Fuel Cell Cost and Performance Analysis

Presentation for the DOE Hydrogen Program

2024 Annual Merit Review and Peer Evaluation Meeting

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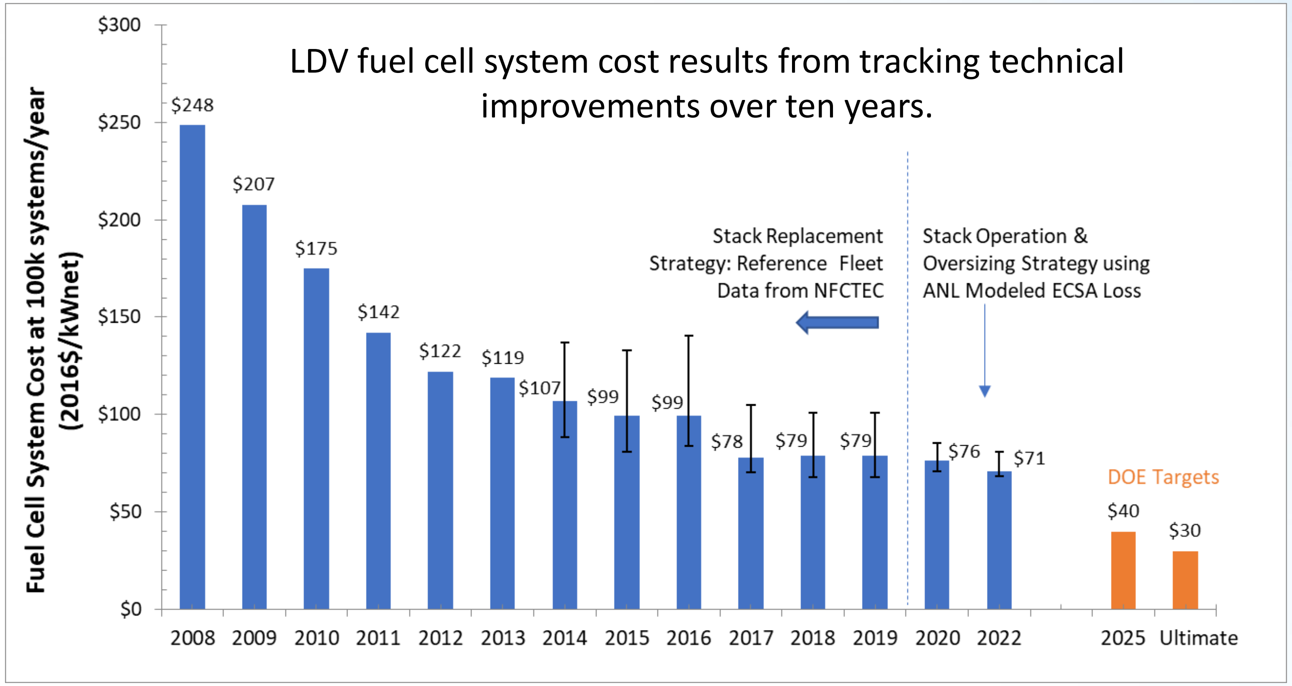
AMR Project ID# FC353

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



STRATEGIC ANALYSIS INC

Overview

Timeline

- Project Start Date: 10/01/21
- Project End Date: 9/30/25
- % complete: ~42% of four-year project (in Year 3 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
  - ~$523k (through March 2024, 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)

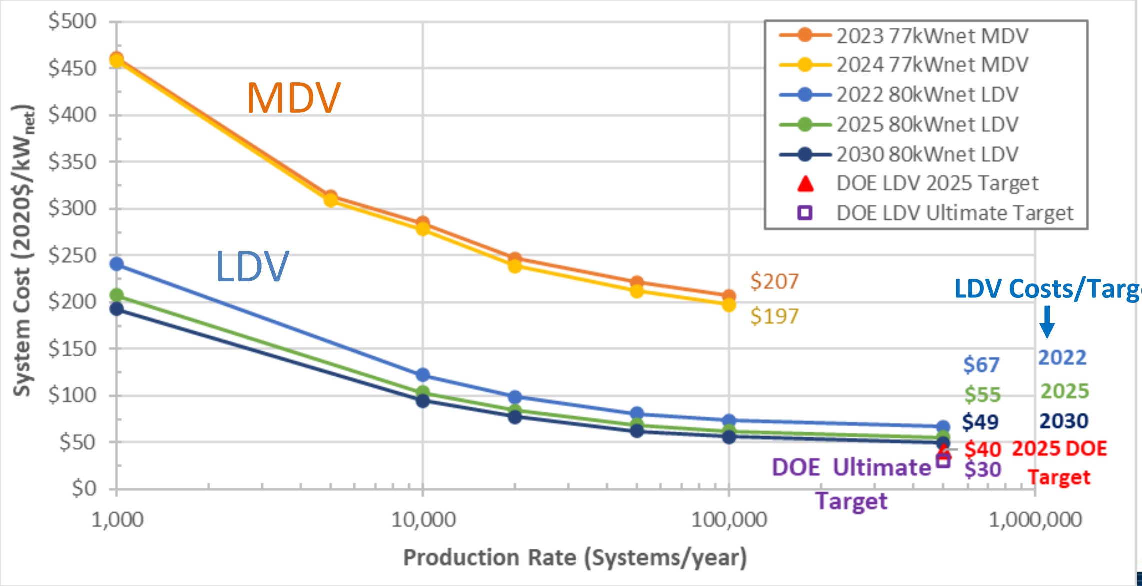
NREL NATIONAL RENEWABLE ENERGY LABORATORY

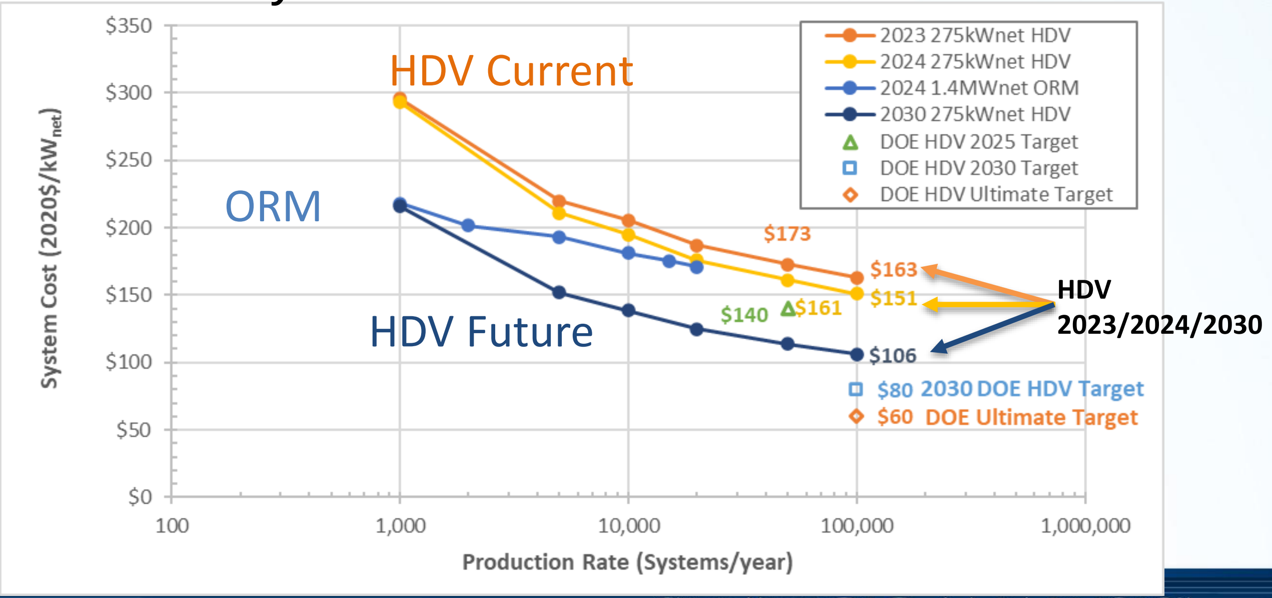
Argonne NATIONAL LABORATORY

Relevance and Potential Impact

Overall Project Objectives:

- Project current (2024) and future (2030) cost of automotive, MD/HD truck, and off-road mining (ORM) truck 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.





