STRATEGIC ANALYSIS INC

Fuel Cell Cost and Performance Analysis

Presentation for the DOE Hydrogen Program

2023 Annual Merit Review and Peer Evaluation Meeting

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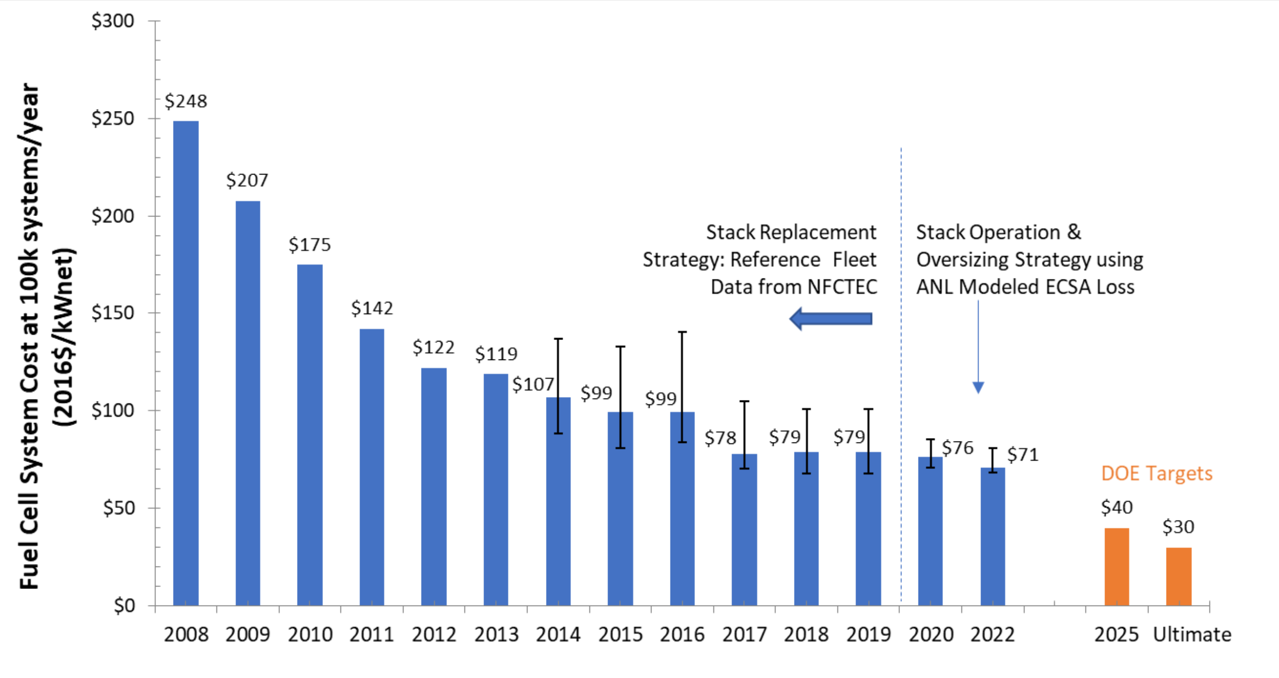
AMR Project ID# FC353

Project Goal

- **Develop technoeconomic analysis models based on Design for Manufacture and Assembly methodology to:**
  - Understand the state-of-the-art FC technology for LDV, MDV, and HDV systems
  - Measure and track the cost impact of technological improvements in FCSs
  - Highlight cost drivers and technical areas requiring improvement to advance the technology
  - Disseminate the above information to the fuel cell industry through comprehensive reports
  - Assist DOE in tracking progress to reach fuel cell system cost targets



LDV fuel cell system cost results from tracking technical improvements over ten years.

Overview

Timeline

- Project Start Date: 10/01/21
- Project End Date: 9/30/25
- % complete: ~38% of four-year project (in Year 2 of 4)

Barriers

- B: System cost
  - Realistic, process-based system costs
  - Need for realistic values for current and future cost targets
- Demonstrates impact of technical targets & barriers on system cost:
  - Balance of plant components
  - Materials of construction
  - System size and capacity (weight and volume)

Budget

- Total Funding Spent
  - ~$309k (through March 2023, SA only)
- Total DOE Project Value
  - $1.26M (over 4 years, excluding Labs)
  - 0% Cost share

Partners

- National Renewable Energy Laboratory (NREL)
- Argonne National Lab (ANL)

Relevance and Potential Impact

Overall Project Objectives:

- Project current (2023) and future (2025 and 2030) cost of automotive, truck, rail, and marine fuel cell systems at high manufacturing rates.
- Project impact of technology improvements on system cost
- Identify low-cost pathways to achieve the DOE target values
- Benchmark against production vehicle power systems
- Identify fuel cell system cost drivers to facilitate HFTO programmatic decisions.
- Quantify the cost impact of components that improve durability.

	System Evaluated	Units (2016$)	Project Status Cost 2022/2023	2025	2030	DOE Targets	DOE Ultimate Target
Final Values	$80kW_{net}$ LDV FC Power Systems (2022)	$\$/kW_{net}$	$64 @500k sys/yr	$53 @500k sys/yr	$48 @500k sys/yr	40 (2025)	30
	$77kW_{net.}$ MDV FC Power Systems (2022)	$\$/kW_{net}$	$200@ 100k sys/yr	$173@ 100k sys/yr	$145@ 100k sys/yr	NA	NA
	$275kW_{net}$ HDV FC Power Systems (2022)	$\$/kW_{net}$	$170@ 100k sys/yr	$132@ 100k sys/yr	$105@ 100k sys/yr	80 (2030)	60 (2050)
Prelim. Values	**$275kW_{net.}$ HDV FC Power Systems (2023)**	$\$/kW_{net}$	$164@ 100k sys/yr	$128@ 100k sys/yr	$108@ 100k sys/yr	80 (2030)	60 (2050)

