STRATEGIC ANALYSIS INC

2020 DOE Hydrogen and Fuel Cells Program Review Presentation

Fuel Cell Systems Analysis

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Project ID# FC163

Overview

Timeline

- Project Start Date: 9/30/16
- Project End Date: 9/30/21
- % complete: 70% of five year project (in Year 4 of 5)

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
  - ~$832k (through March 2020, SA only)
- Total DOE Project Value
  - $1.225M (over 5 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

Overall Project Objectives:

- Project current (2020) and future cost (2025) of automotive, bus, & 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 Fuel Cell Technologies Office programmatic decisions.
- Quantify the cost impact of components that improve durability.

Current Targets	Units (2016$)	Project Status 2020	Project Status 2025	DOE 2020 Target	DOE Ultimate Target
Cost of LDV FC Power Systems [a, b]	$\$/kW_{net}$	46	39	40	30
Cost of LDV FC Stacks [a, b]	$\$/kW_{net}$	19	12	20	15
Cost of LDV Bipolar Plates [a]	$\$/kW_{net}$	6[b] / 3[c]	4[b]	3	NA
Air Compression System Cost [a]	$/system	760	710	500	NA
Cathode Humidifier System Cost [a]	$/system	62	62	100	NA
Cost of HDV FC Power Systems [a, c]	$\$/kW_{net}$	84	71	80 (2030)	60

[a] Based on high production volume (500,000 LDVs per year and 100,000 HDVs per year)

[b] Based on stamped SS316 bipolar plates for LDV

[c] Based on embossed flexible graphite bipolar plates

Relevance: Timeline of Analyses

Year	Project Year	Technology	Proposed Analyses
2017	1	80kW Light Duty Vehicle (LDV)	Current (2017), 2020, 2025
		Med/Heavy Duty Truck	Scoping Study
		LDV System or Stack Component	Validation Study
2018	2	80kW LDV	Current (2018), 2020, 2025
		160kW MDV Class 6 Truck	Current (2018), 2020, 2025
2019	3	330kW HDV Class 8 Truck	Current (2019), 2025
		170kW MDV Class 6 Truck	Current (2019), 2025
2020	4	80kW LDV*	Current (2020), 2025
		275kW HDV Class 8 Truck	Current (2020), 2025
		170kW MDV Class 6 Truck / Class 8 Bus	Current (2020), 2025
2021	5	LDV	Current (2021), 2025
		Update to Buses & Trucks as needed	Current (2021), 2025

Impact since 2019 analysis final results:

- Incorporating ANL performance modeling of heat rejection and catalyst performance for 2020 HDV lead to $12/kW reduction in system cost
- Addition of cost for stack and system components that improve durability

*As recommended by DOE, the LDV cases are limited to modest updates (i.e. less detailed analysis than previous years of the LDV analysis)..

Approach:
Topics Examined Since 2019 AMR

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

2020/2025 Light Duty Automobile Systems

- **Updated Air Filtration System:** Augmentation of air loop components and updated pricing provided by Mann + Hummel (In Process)
- **Impact of Durability on Cost:** Assessment of system operation mitigation techniques (Ongoing Analysis)

2020/2025 Medium Duty/Bus and Heavy Duty Truck Systems

- **Updated Operating Conditions:** Collaboration with ANL and FCPAD (Interim Results)
- **Updated Air Filtration System (same as above)**
- **Hybridization Study:** Modeling of FC system sizing and optimal operation for durability (Interim Results)
- **Total Cost of Ownership (Class 8 Long-Haul System)**

2019/2020 Side Studies for Automotive/MDV/HDV System (not affecting baseline)

- **Ionomer Manufacturing Study:** Evaluation of gas-phase and continuous liquid epoxidation of hexafluoropropylene (HFP) (Preliminary Analysis)