STRATEGIC ANALYSIS INC

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	$275kW_{net}$ HDV Update	Current, 2025, 2030
		$175kW_{net}$ HDV (Side Study)	Current, 2025, 2030
		$75kW_{tract}$ MDV Update	Current, 2025, 2030
2024	3	Off-Road Mining Truck	Current, 2030
		HDV Update	Current, 2030
		MDV Update	Current, 2030
2025	4	HDV, MDV, LDV Update	Current, 2030
		ORM Update	Current, 2030

Year 3: 2024 Analyses

- Originally Rail or Marine was planned, however, DOE prioritized off-road mining (ORM) truck for investigation and updates to HDV and MDV systems
  - Two technology years for each application (2024 and 2030)

Year 4: 2025 Analyses

- **2025: Update to all systems** previously analyzed
  - Two technology years for each application

Task	Description	Completed for 2024 Analysis?
1	Manufacturing Process and Technology Review	Ongoing
2	System Definition and Bill of Materials	Milestone 9 - submitted in December 2023
3	Techno economic Analysis	Milestone 10 - submitted in March 2024
4	Project Reporting	Milestone 11: Response to Reviewer Feedback - to be submitted in June 2024 Milestone 12: Final Annual Report - to be submitted in September 2024 (Go/No-Go decision metric))

Approach: Analysis Methodology and Topics Examined for 2024

Analysis Methodology

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

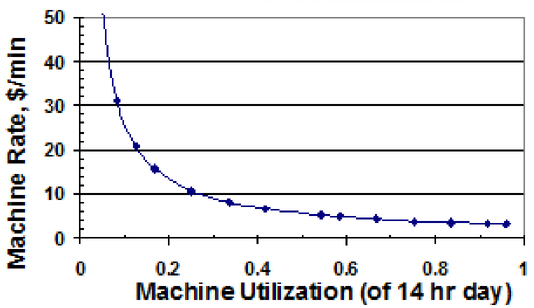
DFMA® = Design for Manufacture & Assembly

Bottom-up cost analysis based on physical design and actual manufacturing/assembly steps

Manufacturing Cost Factors:

1. Material Costs
2. Manufacturing Method
3. Machine Rate
4. Tooling Amortization

Methodology reflects cost of under-utilization:



All cost values in 2020$

1. Literature Review
2. Establish Baseline System Design
3. Establish Baseline Cost Model
4. Obtain Feedback from Industry
5. Update models
6. Conduct Sensitivity and Cost Correlations

ANL Performance and Durability Modeling

Topics Examined for 2024:

- **Baseline Systems Modeled:**
  - *77kW$_{net}$ Medium-Duty Class 6 Delivery Truck*
  - *275kW$_{net}$ Heavy-Duty Class 8 Long-Haul Truck*
  - *1.4MW$_{net}$ Off-Road Mining Haul Truck Systems*
  - Current 2024 and future 2030 at various prod. vol.
- **Costs updated based on reduced Pt loading**
  - Aligned with ANL 2023 performance modeling (Preliminary)
- **Re-evaluation of BOP Replacement Cost**
  - Addresses feedback from industry (Preliminary)

Side studies (not incorporated into baseline systems)

- **Evaluation of new catalyst**
- **DFMA analysis of 175kW$_{tract.}$ HDV Class 8 Long-Haul Truck**
  - Heavily hybridized HDV system with larger battery: 188kWh (BOL) (Completed - 2023)
- **Battery & Power Electronics Cost Study:**
  - Explore tradeoff between battery cost and FC cost (Completed-2023)
- **Rotary Screen Printing:**
  - Evaluation of catalyst coating, gaskets, seals (In Process)

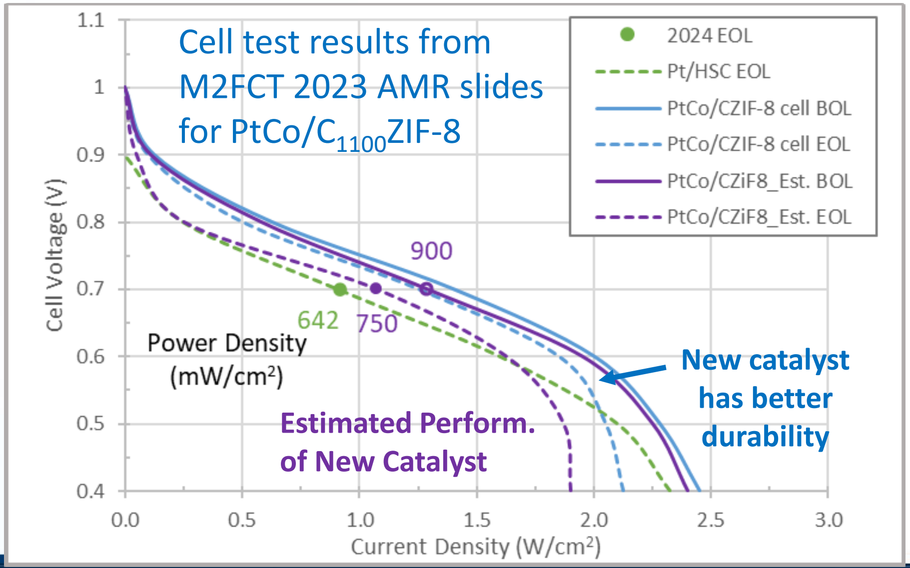
Approach: Safety Planning and Culture

This analysis type project is exempt from submitting a safety plan to the Hydrogen Safety Panel

Accomplishments and Progress:

Operating Conditions for 275kW HDV System

Class 8 Long-Haul HD Truck	2023	2024	2030	Est. New Catalyst
System Net Power (kW_{net})	275	275	275	275
System Gross Power (kW_{gross})	338	338	327	338
Cathode Pt Loading ($mgPt/cm^2$)	0.40	0.30	0.30	0.25
EOL Power Density (mW/cm^2) @ 0.7V	**642**	**642**	953	750
Durability	25khrs	25khrs	25khrs	25khrs
ECSA Loss at EOL	50%	50%	44%	55%
Active Area Oversizing	67%	67%	35%	20%
Ambient Temp for BOP component sizing	40C	40C	40C	40C
Stack Cost ($/$kW_{net}$) @ 50k sys/yr	**$106**	**$95**	**$61**	**$77**