Approach: Timeline of Analyses

Year	Project Year	Technology	Proposed Analyses
2022	1	$275kW_{net}$ HDV	Current, 2025, 2030
		$77kW_{net}$ MDV	Current, 2025, 2030
		$80kW_{net}$ LDV Light Update	Current, 2025, 2030
2023	2	$275kW_{tract.}$ HDV Update	Current, 2025, 2030
		$175kW_{tract.}$ HDV (Side Study)	Current, 2025, 2030
2024	3	Rail or Marine	Current, 2030
		HDV Update	Current, 2030
		LDV Light Update	Current, 2030
2025	4	HDV, MDV, LDV Update	Current, 2030
		Rail, Marine Update	Current, 2030

Year 2: 2023 Analyses

- Originally Rail was planned, however, DOE prioritized HDV systems for investigation
- Two HDV systems will be evaluated (175kW and 275kW)
  - Three technology years for each application

Future Year Analyses: 2024-2025

- **2024: Prioritize Rail or Marine** system analyses
  - Two technology years for each application
- **2025: Update to all systems** previously analyzed
  - Two technology years for each application

Task	Description	Completed for 2023 Analysis?
1	Manufacturing Process and Technology Review	Ongoing
2	System Definition and Bill of Materials	Milestone 5 submitted in December 2022
3	Techno economic Analysis	Milestone 6 submitted in March 2023
4	Project Reporting	Milestone 7: Response to Reviewer Feedback (In Process) Milestone 8: Final Annual Report (to be submitted in September 2023 (Go/No-Go decision metric))

Approach: Topics Examined for 2023

Annually apply new technological advances and design of transportation systems into techno-economic models

2022/2025/2030 77kW$_{net}$ Medium-Duty Class 6 Delivery Truck Systems

- **Projection of Performance and Durability for current systems:** Utilized ANL 2022 analysis of MDV modeling (Preliminary)
- **Re-evaluation of Radiator Fan Cost:** Cost correlation with air mass flow (Preliminary)

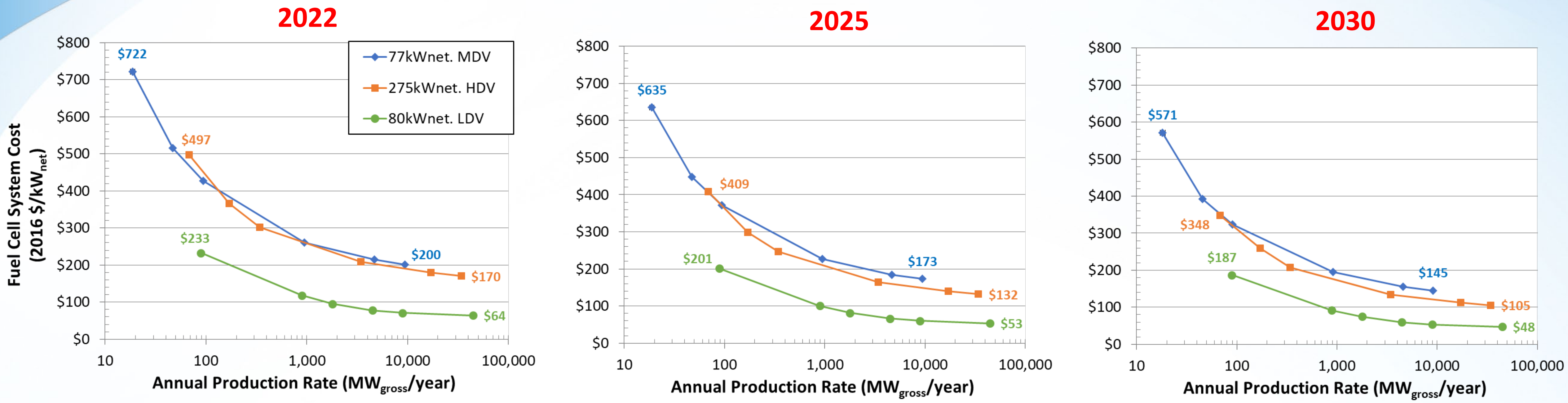
2023/2025/2030 275kW$_{net}$ Heavy-Duty Class 8 Long-Haul Truck Systems

- **Update Operating Conditions and Impact of Durability on Cost:** Collaboration with ANL based on annealed Pt/HSC cathode catalyst with stack active area oversizing for estimated 50% electrochemical surface area (ECSA) loss after 25,000 hours (Preliminary)

Side studies not affecting baseline system analysis

- **Design for Manufacture and Assembly (DFMA) analysis of 191kW$_{net}$ HDV Class 8 Long-Haul Truck Systems:** Heavily hybridized HDV system with larger 183kWh battery (Preliminary)
- **MEA roll-to-roll manufacturing approaches:** Evaluate CCM vs. GDE, and direct coat vs decal transfer (Preliminary)
- **DFMA analysis of 275kW HDV Class 8 Long-Haul Truck System with limited lifetime:** Evaluate system assuming either a stack replacement or shorter vehicle application lifetime (In Process)
- **Battery & Power Electronics Cost Study:** Estimate the cost impact of larger batteries in hybrid FC systems (Future study)
- **Detailed manufacturing evaluation:** Identify gaps in manufacturing technology (Future study)