***Milestone 1: Validation Study* – Completed in 2017**

***Milestone 2,5,8,11: System Definition* – Completed for 2020/2025 LDV, MDV and HDV Systems**

***Milestone 3,6,9,12: DFMA® Cost Analysis* – Completed for 2020/2025 LDV, MDV and HDV Systems**

***Milestone 4,7,10,13: Reporting of Cost Results* – (due Sept 2020) => Go/No-Go Decision**

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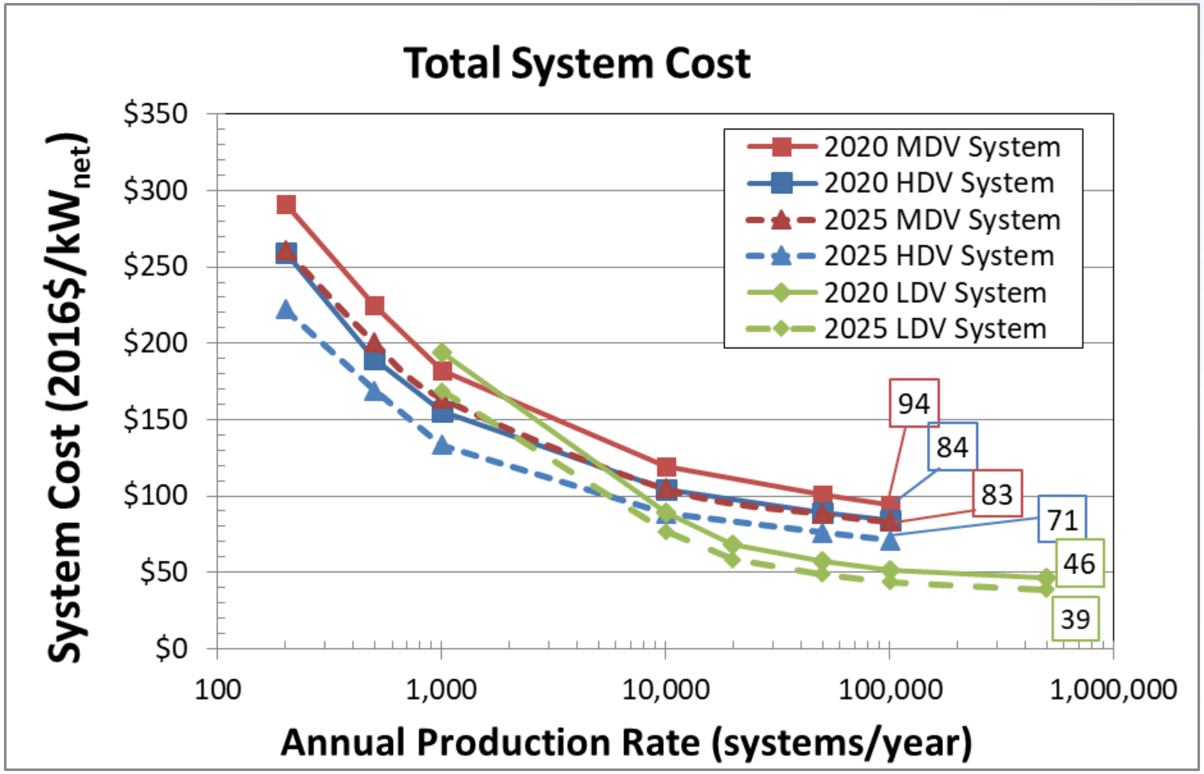
Accomplishments and Progress:

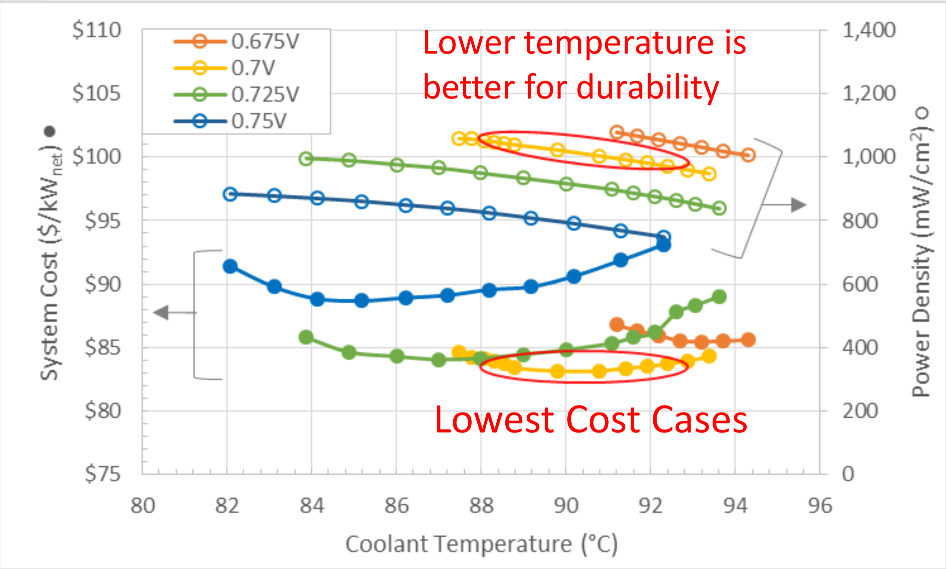
Preliminary Cost Results for 2020 Systems

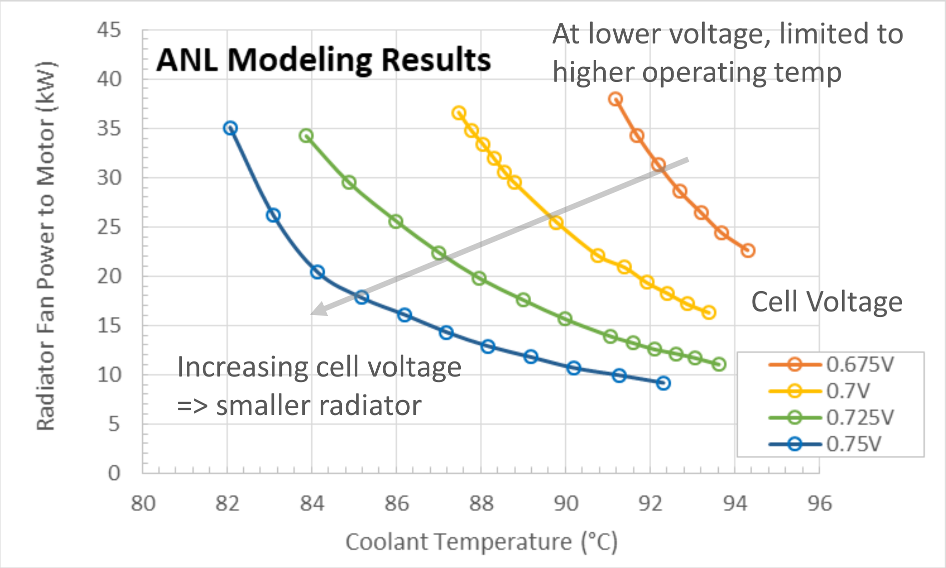


- Cost differences between LDV and MDV/HDV at 100k sys/year due to:
  - Total Pt loading (0.125mgPt/cm^2 for LDV vs 0.40mgPt/cm^2 for MDV/HDV)
  - LDV system considered as a vertically integrated OEM vs. MDV/HDV systems assume a non-vertical integration
    - Applied extra markup for MDV/HDV FC developer and power system integrator
    - Additional vendor/job-shop assumptions in non-vertically integrated systems

Accomplishments and Progress: Class 8 Long-Haul HDV System Performance Modeling Shows Capital Cost- and Durability-Optimal Operating Conditions ($84/kW at 0.7V/cell at 88°C)

- ANL modeling of radiator heat rejection at various FC stack conditions shows limitation of heat transfer
- Power density has larger impact on cost than radiator sizing