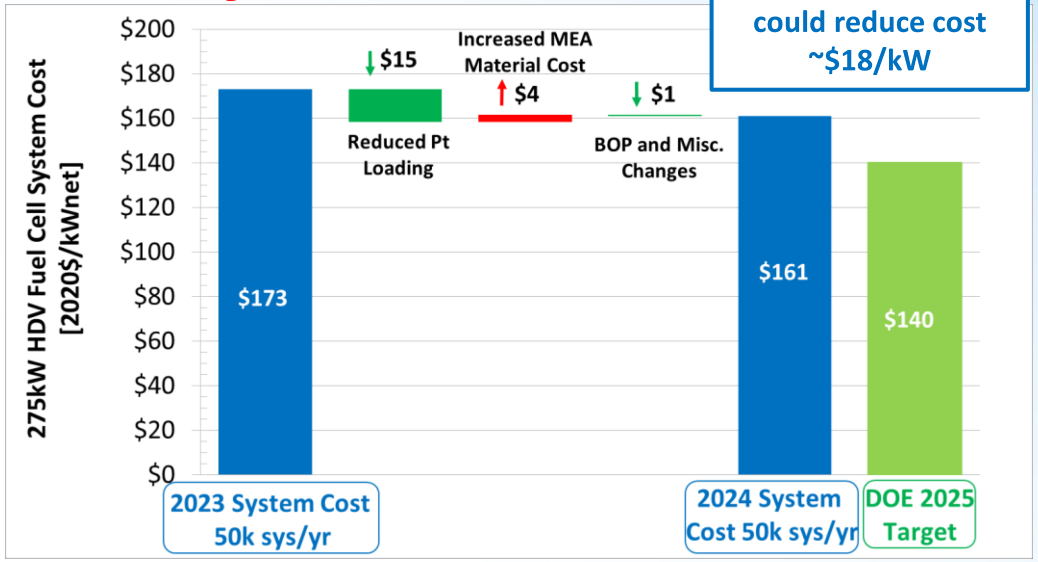
- HDV system sized for End-Of-Life $275kW_{net}$
- Cathode Pt loading reduced from 0.4 to $0.3mgPt/cm^2$ to better align with ANL modeling (test data at $0.25mgPt/cm^2$)
  - 2024 cost modeling basis: Based on ANL 2023 modeling but with slightly higher catalyst loading (to be conservative)
  - 2030 cost modeling basis
    - 20% higher BOL power density (at 0.7V/cell) (projection)
    - Only 35% oversizing required (projection)
- **New PtCo/C-ZIF-8 cathode catalyst**:
  - Developed by M2FCT Consortium
  - Preliminary performance modeling by ANL
  - Prelim. estimates show substantial improvement over aPt/HSC cathode catalyst: work continuing
    - Assume M2FCT target of $750mW/cm^2$ (at 0.7V at EOL) although ANL modeling suggests $>750mW/cm^2$
    - ECSA loss may be similar to aPt/C, but EOL mass activity substantially better and would require less oversizing. Assume 20% oversizing based on ratio of power densities for BOL and EOL (900/750).

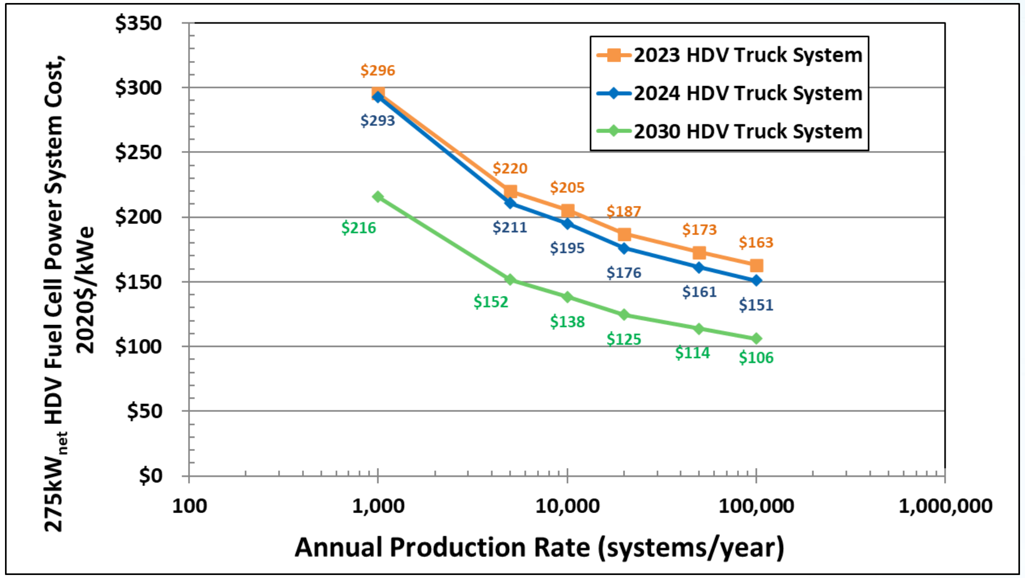
*Waiting on additional experimental test data for new PtCo/C-ZIF catalyst. Durability modeling will include data based on electrode degradation in ECSA Loss over Class 8 Long-Haul highway drive cycle of 25khr. Membrane mechanical and chemical degradation to be included in future analysis by ANL.

Accomplishments and Progress:
2024 HDV System Design and Preliminary Cost Results

- Cost impact of 2024 HDV System Design Changes
  - HDV system cost reduced by ~$12/kW from 2023 analysis at 50k sys/yr
  - Largest cost impact -$15/kW: Total Pt reduction from 0.45 to 0.35mgPt/cm^2
  - **Updated modeling/data may alter cost projections**
- MEA Price Change: Updated prices for ionomer, ePTFE, and GDL
  - **Increased cost by ~$4/kW**
  - In response to industry feedback that material costs should be higher
  - First estimate based on one source of membrane material pricing
    - Increased 30% from last year. New costs at 50k sys/yr: $650/kg ionomer, $9/m^2 GDL, $9.5/m^2 ePTFE (2016$)
  - **Currently seeking to update quotes for ionomer, ePTFE, and GDL**
- BOP changes: removal of air demister upstream of the air compressor and updated air filtration to handle HDV air mass flow
  - **Additional BOP changes planned for additional robustness and design improvements**
    - Air compressor – update to design (considering alternative bearing technology)
    - Humidifier – update to materials and design (considering more robust and possibly recycled materials)
    - Water separator – update to design (mesh to cyclone)
- Projected 2030 system cost based on 953mW/cm^2 at 0.7V at EOL, 0.35mgPt/cm^2, and 35% active area oversizing.

*PtCo/C-ZIF catalyst could reduce cost ~$18/kW





Accomplishments and Progress: In Process

Re-evaluation of BOP Components for Performance and Durability

Air Compressor

- **Air bearings may not meet 25,000 hrs of operation**
  - Air bearing replacement included in BOP replacement cost – requiring two replacements over the life of the vehicle
- **Consideration of liquid lubricated bearings**
  - Water-glycol mixture can be used in bearing and motor cooling
  - Risk of glycol mixture impacting performance of FC MEA

Humidifier

- Lifetime currently only 5-6k hours
- Current system requires 2 replacements for 25khr
- Future system could require 1 replacement

Adjustment to Increase Durability	Impact to Manufacturing and Cost
Membrane Material	Switch FC-grade PFSA & ePTFE to possibly lower cost recycled membrane material
Membrane thickness	More challenging to assemble
Housing Material	Al to SS would increase cost

Air Filter

- Seeing designs of larger filters to reduce pressure drop
- The same carbon filter materials are expected for LDV/HDV FCS
- Robust design for extreme mining environments
  - Current air filters would have short life (~days to replacement)
  - Reusable air filters can extend lifetime & replacement schedule
  - Particulate and gas filters recommended