2022 Finalized System Cost Comparison

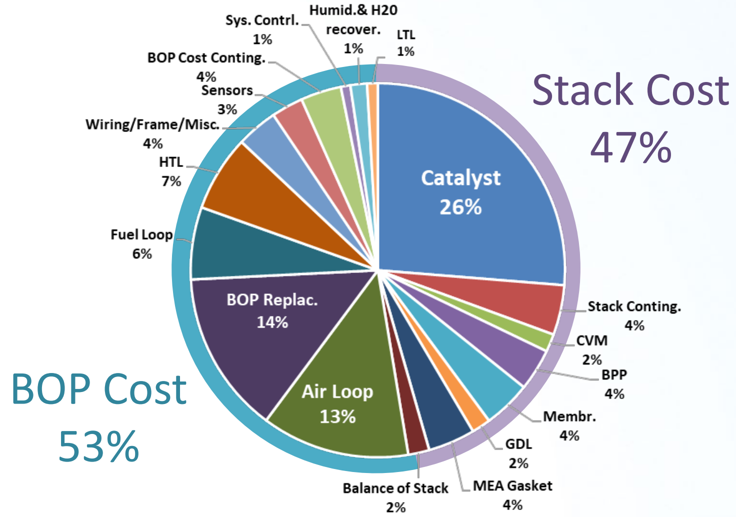


- MDV and HDV are greater cost than LDV at the same MW/yr production volume
  - MDV and HDV systems require 25,000 hrs operation (compared to 8,000 hrs for LDV)
  - MDV and HDV require higher Pt loading, greater active area oversizing, and greater BOP component replacement cost (compared to LDV)
  - MDV and HDV assume a more horizontally integrated system & include additional markup for the FC system manufacturer & powertrain system integrator
- MDV system has slightly higher cost due to lower net power 77kW_{net} (assuming a greater degree of hybridization (larger battery))
- Consistently lower future system cost based on similar improvements in performance, durability, and reduction in Pt loading

Accomplishments and Progress: 2022 77kW MDV System Design

- MDV Class 6 Delivery Truck FC System Assumptions
  - ANL modeled performance & durability specifically for the MDV system
  - Heavily hybridized FC system
  - Battery Thermal Management (BTMS) electrical load
    - Compressor load included in peak net power (2.4kW)
  - Cabin air conditioning (AC) cooling load
    - Currently not included in peak power calc (i.e., no AC during peak power)
  - System performance model
    - Includes both FC and battery degradation and oversizing
  - Degradation Model
    - Fuel Cell Key-On Operating hours 14.5khrs compared to 25khrs Vehicle Lifetime Duty Cycle hours
    - Electrochemical surface area (ECSA) loss predicted over Class 6 delivery truck drive cycle
    - Includes FC voltage clipping at 835mV (at part power)
    - Battery degradation based on LiFePo battery chemistry
      - LFP chosen for MDV for safety and durability features

Class 6 MDV System Parameters	2022
FC System Traction Power ($kW_{tract.}$)*	**75**
FC System Net Power (kW_{net})**	**77**
FC System Gross Power (kW_{gross})	94
Battery Energy (useable/peak, in kWh)	66 / 110
Cathode Pt Loading ($mgPt/cm^2$)	0.4
EOL Power Density (mW/cm^2) @ 0.7V	750
ECSA Loss at EOL	38%
Active Area Oversizing	46%
System Cost ($/$kW_{net}$) @ 100k sys/yr	**$200**

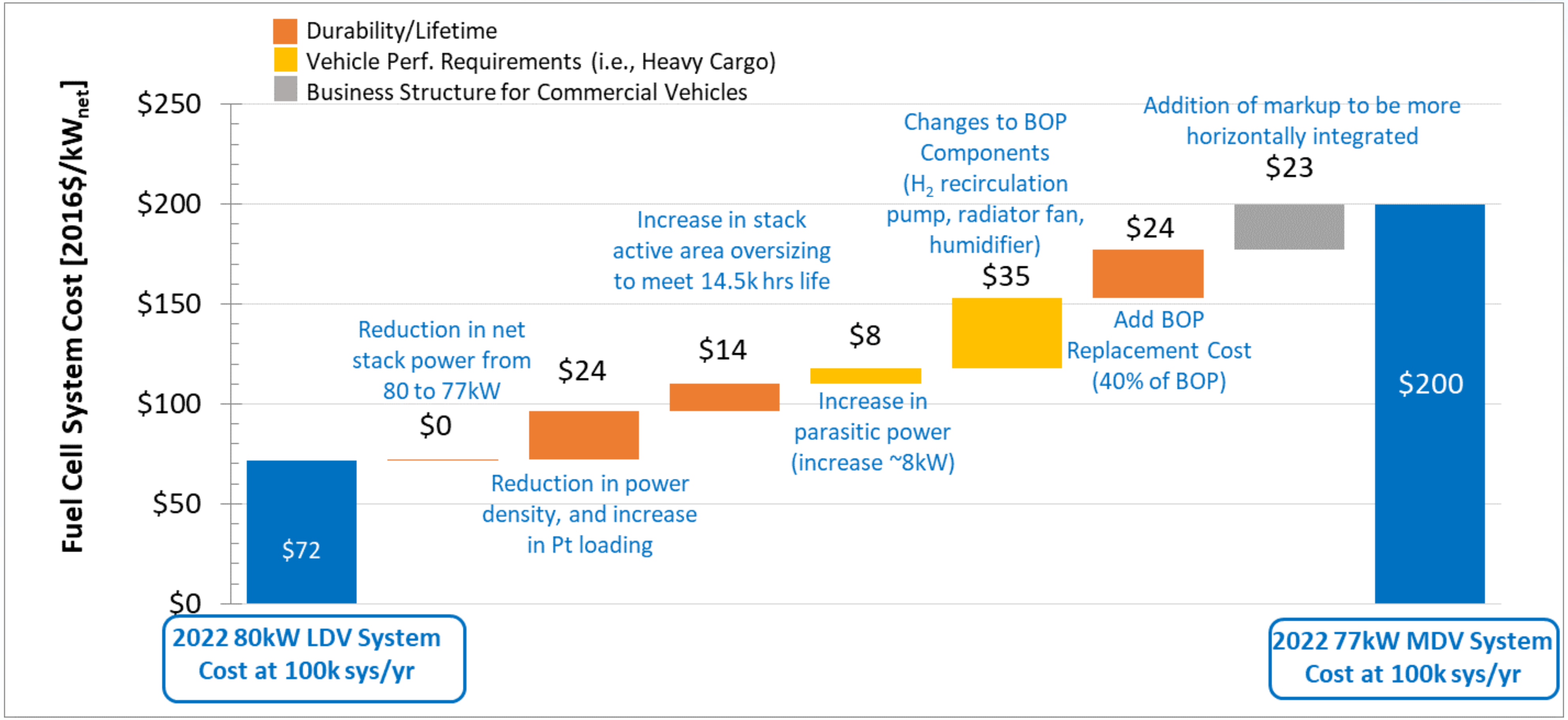


*Traction power refers to power input to drive electric motor

**Net power refers to the power input to the powertrain (includes traction power plus BTMS power load)

Accomplishments and Progress:
2022 77kW MDV Compared to 80kW LDV System Design

- Although traction power is close between LDV and MDV systems, MDV cost is almost 3x higher at the same production volume
- Durability is the greatest contributor to the difference in cost in addition to markup assumptions



