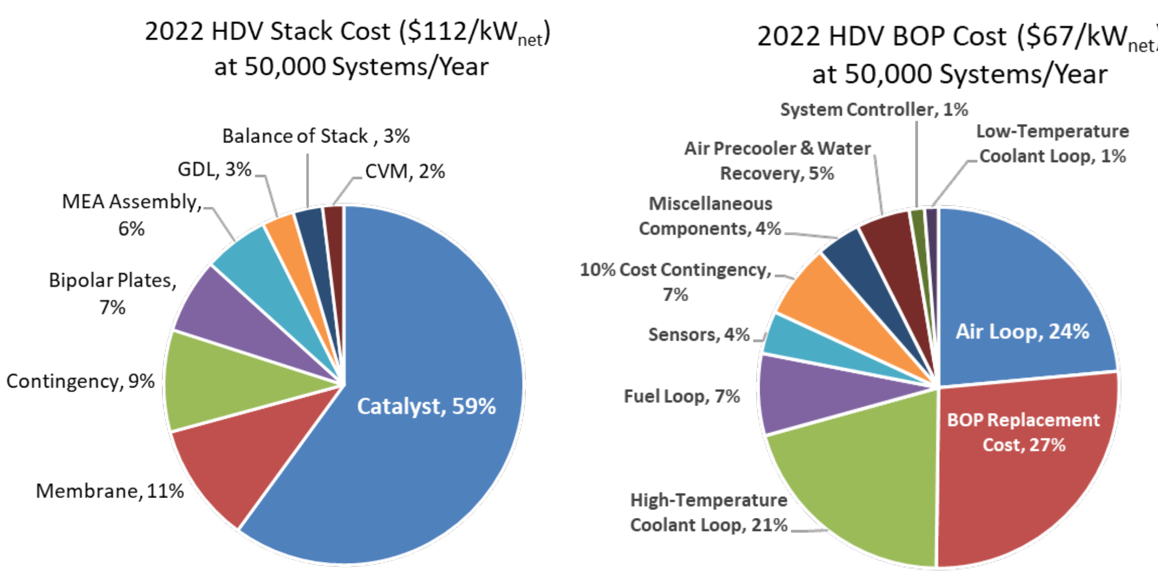


*Figure 5. 2022 Cost breakdown for stack (left) and balance of plant (right) components at 50,000 systems per year*

## **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.[15] 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 2022 system cost at 50,000 units per year is projected to be between \$151/kW and \$200/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.[16]