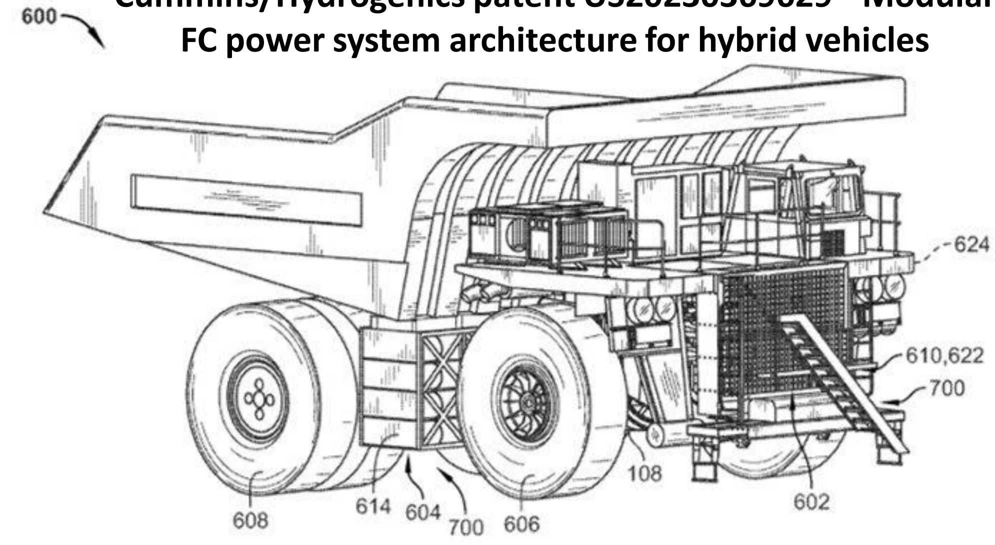
Demister (water separator)

- LDV system contains membrane separator
- HDV system would require a cyclone-type demister to handle increased flow rate
- Cathode side separation ~85% at 15m^3/min
- Anode side separation need >90%
- Injection molded part
- SA estimated cost for HDV cathode demister: ~$40 at 50k sys/yr

Accomplishments and Progress:
Off-Road Mining Truck Design Configuration

- Preliminary basis: **3,500hp ultraclass haul truck**, modeled by ANL https://www.mdpi.com/1996-1073/16/1/286
- **FC dominant architecture:** FCS delivers max power during ascent, idles during descent, and delivers 36% power otherwise.
- The fuel cell system and battery are sized to **satisfy duty cycle power demand at end of life (EOL)**
- Assume ORM truck includes **liquid H2 storage**
- **Modularization:** Each module has its own fuel, water, and thermal subsystems but shares a common radiator and coolant loop for heat rejection
- **Durability: assume 25,000hrs fuel cell lifetime**
  - FC stack oversized to meet EOL operating conditions
  - Oversizing determined by the amount of ECSA loss due to catalyst degradation under mining truck drive cycle – to be included in future analysis

Cummins/Hydrogenics patent US20230369629 - Modular FC power system architecture for hybrid vehicles



- **Review of patent literature** suggests different architectures of FC modules and BOP, however, no mention of differences between HDV and ORM FC stacks.
- Discussions with OEM/BOP component supplier **suggest FC stack design and operating conditions are the same between HDV and ORM trucks**, but with **adjust BOP components** to ensure the stack experiences the same conditions

Accomplishments and Progress: Off-Road Mining Truck Environmental Considerations Compared to HDV

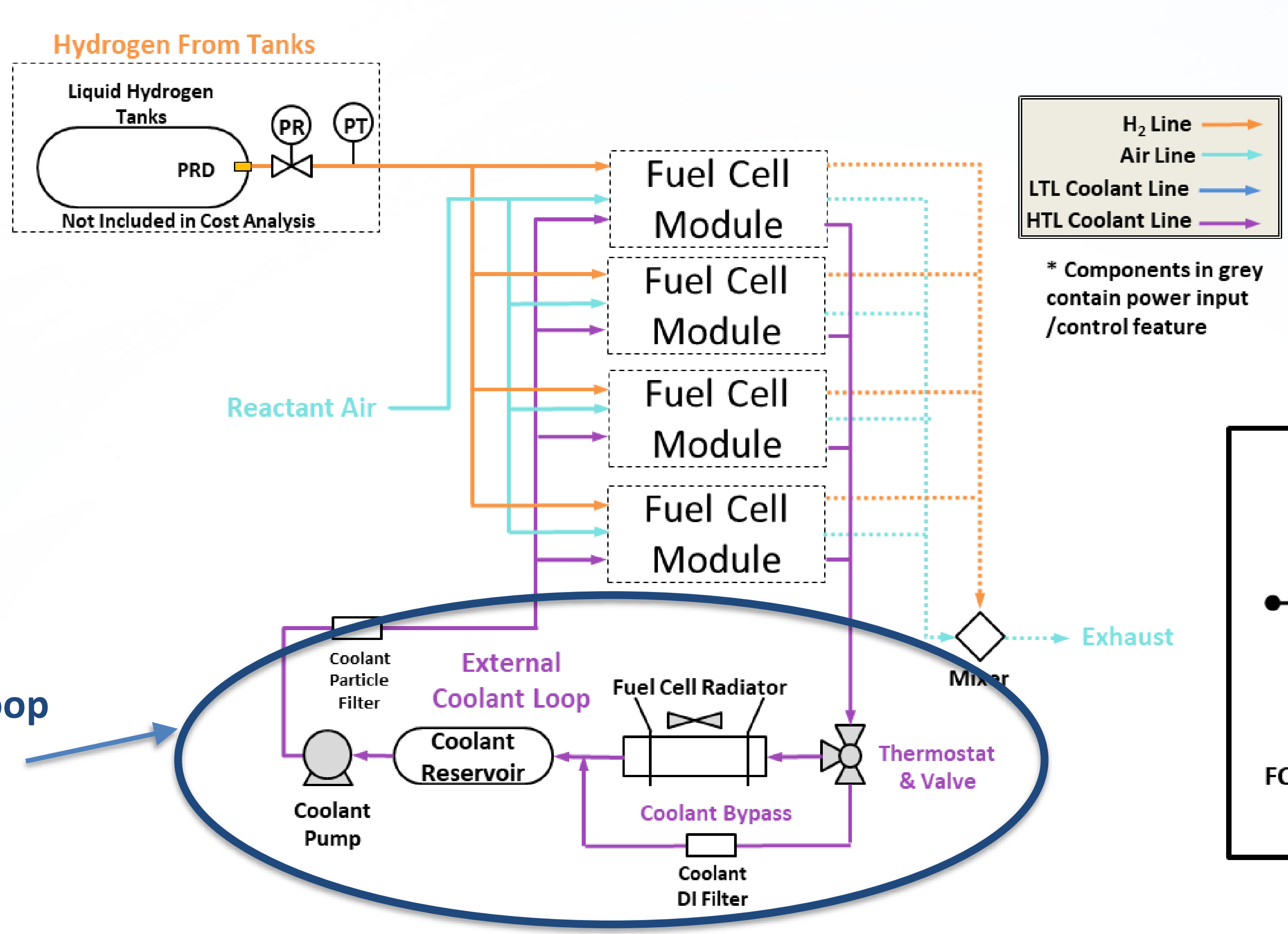
Largest BOP Changes are to:
- **Air Filter**
- **Air Compressor**
- **Radiator**