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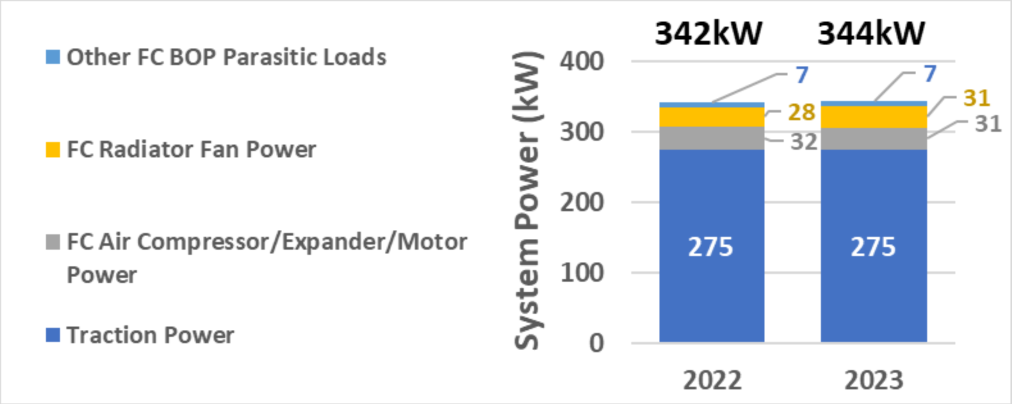
Accomplishments and Progress:

Operating Conditions for 275kW HDV System

Class 8 Long-Haul HD Truck	2022	2023
System Net Power (kW_{net})	275	275
System Gross Power (kW_{gross})	342	344
Cathode Pt Loading ($mgPt/cm^2$)	0.4	0.4
EOL Power Density (mW/cm^2) @ 0.7V	606	642
Durability	25khrs	25khrs
ECSA Loss at EOL	56.5%	50%
Active Area Oversizing	100%	67%
Ambient Temp for FC Air Compressor Peak Operation	40C	40C
Ambient Temp for Radiator Peak Operation	27°C	40°C
System Cost ($/$kW_{net}$) @ 100k sys/yr	**$170**	**$164**



- HDV system sized for End-Of-Life $275kW_{net}$
- Durability modeling conducted by ANL currently only includes data based on electrode degradation in ECSA Loss over Class 8 Long-Haul highway drive cycle of 25khrs
  - New for 2023: adjustment to voltage clipping reduced ECSA loss and resulted in increase in power density
  - Data used in ANL models at $0.25mgPt/cm^2$ (cathode) but $0.4mgPt/cm^2$ (cathode) loading results are projections
  - Membrane mechanical and chemical degradation to be included in future analysis by ANL
- EOL cell voltage is set to 0.7V (based on DOE target), however, current systems are unable to meet this EOL voltage
- Increased ambient air temperature for radiator peak operation for 2023 system (consistent with Davis Dam at lower elevation and higher temp)

Accomplishments and Progress:

Durability Adjusted Operating Conditions for Future 275kW HDV Systems

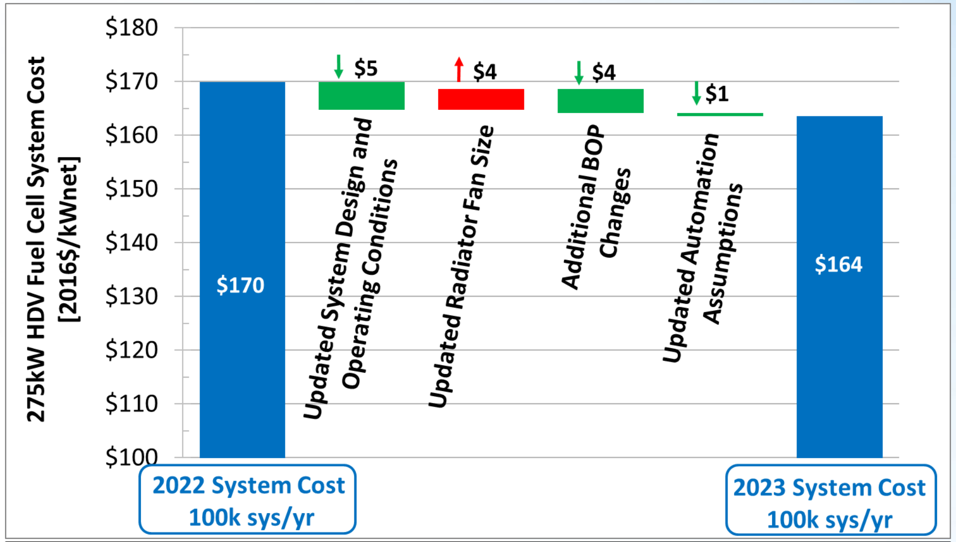
Primary variables adjusted: catalyst loading, power density, BOP replacement