	2019 HDV System (330kW$_{net}$)	2020 HDV System (275kW$_{net}$)
Gross Power (kW$_{gross}$)	415	346
Power Density (mW/cm²)	840	1,050
Total Pt loading (mgPt/cm²$_{total\ area}$)	0.4	0.4
System Voltage (cell voltage)	400V (0.769V)	400V (0.70V)
Stack Temp. (Coolant Exit Temp) (°C)	85 (peak temp. during 6% grade)	88 (peak temp. during 6% grade)
Q/ΔT (kW$_{th}$/°C) (T$_{ambient}$=25°C)	4.3	4.3
System Cost ($/kWnet)	$97	$84

Current system does not include external humidification to limit Pt dissolution

Accomplishments and Progress:
Quantifying the Impact of Durability on Cost

- Review of areas where durability issues could impact the system cost
  - Collaborated with NREL, ANL, and LANL to create list of mitigation steps
  - List broken into two categories: Materials and System Solutions

Mitigation Step	Hardware	Other Impacts	Currently in Models?	Current Status
Material Solutions (to improve stack durability)				
Increase Pt loading	Increase total Pt loading to 0.35mgPt/cm^2	Enhances power density	LDV: No MD/HDV: Yes	Collab. With ANL
Use radical scavengers	Add 9 micrograms Ce/cm^2 (in form of CeO_2 nanopowder) to cathode catalyst ink		LDV: To be added MDV/HDV: Yes	Easy and inexpensive to add
Manage particle agglomeration	Novel catalyst geometries and formulations	Probable increase in synthesis costs. Potential water management issues.	Not currently modeled	R&D needed
Limit leaching	Mirai approach: use <10%mol Co (in cathode catalyst)		LDV: No MDV/HDV: Yes	Not applied to baseline LDV
Bipolar Plate Base Material	LDV: Ti plates (used in Mirai) MDV/HDV: Graphite Plates	Ti material would increase material cost.	LDV: No MD/HDV: Yes	Flexible Graphite BPP analyzed
Other material solutions	Eg. Use of high performance, inherently durable catalysts with high surface area carbon supports	Unknown	No	R&D needed

Accomplishments and Progress:

Mitigation Step	Hardware	Other Impacts	In Current Model?	Current Status
System Solutions (to improve stack durability)				
Thicker membrane to delay failure due to membrane thinning	25 micron membrane (instead of <14 micron)	Lowers power density	No	ANL perf. based on 14 µm
Dummy cells on stack ends to prevent condensation	1 or 2 dummy cells on each end of stack. adds $0.05 to $0.10/kW$_{net}$	Ensures temperature uniformity for all power generating cells	Yes	Toyota and Honda Patents describe use.
Gas-purge of Anode at shut-down	Add 3-way valve, $24-$50 each, 1 per stack	Additional H_2 loss during each shutdown. Shutdowns more frequent than current/baseline sys. Partially offset by reduced anode purges (of N_2 &water buildup)	LDV: No MD/HDV: Yes	Air-purge questioned. Investigating.
Limit temperature to <90°C	Larger radiator: at peak 85°C 18% area increase (93°-40°)/(85°+40°)=1.18	Results in (slightly) lower power-density and larger-stack	LDV: No MD/HDV: Yes	ANL analysis
Clip voltage at 0.85V/cell	Cell-by-cell voltage monitoring system	Regulate air flow, temperature, and humidity to avoid stack operation at high cell voltage while still load-following.	In Process	ANL/FCPAD analysis & testing. SA to quantify cost
Limit voltage slew rate	No hardware change needed	Time delay expected to be ~1 sec. Negligible battery size impact expected.	No	R&D needed