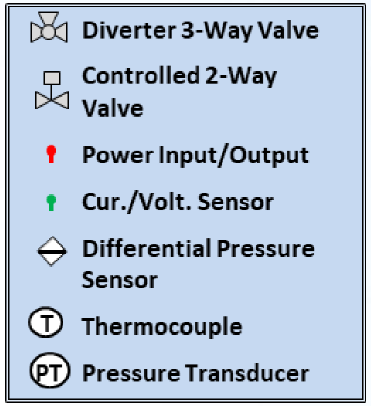
FC System Components	ORM System Changes from HDV System			
		Environment 1: Sea Level Temp: 25°C Humidity: 30% RH Air Pressure: 1.00atm	**Environment 2: Low Elevation** 1,000ft below sea level Temp: 30-45°C Humidity: 80-95% RH Air Pressure: 1.04 atm	**Environment 3: High Elevation** 7,500ft above sea level Temp: 25°C Humidity: 0%-24% RH Air Pressure: 0.76atm
	FC Stack	No change	No change	No change
	Air Filter	3-stages of air filtration (2 particulate filters and one semi-active adsorbent filter)	3-stages of air filtration (2 particulate filters and one semi-active adsorbent filter)	3-stages of air filtration (2 particulate filters and one semi-active adsorbent filter)
	Demister	No change	No change	No change
	Air Compression	No change	No change	2-stage compression required
	Humidfier	No change	No change	No change if FC experiences sea-level conditions.
	Thermal Management	Adjusted for system Ht rejection but otherwise similar sizing to HD systems. Coolant loop is considered external to FC modules.	Higher ambient temp will furtjer increase the radiator and fan sizing. Coolant loop is considered external to FC modules.	Low pressure will require larger radiator and fan sizing. Coolant loop is considered external to FC modules.
	Fuel Management	Liquid storage, although more energy dense, has more complexity.	Liquid storage, although more energy dense, has more complexity.	Liquid storage, although more energy dense, has more complexity.

- Baseline system assumes sea level operation: will estimate cost variation for different environments.
- Preliminary results based on simple component changes. Future work will model impact of perf./durability.

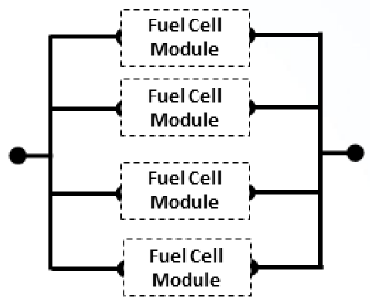
Accomplishments and Progress: 2024 & 2030 System Configuration: 1,387kW$_{net}$ ORM Haul Truck

1,387kW FC System = 4 x 347kW$_{net}$ Fuel Cell Modules





Common cooling loop for all 4 Fuel Cell Modules

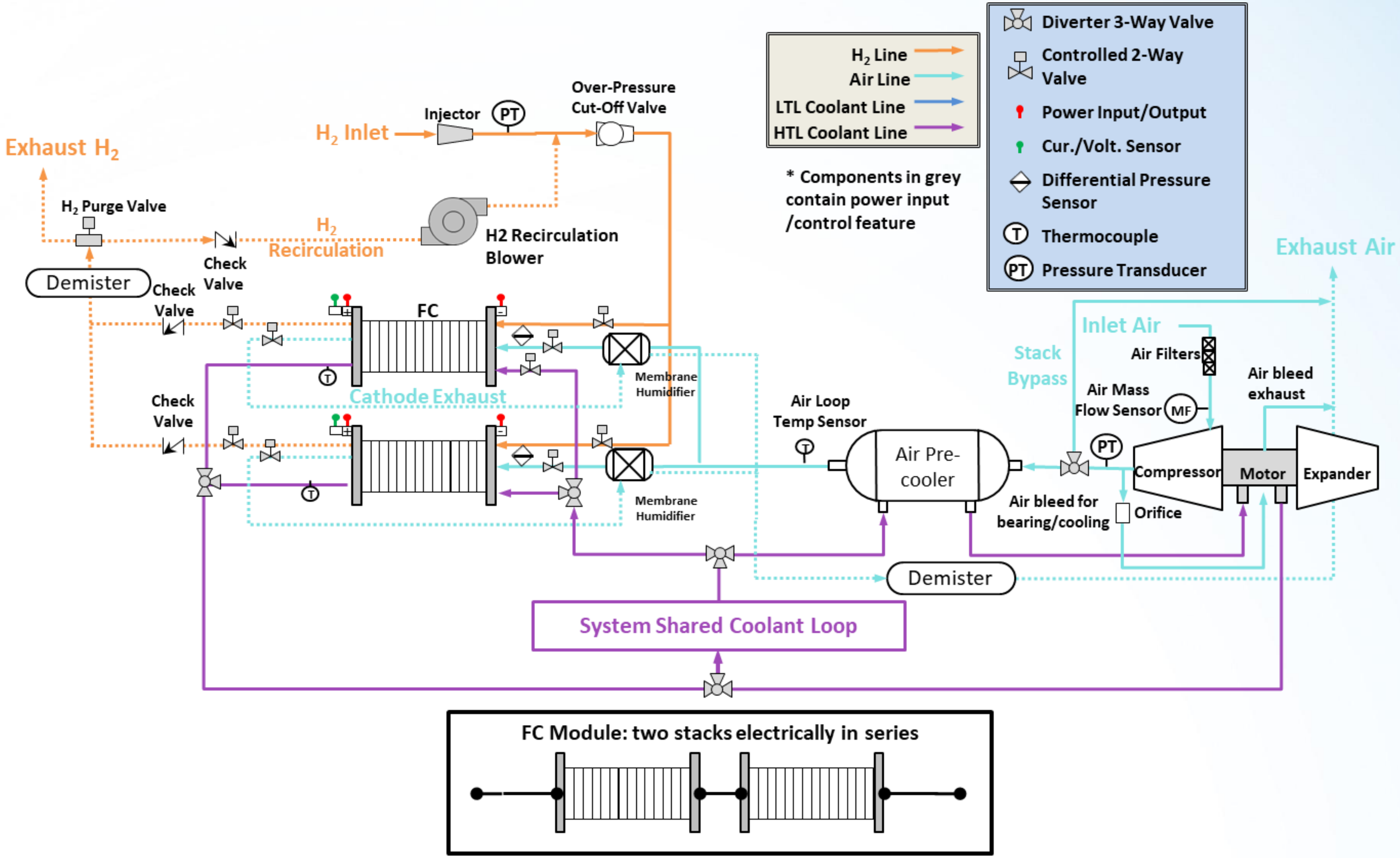


FC System: four FC modules electrically in parallel

Accomplishments and Progress:
2024 & 2030 FC Module Configuration 1,387kW$_{net}$ ORM Haul Truck