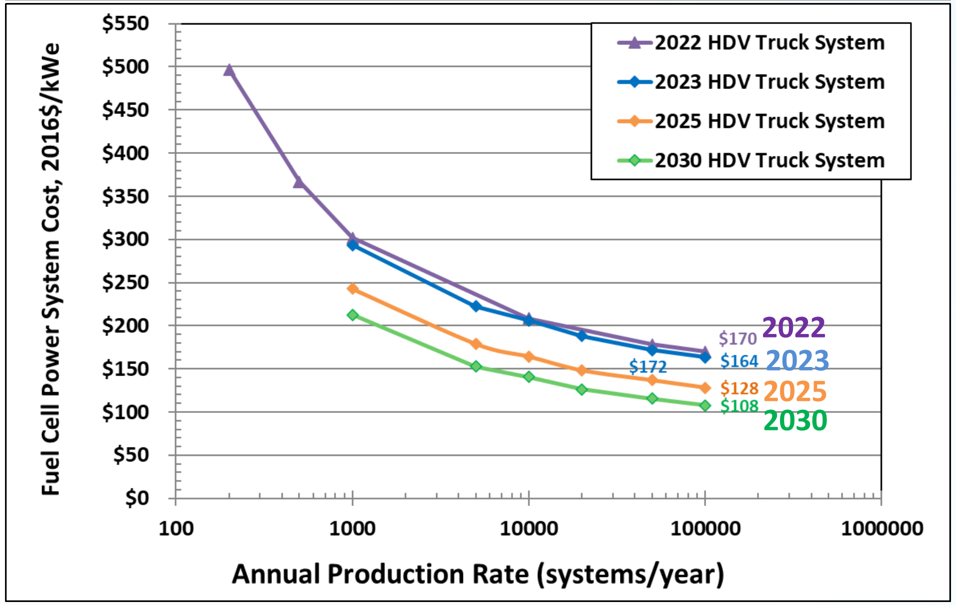
	2023 HDV Technology System	2025 HDV Technology System	2030 HDV Technology System	Notes
Net Rated Power (kW_{net})	275 (EOL)	275 (EOL)	275 (EOL)	
Gross Power (kW_{gross})	344 (EOL)	341 (EOL)	334 (EOL)	
CEM Efficiencies	72%C., 75%Exp., 84.3%M/MC	72%C., 75%Exp., 86.4%M/MC	75%C., 80%Exp., 92%M/MC	Assume more efficient CEM for 2030
Net CEM Input Power Parasitic (kW)	31	29	24	
Radiator Fan Power Parasitic (kW)	31	30	29	5% reduction in radiator fan power between 2025 and 2030 technology years
System Efficiency (%)	44.7%	45.0%	46.0%	At rated power EOL.
Cell Voltage (V)	0.779 (BOL), 0.70 (EOL)	0.779 (BOL), 0.70 (EOL)	0.779 (BOL), 0.70 (EOL)	
Stack Power Density @ Rated Power (mW/cm^2 active area)	642 (EOL)	771 (EOL)	899 (EOL)	Assume increased power density (~10% catalyst improvement, ~10% from reduction in oversizing) for 2025 and 2030 systems
Total Pt loading ($mgPt/cm^2$ $_{total\ area}$)	0.45 (0.4 cath,0.05 anode)	0.35 (0.3 cath,0.05 anode)	0.3 (0.25 cath,0.05 anode)	Assume reduction in Pt loading down to $0.25mgPt/cm^2$ on cathode for 2030
Pt Group Metal (PGM) Total Content (g/kW_{gross})	0.738	0.481	0.355	
Catalyst Durability: ECSA loss after 25k hours operation	50% (ANL Modeling)	40% (Est.)	34% (Est.)	2025 and 2030 values likely to change
Operating Pressure (atm)	2.5	2.5	2.5	
Stack Temp. (Coolant Exit Temp) (°C)	90	90	90	
Air Stoichiometry	1.5	1.5	1.5	
H2 Stoichiometry	2	2	2	
Active Cells per system	1,000	1,000	1,000	500 cells per stack
Cell Active Area (cm^2)	535	442	372	
Active to Total Area Ratio	0.625	0.65	0.65	
Stacks per System	2 stacks	2 stacks	2 stacks	Feedback from Industry: 2 stacks max per system. All stacks electrically in series.
Total System Voltage @ Rated Power	700	700	700	
System Max Voltage (V)	835	835	835	Cell voltage clipping at 0.835V
System Max Current Density (mA/cm^2)	918	1,101	1,284	
Stack Oversizing	67% (ANL Modeling)	53% (Est.)	43% (Est.)	2025 and 2030 values likely to change
Total Active Area per System (m^2)	54	44	37	
FC BOP Replacement Cost Over Vehicle Life (% of Total BOP Cost)	35%	35%	30%	2030 system assume humidifier and air bearings in air compressor motor only need single replacement over life, reducing BOP replacement cost from 35% to 30%.

Values in green are a change from the previous year

Accomplishments and Progress:
2023 HDV System Design and Preliminary Cost Results

- Cost impact of 2023 HDV System Design Changes
  - HDV system cost reduced by ~$6/kW from 2022 analysis
  - Largest cost impact: increase in power density from 606 to 642mW/cm^2
- High Temp Loop radiator and fan size based on 20-minute hill climb (6.5% grade) continuous FC peak power load (344kW$_{gross}$)
  - Increased from 27°C to 40°C ambient temp, increased max radiator fan power required **(fan power increased 18% from 28kW in 2022 to 31kW in 2023)**
  - **Increased cost by $4/kW**
- BOP Changes include reduction of BOP replacement cost (40% to 35% of BOP cost) and reduction in air filter pressure drop (1.3 to 0.5psi)
- Updated Automation: Switched from Pick-&-Place to Roll-2-Roll processing for MEA manufacturing at high volume
- 22% Cost reduction from 2023 to 2025
- 16% Cost reduction from 2025 to 2030