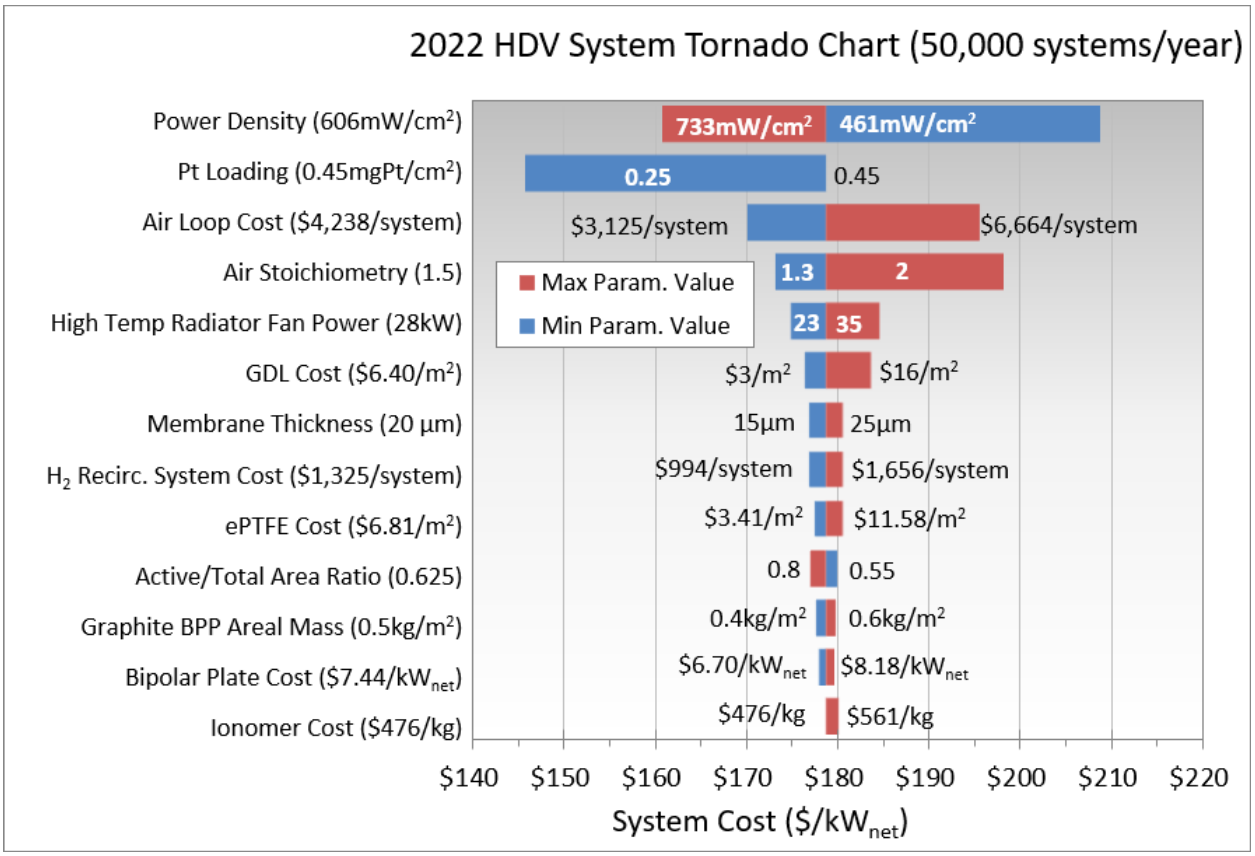


***Figure 6. Tornado chart of single variable sensitivity analysis of HDV system cost at 50,000 systems per year***

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[15] The range in parameter values for the single variable sensitivity analysis are the same as the multi-variable sensitivity analysis parameter values except for the bipolar plate (BPP) cost which only occurs in the single variable analysis. The air loop cost in the Tornado chart includes the same variations in the air compressor cost, compressor-expander-motor (CEM) efficiencies, and balance of air compressor cost variation.