1,387kW FC System = 4 x 347kW$_{net}$ Fuel Cell Modules

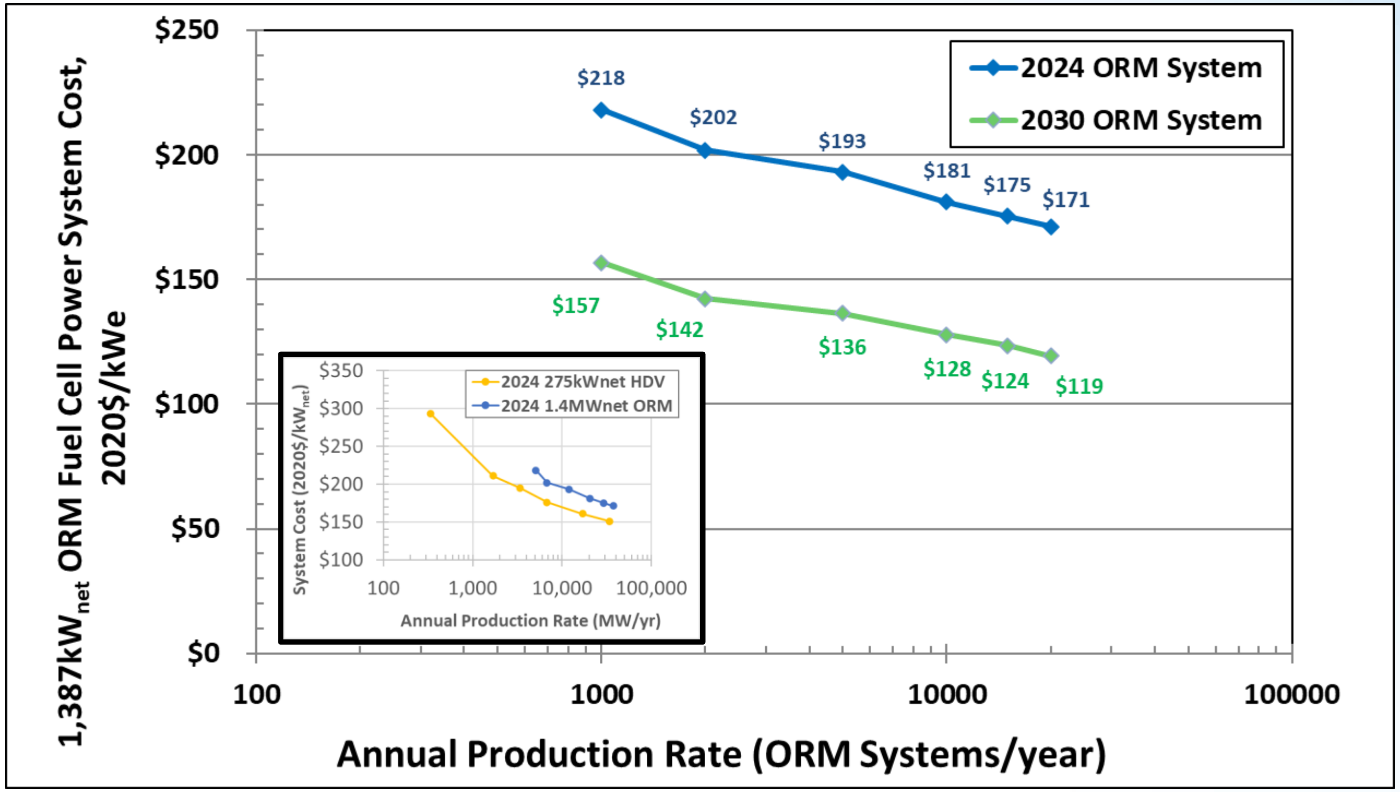
- Baseline (sea-level operation) BOP components within module are assumed to be the same as HDV components
  - Also assumed to benefit in cost from HDV production volumes
  - Exceptions: air filtration, thermal management, and fuel management
- Higher elevation compressor could be an add-on:
  - Supercharger to a CEM or
  - Turbocharger to a C/M unit



Accomplishments and Progress:

Preliminary ORM System Cost Evaluation (for Sea-Level Baseline)

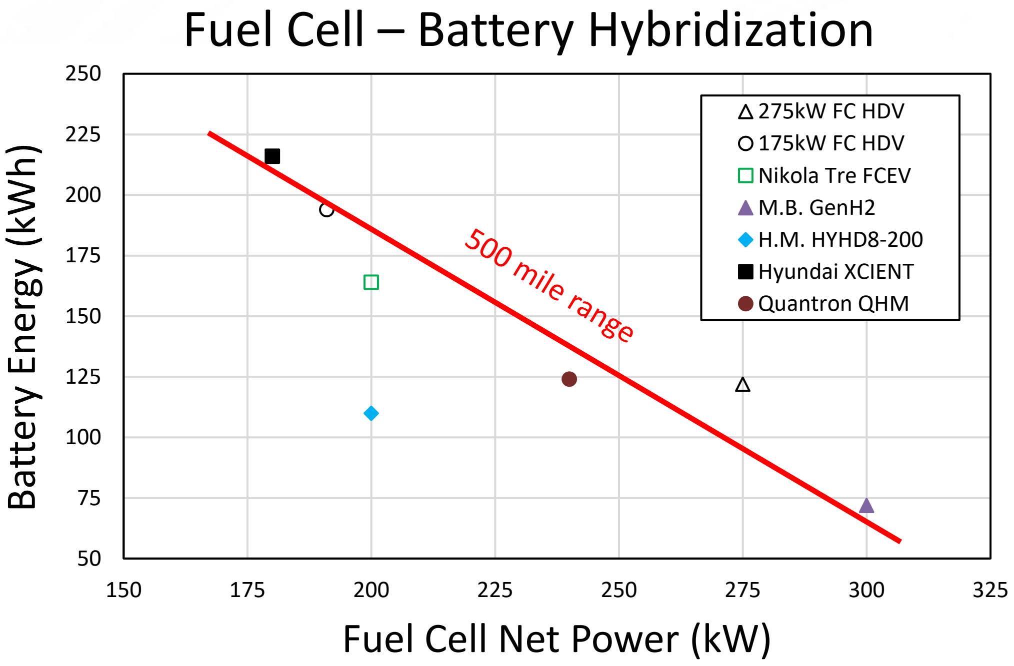
- Production Volumes
  - Stack & FC modules share in economies at scale with HDV.
  - Assuming 10k HDV modules/year in addition to the ORM production volumes.
  - BOP components outside the module (i.e., coolant loop) are produced at the same volume as the ORM trucks.
- Non-vertical integration
  - Similar to HDV trucks, ORM trucks are considered non-vertically integrated systems. Will have common, if not the same, component suppliers for FC and BOP components.
  - Additional markup included for suppliers on built and pass-through components
- Next Steps
  - Conduct a detailed DFMA cost analysis on single large radiator and coolant system components
  - Evaluate the cost of a 2nd stage of compression (supercharger and turbocharger options)
  - Obtain additional feedback from FC stack/module suppliers working in ORM space
  - Further explore component synergies with HDV systems