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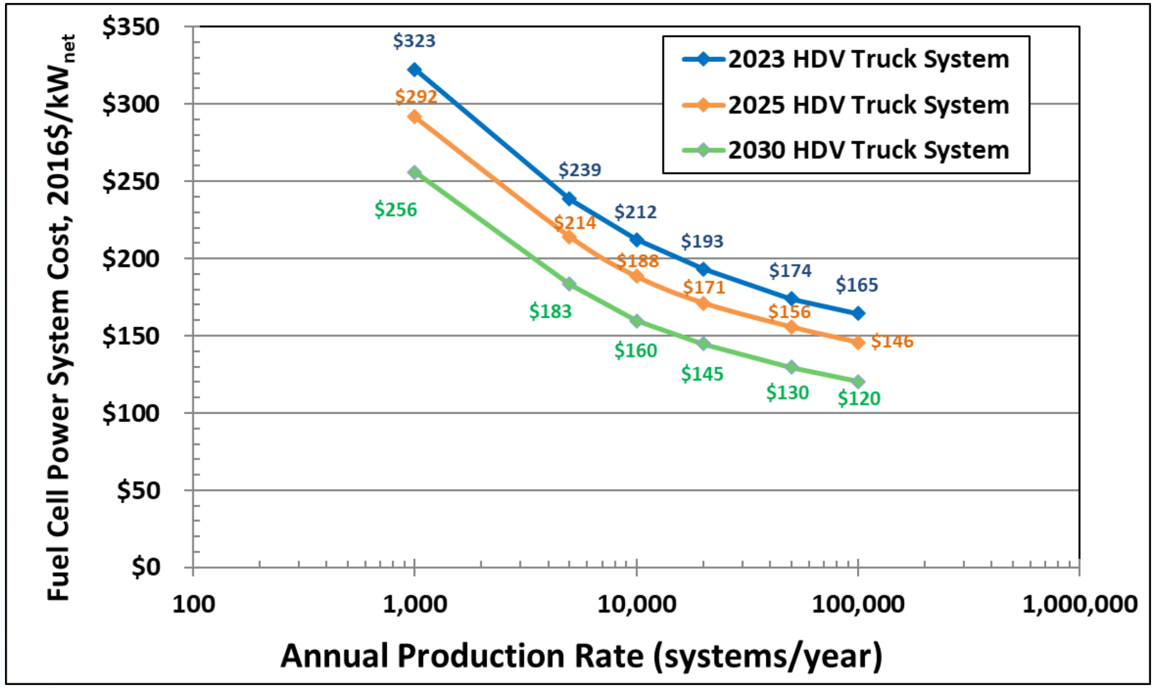
Accomplishments and Progress:
Side Study: 175kW HDV System Design

- To enable 40°C ambient temp. condition on 20-minute hill climb without increasing the size of the radiator, the HDV FC system would have to reduce FC power from 275 to 175kW and pair with a larger battery.
- Same constraints as 275kW HDV long-haul truck system
- Performance and durability modeling conducted by ANL includes degradation of both FC and battery system

2023 HDV System Parameters	175kW	275kW
FC System Traction Power ($kW_{tract.}$)	175	275
FC System Net Power (kW_{net})	191*	275
FC System Gross Power (kW_{gross})	238	344
Cathode Pt Loading ($mgPt/cm^2$)	0.4	0.4
Battery Energy (kWh)	183	38
EOL FC Power Density (mW/cm^2) @ 0.7V	750	642
Durability	25khrs	25khrs
ECSA Loss at EOL	38%	50%
Active Area Oversizing	44%	67%
System Cost ($\$/kW_{net}$) @ 100k sys/yr	**$165**	**$164**