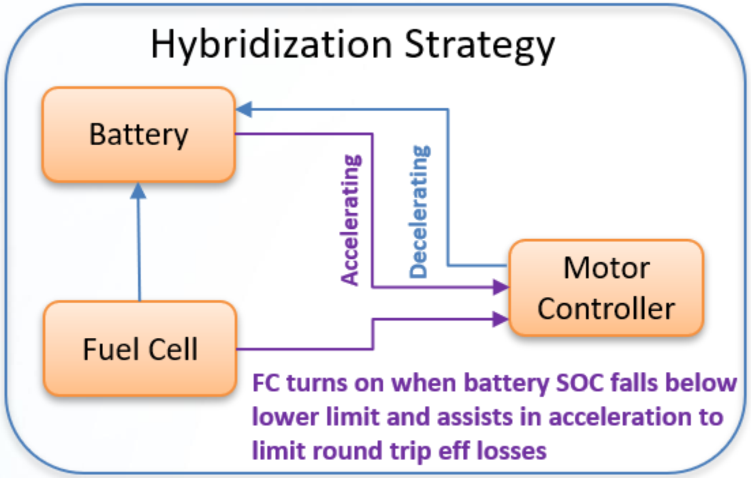
Accomplishments and Progress:

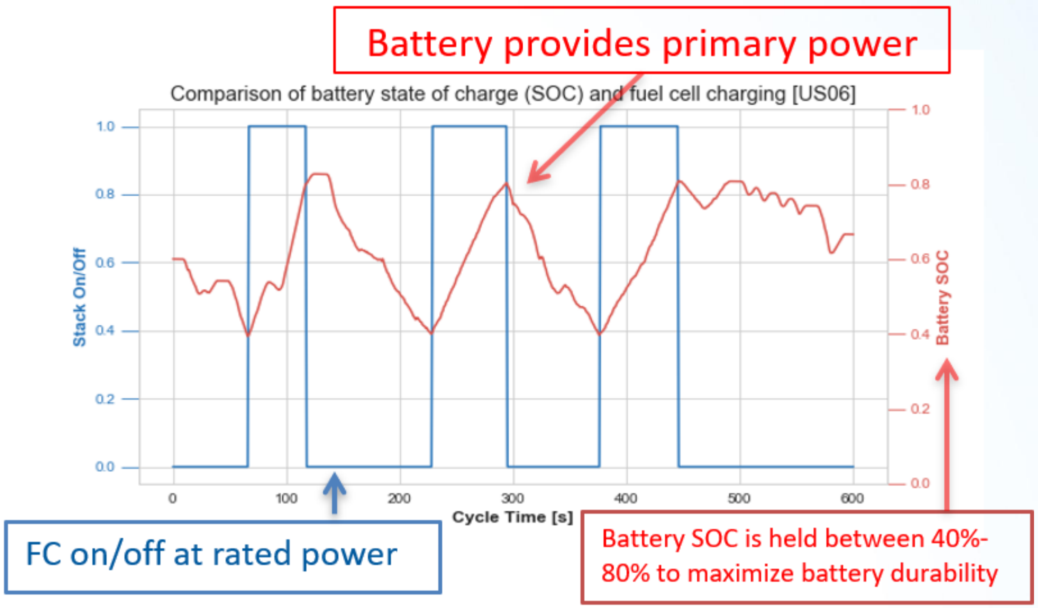
Mitigation Step	Hardware	Other Impacts	In Current Model?	Current Status
System Solutions (to improve stack durability)				
Run drier, lower RH reduces Pt dissolution	Remove humidifier	Lowers power density, restricted operation to prevent membrane dry-out.	LDV: No HDV: Yes	ANL 2020 Analysis
Run wetter/ Run with less RH variability	Possibly larger humidifier. Ballard Bus approach: “run wetter”. Approach: avoid RH swings that cause pin-holes at inlet and outlet	Impacts power density	No	Potential ANL analysis
Run load through shut-down and don’t let voltage go up	Additional system controls maybe needed: +$100/system		In Process	SA to quantify cost
Oversize stack	Increase in stack size	Increased stack size would increase cost (<$2/kW for LDV and <$5/kW for HDV at high volume) but also increases fuel economy.	LDV: No MD/HDV: Yes, +10% of active area	SA to analyze impact on fuel economy
Accept >10% power degradation over system lifetime	No/limited hardware impact Approach: redefine “durability”	System will provide <90% rated power in later years of lifetime	No	Easy to postulate, but really supplier decision.
Hybridization	Increase in battery size.	Decrease in fuel economy.	In process	SA to analyze