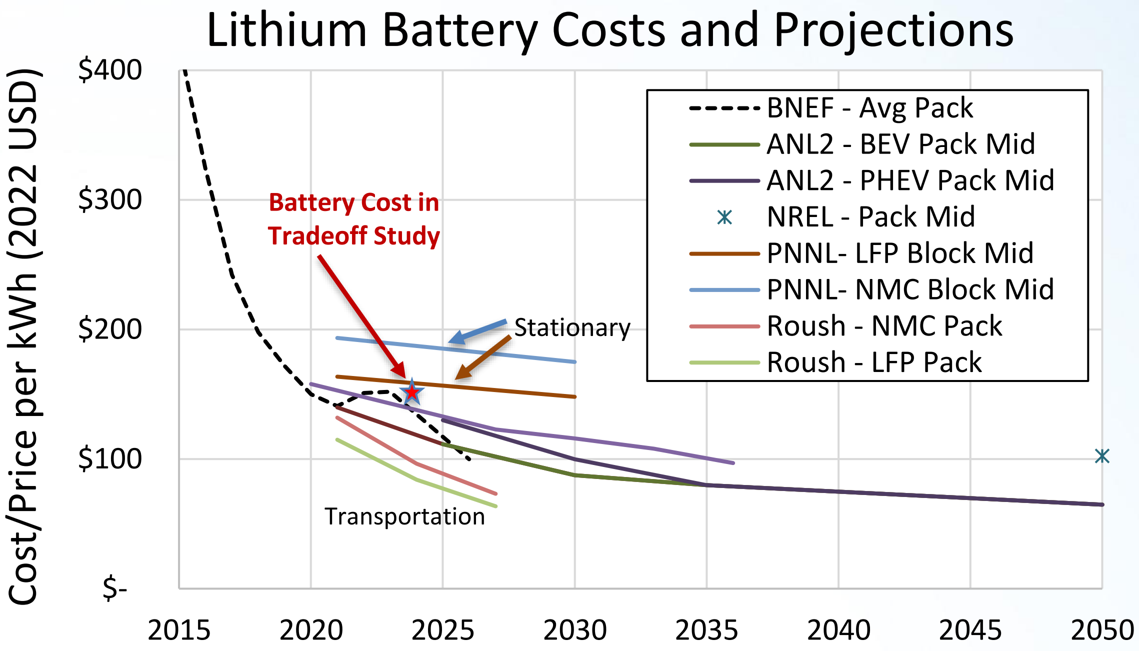


Annual Production Rate of ORM Systems	systems/year	1,000	2,000	5,000	10,000	15,000	20,000
Annual Production Rate of HDV System	systems/year	10,000	10,000	10,000	10,000	10,000	10,000
Equivalent ORM Systems (including HDV)	Eq. ORM sys/yr	3,500	4,500	7,500	12,500	17,500	22,500
Annual Production Rate of ORM Modules	modules/year	14,000	18,000	30,000	50,000	70,000	90,000
ORM Modules per system	modules/system	4	4	4	4	4	4

Accomplishments and Progress:
Battery System Impact on FC HDV

Tradeoff between FC power and Battery Energy. What are the capital costs for different **hybridization** and **battery chemistries?**





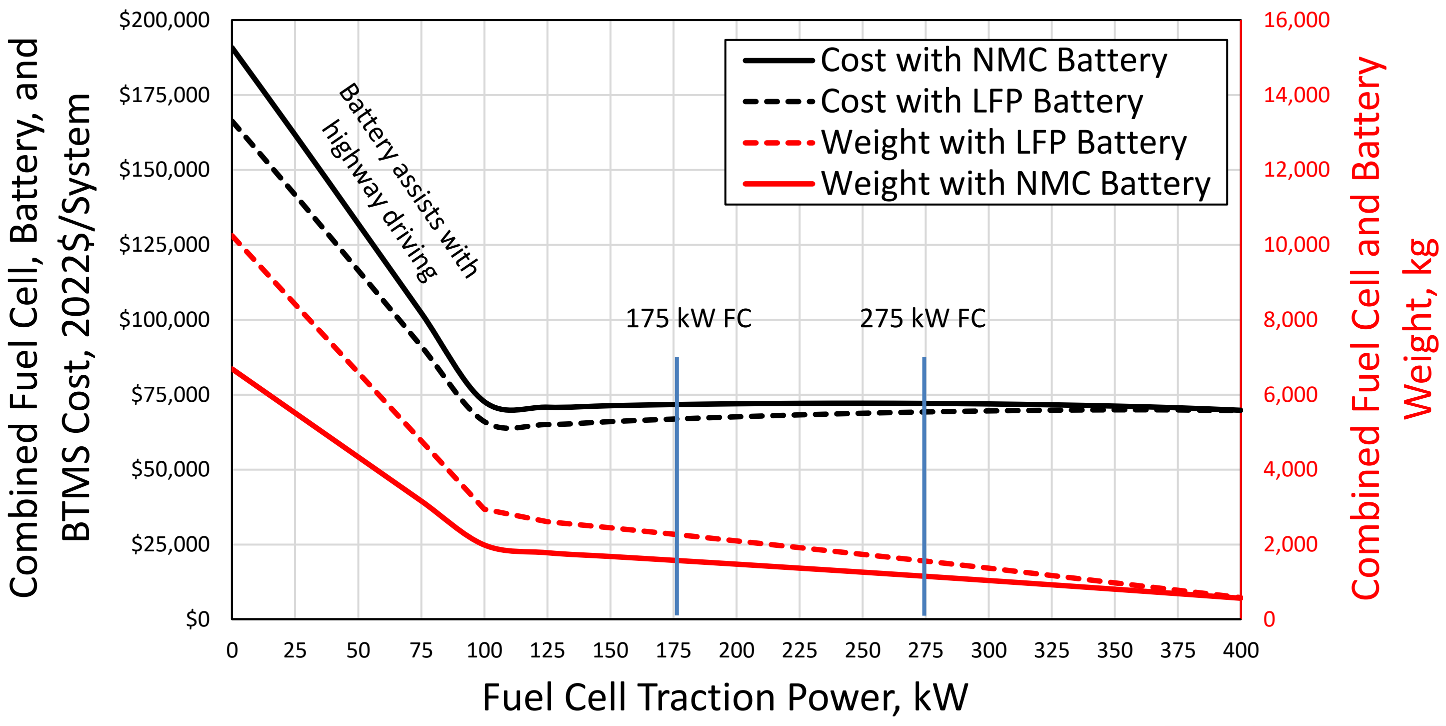
- 2021 battery pack cost in range of 115 to 194 $/kWh
- LFP batteries are 13-15% cheaper than NMC
- Transportation batteries are lower cost than stationary

https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/
https://vms.taps.anl.gov/document-download/?name=BEAN%20Heavy%20Duty%20Vehicle%20Techno-Economic%20Analysis
https://doi.org/10.2172/1866349
https://theicct.org/wp-content/uploads/2023/03/cost-zero-emission-trucks-us-phase-3-mar23.pdf
https://atb.nrel.gov/transportation/2020/definitions#batteryelectricvehicles
https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf

https://blogs.edf.org/climate411/files/2022/02/EDF-MDHD-Electrification-v1.6_20220209.pdf
https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9795037

Accomplishments and Progress:
Cost with Hybridization and Battery Chemistries

Model Inputs		275-kW FC	175-kW FC
Fuel Cell			
Fuel Cell Power Supplied to Motor Inverter	kW	275	175
Fuel Cell Cost (100k sys/yr in 2016$)	$	159	165
Battery			
Battery Power (traction)	kW	125	225
Battery Maximum Discharge Rate	E	1.91	1.91
Battery Depth of Discharge	%	70	70
Battery Capacity Loss	%	38	36
Battery Pack Average Cost, Energy Basis	$/kWh	151	151
Battery Manufacturing Margin	%	10	10
Battery Pack Chemistry Cost Difference	%	13.8	13.8
Other			
Cabin AC Parasitic Load	kW	5	5
Cabin AC Power Source		Battery	Fuel Cell
BTMS Coefficient of Performance		1.4	1.4
BTMS Markup	%	20	20
DC-DC Converter Efficiency, one-way	%	98	98



- Battery pack sized for range, acceleration, and hill climb scenarios
- Battery max discharge E-rate of 1.9

Results

- No major capital cost impact from hybridizing between 175 and 275 kW
- System with LFP battery saves $2,800-4,800 per system
- Larger 275 kW fuel cell system saves weight, 400-700 kg
- Need to consider hybridization tradeoff of capital cost vs. weight in a Total Cost of Ownership (TCO) model