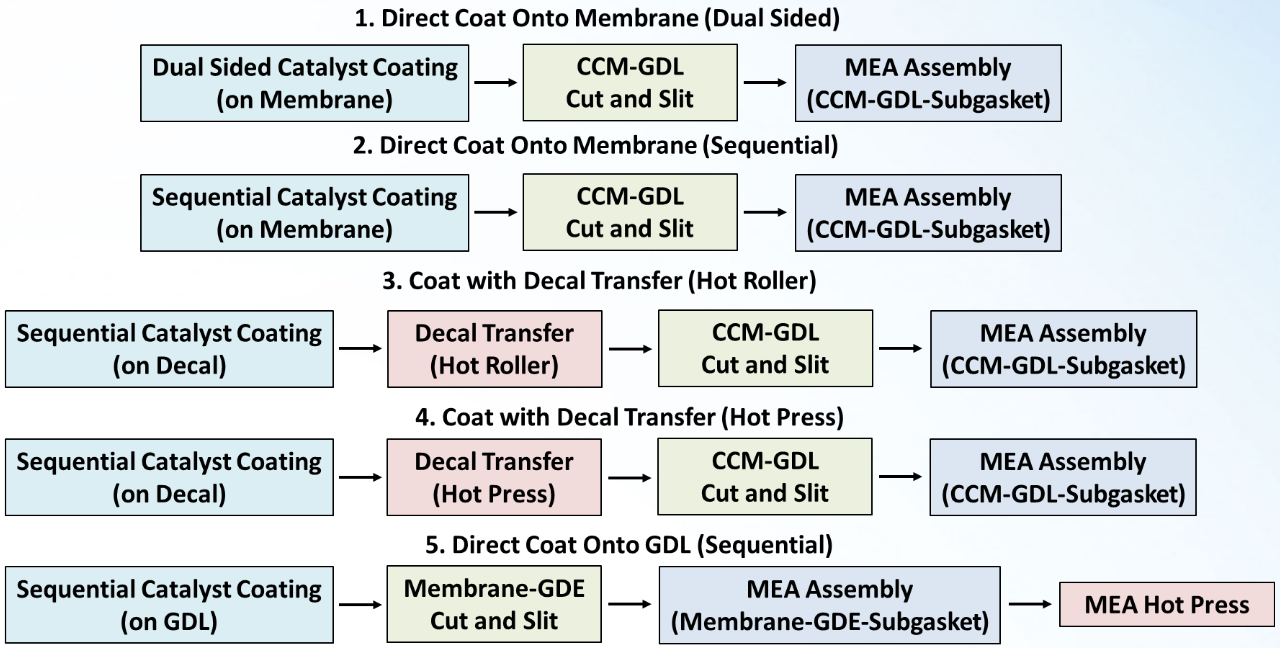


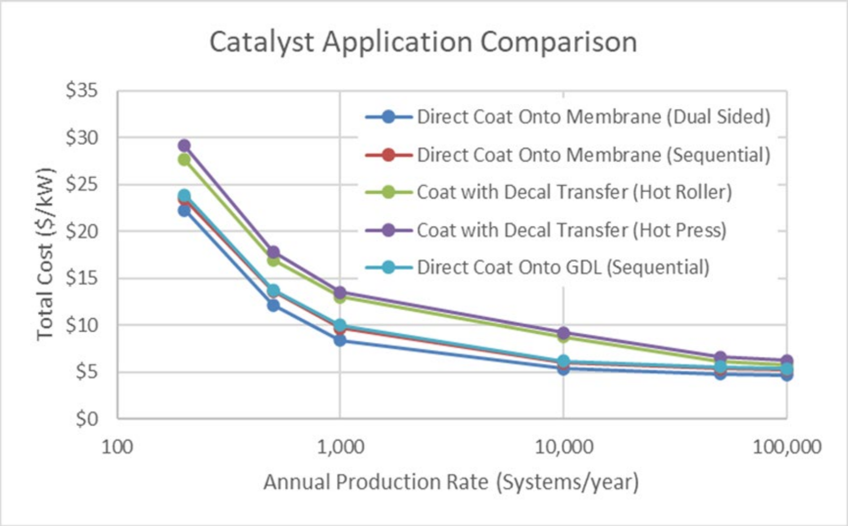
- Smaller FC system can be operated in battery charging mode and reduce the ECSA loss compared to 275kW system
- Higher power density than 275kW system leads to similar total system cost between systems
- Future systems assume increase in power density and reduction in Pt loading

* Includes BTMS and AC electrical loads

Accomplishments and Progress:
Side Study: MEA Manufacturing Comparison

- Five MEA Processes Evaluated
  - CCM (Four)
    - Catalyst Coating: Single-Sided & Dual-Sided
    - Decal Transfer: Hot Roller & Hot Press
  - GDE (One)
    - Single-Side Catalyst Application with Hot-Pressed Decal Transfer
- Assume same performance between CCM and GDE
- Manufacturing cost only (material scrap not included)
- GDE requires hot pressing (differing opinions)





Conclusion:

- Direct coating processes, whether CCM or GDE, tend to have lower cost than decal transfer processes
- Variation in manufacturing cost is quite small compared to the catalyst material cost

Accomplishments and Progress:
Side Study: Battery and Additional Powertrain Component Cost Study

- Given the interest in hybrid system cost, there is a need to understand the cost impact on battery and other powertrain component costs
- Current performance models do not account for the battery cost when determining cost-optimal systems
- Performance and durability are estimated for LFP batteries within current model for MDV and HDV
- **Battery Cost Approach**
  - **Review of vehicle battery cost references**
    - EERE VTO AMR presentations and APRs
    - NREL ATB Battery Cost [1,2]
    - PNNL 2022 Report – Grid Energy Storage Cost
    - Roush 2022 Report [3]
  - **Consider Different Battery Chemistry**
    - LiFePO vs NMC – cost vs performance and lifetime
    - Application-specific (MDV vs HDV)
    - Chemistries used in current FC trucks
  - **Battery Cost Modeling Sources**
    - SA internal DFMA model evaluating multiple chemistries
    - BatPac – ANL-developed tool for estimating manufacturing cost of Li-ion battery chemistries [4]
- Evaluate the impact of additional battery power on battery and other power electronics cost

	Class 8 275kW HDV	Class 8 175kW HDV	Class 6 75 kW MDV
FC Power ($kW_{tract.}$)	275	175	75
FC Power (kW_{net})	275	191	77
FC Power (kW_{gross})	344	238	94
FC Lifetime (hrs)	25,000	25,000	14,500
Battery Continuous Power (kW)	TBD	225	110
Battery Energy (BOL Total) (kWh)	TBD	183	78

			Battery		
Truck OEMs	Truck Name	Class	Energy (kWh)	Power (kW)	Chemistry
CellCentric (Daimler/Volvo)	Mercedes-Benz GenH2	8	70	70 (rated), 400 (peak)	Lithium-ion
Nikola Motors	Nikola Tre	8	164		NMC
Hyzon Motors	HYHD8-110KW	8	110		LFP
Hyundai	XCIENT	8	216 (3x 72 kHw battery packs)		Lithium-ion
Kenworth	T680 FCEV	8	12 (drayage)		Lithium-ion
Scania		8	104		NMC
Quantron	QHM FCEV	8	118		Lithium-ion

1. https://atb.nrel.gov/transportation/2020/definitions#batteryelectricvehicles
2. Islam et. al, "Energy Consumption and Cost Reduction of Future Light-Duty Vehicles through Advanced Vehicle Technologies: A Modeling Simulation Study Through 2050", Argonne National Laboratory, June 2020. https://publications.anl.gov/anlpubs/2020/08/161542.pdf
3. Nair et al, "Technical Review of: Medium and Heavy-Duty Electrification Cost for MY 2027-2030", Roush report for Environmental Defense Fund, February 2022.
4. https://www.anl.gov/partnerships/batpac-battery-manufacturing-cost-estimation

Collaboration & Coordination

Partner/Collaborator/Vendor	Project Role
National Renewable Energy Laboratory (NREL) (sub on contract)	• Provided knowledge & expertise on QC systems for LDV and HDV FC manufacturing lines. • Reviewed and provided feedback on automation equipment for MEA manufacturing. • Provided feedback on current 2023, 2025, and 2030 analysis systems & manufacturing processes. • Participates in researching the affect of durability on cost. • Provided review of MEA coating methods analysis (CCM/GDE/Direct Coat/Decal Transfer)
Argonne National Laboratory (ANL) (sub on contract)	• Supplied detailed modeling results for optimized fuel cell operating conditions (based on experimental cell data) for HDV Class 8 long-haul truck and MDV Class 6 delivery truck . • Provided SA with model results for system pressure, mass flows, CEM η, and membrane area requirements for optimized system. • Provided modeling data for both 175kW and 275kW HDV systems. • Modeled HDV cooling system requirements and optimized FC operating conditions.
2022/2023 Collaborators	• Formal Review on HDV system operation and components: CellCentric, GM, Cummins • Optima and Mühlbauer: Details on automated stacking, R2R MEA processing lines, and stack testing • Graebener: Provided latest BPP manufacturing equipment