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

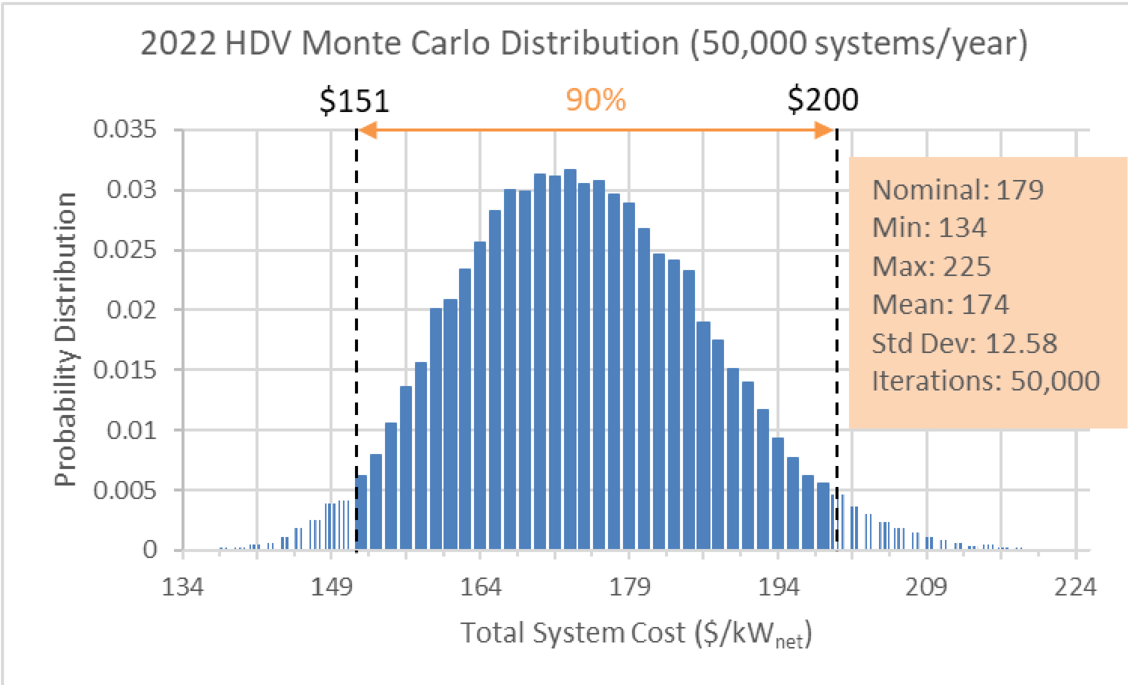


*Figure 7. Monte Carlo analysis of system cost probability at 50,000 systems per year*

*Table 2: 2022 HDV Technology Tornado and Monte Carlo Analysis, 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]** | **$mW/cm^2$** | 461 | **606** | 733 | -24%/+22% 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** | $476 | **$476** | $561 | Min Value: Same as Baseline Value<br>Max Value: from extrapolation of quoted ionomer cost is $561/kg at 130 tons/yr or 50,000 HDV systems/yr |
| **Gas Diffusion Layer (GDL) Cost** | **$\$/m^2$** | $3.00 | **$6.40** | $16.00 | Range of reported GDL Costs ($\$3/m^2$ to $\$16/m^2$) |
| **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<br>Max. Value = Reasonable system operating condition |

| | | | | | |
|---|---|---|---|---|---|
| **Compressor Efficiency [a, b]** | **%** | 64.7% | **72%** | 75% | Using ANL's assumptions for range in compressor/expander/motor/controller efficiencies:<br>Compressor Efficiency: 64.7% min (72.5% baseline) to 75% max<br>Expander Efficiency: 71% min (71.5% baseline) to 80% max<br>Motor Efficiency: 89.5%min (89.5% baseline) to 95% max<br>Controller Efficiency: 89.5% (95% baseline) to 95% max<br>Combined Motor/Controller Efficiency: 80% min (85% baseline) to 90% max |
| **Expander Efficiency [a, b]** | **%** | 71.0% | **75%** | 80% | |
| **Motor/Controller Efficiency [a, b]** | **%** | 81% | **86%** | 95.0% | |
| **Air Compressor Cost** | **$/system** | $2,970 | **$3,300** | $3,960 | Min. Value = 90% of calculated cost<br>Max. Value = 120% of calculated cost |
| **Balance of Air Compressor Cost** | **$/system** | $625 | **$937** | $1,593 | Min. Value = 66% of calculated cost<br>Max. Value = 170% of calculated cost<br>1.5x base value with added 30% more for three $30 components possibly included (gas-capture filter, resonator, and shut-off valve) |
| **Hydrogen Recirculation System Cost** | **$/system** | $994 | **$1,325** | $1,656 | Min Value: 75% of calculated cost<br>Max Value: 125% of calculated cost |
| **Expanded polytetrafluoroethylene (ePTFE) Cost** | **$/m²** | $3.41 | **$6.81** | $11.58 | Range of industry quotes |
| **Active to Total Area Ratio** | | 0.55 | **0.625** | 0.8 | Min Value = Based on discussions with vendors<br>Max Value = Based on value used in previous years studies |
| **Membrane Thickness** | **µm** | 15 | **20** | 25 | Range based on feedback from HD fuel cell system integrators |
| **HTL Radiator Fan Power** | **kW** | 23 | **27.7** | 35 | Min Value = 23 kW based on EMP fan power for Class 8 HD fuel cell truck<br>Max Value= 35 kW based ANL range at 0.7 V |
| **Stack Oversizing** | **%** | 52% | **103%** | 103% | Min Value: 50% based on feedback of limit on active area of stack<br>Max Value: No change from likeliest value |
| **Cost Contingency** | **%** | 5% | **10%** | 15% | +/- 50% on the computed likeliest value |
| **CVM Cost** | **$/kW** | $1.06 | **$2.11** | $4.22 | +100% on the computed likeliest value<br>- 50% on the computed likeliest value |

[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 $Q/\Delta T$ value causing a change in the value of $Q/\Delta T$ within the Monte Carlo analysis.
[c] For all parameters, the "likeliest value" is set to the 2022 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.