Accomplishments and Progress:

Response to 2023 AMR Reviewer Comments

Reviewer Comment	SA Response to Reviewer Comment
"Approach should include total cost of ownership (TCO)"	Other DOE-funded projects focus on TCO analysis. Although SA has conducted TCO in the past, it is not considered a focus for this project. Capital cost results from this study have been used within TCO analyses in the past.
"Stacks lasting 25,000 (with selected materials) is difficult to see. Team should be looking at stack replacements."	When SA started looking at durability, we compared different strategies (oversizing vs stack replacement). Feedback from industry suggested oversizing as the best pathway to extend lifetime. This approach was reasonable for tracking cost improvements to reduce the sizing of the stacks.
"The project should assess the sensitivity of the battery cost...and include battery energy and chemistry."	At the end of 2023, SA conducted a detailed analysis of the battery sizing for two different levels of hybridizations for the HDV truck. The analysis took into account the differences in performance and cost of NMC vs LMP.
The project should assess the impact of using non-polyfluoroalkyl substances (non-PFAS) membranes."	SA will consider future analysis of non-PFAS membranes including hydrocarbon membranes.
"The project should compare against H_2 combustion ICE trucks"	H_2 used in ICEs is being investigated within the Vehicles Technology Office of DOE. Although H_2 ICEs may result in lower initial capital cost, efficiency and NOx emissions should be considered in a full comparative analysis against FC systems.

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. • Provided feedback on current 2024 & future 2030 analysis systems & manufacturing processes. • Participates in researching the affect of durability on cost. • Will contribute to rotary screen-printing evaluation by providing feedback on suitable materials and components and the impact to QC processes
Argonne National Laboratory (ANL) (sub on contract)	• Currently modeling the HDV Class 8 long-haul truck performance and durability based on new experimental results of PtC/C-ZIFF catalyst • Will supply detailed modeling results for optimized fuel cell operating conditions. • Provided SA with feedback on possible performance and durability for prelim. 2024 analysis. • Provided documentation and analysis results of off-road mining truck and provided feedback on modularization and system configuration. • Modeled HDV cooling system requirements and optimized FC operating conditions.
2023/2024 Collaborators	• Formal review of HDV system operation and components: FCJTT, companies TBD. • Off-road mining truck system design, operation, and configuration: Mining 3, Mahle, CellCentric, Mission Innovation Hydrogen Fuel Cell Offroad Working Group • Air loop components: Mann+Hummel and Mahle • Metallic BPP: Clenersys • Rotary screen printing: Zimmer

DEIA/Community Benefits Plans and Activities

This project does not have a Diversity, Equity, Inclusion, and Accessibility (DEIA) plan or Community Benefits Plan (CBP)

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. Membrane durability is not included in modeling and can certainly impact vehicle lifetime.
- 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.

MDV/HDV Study

- Catalysts with Enhanced Performance & Durability: Ordered intermetallic catalysts show great promise for both enhanced performance & durability. Testing under real and simulated considers is needed to verify performance.
- Hybridization: The optimal sizing and operating strategy to maximize durability and minimize cost of FC/battery hybrids is not well understood.
- Total Cost of Ownership: Many relevant topics evaluated in this project can affect the TCO. Deeper interaction with TCO analysis teams is needed.
- 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: Need perf. levels beyond those currently projected for 2030 to achieve targets.

Automotive System (based on 2022 analysis)

- 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 projected cost for 2025 system is $55/kW compared to $40/kW DOE target).
- $30/kW DOE target even harder to achieve: Projections for 2030 analysis ($49/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.

Proposed Future Work

Future Work for Baseline Models

- **Update Baseline DFMA Models for HDV, MDV, and ORM Systems**
    - Update models based on feedback from the Fuel Cell Joint Technical Team (FCJTT) –(US Drive and 21st Century Truck Partnership)
    - Incorporate ANL's performance and durability modeling and adjust future system projections based on those results
    - Complete ORM cost estimates with detailed radiator and coolant system
    - Obtain additional material quotes for ionomer, ePTFE, and GDL
    - Complete evaluation of cost addition for more durable BOP components
- Complete sensitivity analysis on HDV, MDV, and ORM Systems
- Document HDV systems in 2024 Final Report - due September 2024

Future Work for Side Studies

- Evaluate rotary screen printing process for several FC stack components
- Conduct DFMA analysis of new carbon coating for metallic bipolar plates
- Complete study on air loop components (air compressor bearing, demister, humidifier, and air filter)
- Conduct DFMA analysis of dry electrodes process (high solids-to-liquids ratio)
- Evaluate ORM FC thermal management system interaction with liquid hydrogen storage system

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

Summary of Findings

- **2023 MDV 77kW$_{net}$ Delivery Truck System**
  - Final results: ~\$207/kW$_{net}$ (current 2023), ~\$189/kW$_{net}$ (2025), ~\$147/kW$_{net}$ (2030) at 100k sys/year
- **2023 HDV 275kW$_{net}$ Long-Haul Truck System**
  - Final results: ~\$173/kW$_{net}$ (current 2023), ~\$146/kW$_{net}$ (2025), ~\$112/kW$_{net}$ (2030) at 50k sys/year
- **2023 HDV 175kW$_{net}$ Long-Haul Truck System (Side Study)**
  - Final results: ~\$180/kW$_{net}$ (current 2023), ~\$164/kW$_{net}$ (2025), ~\$129/kW$_{net}$ (2030) at 50k sys/year
- **2024 MDV 77kWnet Delivery Truck System**
  - Final results: ~\$197/kW$_{net}$ (current 2024), ~\$138/kW$_{net}$ (2030) at 100k sys/year
- **2024 HDV 275kW$_{net}$ Long-Haul Truck System**
  - Preliminary results: ~\$161/kW$_{net}$ (current 2024), ~\$114/kW$_{net}$ (2030) at 50k sys/year
  - Reduction in total Pt loading from 0.45 to 0.35mgPt/cm^2 reduced system cost by \$15/kW. Plan to update HDV system with optimized operating conditions from ANL in the future.
  - Preliminary adjustment to MEA material pricing increased cost by \$4/kW
- **2024 Ultraclass 1.4MW Off-Road Haul Mining Truck System**
  - Preliminary results: ~\$171/kW$_{net}$ (current 2024), ~\$119/kW$_{net}$ (2030) at 20k sys/year
  - Baseline system assumed to operate at sea level. Separate add-on BOP components to be evaluated for high elevation scenarios.
  - FC stacks assumed to be the same as HD stack and BOP components will change to ensure similar operating conditions in HDV.
  - Multiple gas and particle filters will be needed for mining environments. Large radiator and cooling system will be shared between four ~350kW FC modules.

Project Summary

- **Overview**
  - Exploring subsystem alternative configurations and benchmark cost where possible for LDV, MDV, HDV, and ORM FC Systems
  - In third 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 & results, extensive briefing to industry/researchers for validation & correction
- **Accomplishments**
  - Analyses:
    - Final system design and cost results for MDV and HDV FC systems for 2023, 2025, and 2030 technology years
    - Preliminary 2024 system design and cost results for 77kW MDV, 275kW HDV, and 1.4MW ORM systems
- **Collaborations**
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
  - Extensive discussions, interviews, feedback with many industry vendors/suppliers
- **Future Work**
  - Finalize MDV, HDV, and ORM system designs, complete sensitivity analyses, and draft 2024 final report.
  - Evaluate rotary screen printing, dry electrodes, and new carbon coating for bipolar plates
  - Complete study on air loop components