Remaining Barriers and Challenges

- Durability: Stack degradation mechanisms are not fully understood and predicting system durability is difficult. Durability-optimal operating conditions have been identified but are unproven. Material interactions can adversely affect durability. Procedures for system shut-down are often OEM specific/proprietary and thus not open to review.
- Factory Automation: Cell stacking, testing, MEA assembly, and conditioning all require high-volume commercial systems to be developed. However, there is substantial recently demonstrated production-line vendor activity in these areas with new low Takt time options becoming available.

Automotive System

- BPP material cost: Base material 316SS contributes ~\$3/kW_{net} making it difficult to reach DOE's 2025 LDV cost target of \$3/kW total BPP (material/forming/coating).
- \$40/kW DOE target difficult to achieve: With adjustments to the system to achieve 8k hrs, multiple rounds of performance and durability technical improvements must be made to achieve this target by 2025. SA status cost for 2025 system is \$53/kW compared to \$40/kW DOE target).
- \$30/kW DOE target even harder to achieve: Projections for 2030 analysis (\$48/kW) suggest the DOE ultimate target of \$30/kW may be difficult to achieve and will require much lower material costs, removal or consolidation of BOP components, and improvement in durability.
- Massively parallel BPP forming lines: Even with ~2 sec/plate forming speed, many parallel BPP production lines are needed for 500k systems/year. This presents part uniformity problems.

MDV/HDV Study

- Enhanced Durability: Durability of MDV/HDV systems is vital. Ballard buses have shown 25k+ hours durability but the exact "solution" to long life is not fully understood.
- Hybridization: Better understanding of the FCV truck preferred operating mode is needed (i.e., larger battery maybe cost and durability optimal).
- Stack cooling system: designs will need to improve as the fan motor electrical parasitic load is comparable to the air compression system (~30kW)
- \$80/kW and \$60/kW DOE targets difficult to achieve: With adjustments to the system to achieve 25k hrs, multiple rounds of performance and durability technical improvements must be made to achieve these targets.

Proposed Future Work

Future Work for Baseline Models

- Update models based on feedback from OEM and companies in the Fuel Cell Joint Technical Team (FCJTT) – (US Drive and 21st Century Truck Partnership)
- Complete sensitivity analysis on HDV Systems
- Document HDV systems in 2023 Final Report: Report due September 2023

Future Work for Side Studies

- Conduct battery cost and electrical component cost evaluation to show impact on full system cost for more hybridized systems
- Conduct DFMA analysis of 275kW HDV Class 8 Long-Haul Truck System with limited lifetime, considering either a stack replacement or shorter vehicle application lifetime
- Identify gaps in manufacturing technology through rigorous analysis of current DFMA models

Any proposed future work is subject to change based on funding levels.

Summary of Findings

- **2022 LDV 80kW_{net} Automotive System**
  - Final results: ~\$64/kW_{net} (current 2022), ~\$53/kW_{net} (2025), ~\$48/kW_{net} (2030) at 500k sys/year
- **2022 MDV 77kW_{net} Delivery Truck System**
  - Preliminary results: ~\$200/kW_{net} (current 2022), ~\$173/kW_{net} (2025), ~\$145/kW_{net} (2030) at 100k sys/year
  - Incorporated performance and durability modeling for FC and battery system
  - Although similar in traction power, the MDV FC system cost could be is 3x the LDV system cost
- **2022 HDV 275kW_{net} Long-Haul Truck System**
  - Final results: ~\$170/kW_{net} (current 2022), ~\$132/kW_{net} (2025), ~\$105/kW_{net} (2030) at 100k sys/year
- **2023 HDV 275kW_{net} Long-Haul Truck System**
  - Final results: ~\$164/kW_{net} (current 2023), ~\$128/kW_{net} (2025), ~\$108/kW_{net} (2030) at 100k sys/year
  - Improvement in FC power density from 606 to 642mW/cm^2 reduced system cost by \$5/kW
  - Increasing ambient temperature from 27 to 40°C on the hill climb increased the radiator fan power by 18%, resulting in \$4/kW increase in system cost
- **2023 HDV 191kW_{net} Long-Haul Truck System**
  - Final results: ~\$165/kW_{net} (current 2023), ~\$146/kW_{net} (2025), ~\$120/kW_{net} (2030) at 100k sys/year
- **MEA Manufacturing Comparison**
  - Direct coating processes, whether CCM or GDE, show lower cost than decal transfer processes, excluding precious metal scrap

Project Summary

- **Overview**
  - Exploring subsystem alternative configurations and benchmark cost where possible for LDV, MDV, and HDV FC Systems
  - In first year of project
- **Relevance**
  - Cost analysis used to assess practicality of proposed power system, determine key cost drivers, determine the cost impact of durability, and provide insight for direction of R&D priorities
  - Provides non-proprietary benchmark for discussions/comparison
- **Approach**
  - Process-based cost analysis methodologies (e.g., DFMA®)
  - Full transparency, open discussion of assumptions and results, extensive briefing to industry/researchers for validation
- **Accomplishments**
  - Analyses:
    - Final system design and cost results for LDV, MDV, and HDV FC systems for 2022, 2025, and 2030 technology years
    - Preliminary 2023 system design and cost results for 275kW HDV and 175kW HDV systems
- **Collaborations**
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
  - Extensive discussions, interviews, feedback with 30+ industry vendors/suppliers
- **Future Work**
  - Finalize HDV system design, complete sensitivity analyses, and draft 2023 final report.
  - Battery and electrical component cost estimates
  - Identify gaps in manufacturing technology