- ANL modeling shows 8,000hrs can be achieved with <53% ECSA loss (correlates with 10% power loss, i.e. end of life) if durability-optimized operating conditions are maintained (primarily cell voltage <0.85V)
- SA to continue working with ANL on these activities in the future to estimate the cost impact for systems capable of meeting 8,000hrs without accepting 10% power derating

Accomplishments and Progress:
Hybridization Study Motivation and Background

- Primary motivation: **develop additional strategies** to evaluate the cost impacts of durability
- Stack cycling, particularly at part power and high voltage, is a significant source of degradation
- FC-dominant architectures operate at part power for the majority of the drive cycle
- Alternative hybridization schemes with the **stack operating at constant power in an on/off mode can increase the effective life of the stack (by turning FC off during large fractions of vehicle motion)**
- Goal is to **study the cost, efficiency, and durability tradeoffs** for alternative hybridization strategies compared to a fuel cell dominant architecture across a number of vehicle applications: LDV, MDV, and HDV





- Stack cycles on/off depending on battery SOC and motor controller requirements
- Simulation is adapted from FASTSim* model (2018 python version)

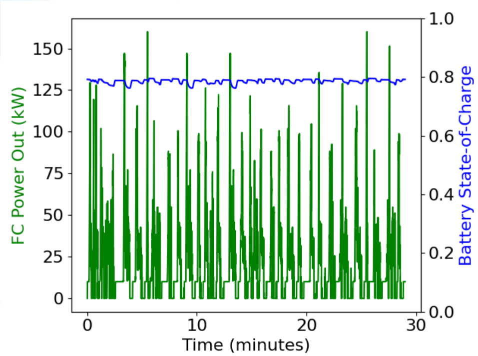
*Brooker, Aaron, Jeffrey Gonder, Lijuan Wang, Eric Wood, Sean Lopp, and Laurie Ramroth. "FASTSim: A Model to Estimate Vehicle Efficiency, Cost and Performance," 2015-01–0973, 2015. https://doi.org/10.4271/2015-01-0973.

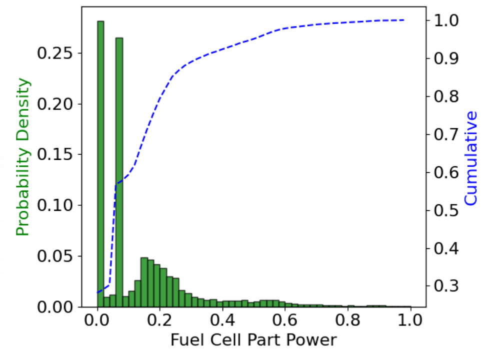
Accomplishments and Progress:

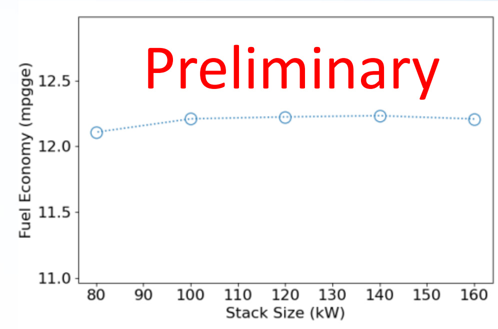
Hybridization Study Results for FCEB on Braunschweig Drive Cycle

FC dominant system: Load-Following Mode

FCEB= Fuel Cell Electric Bus

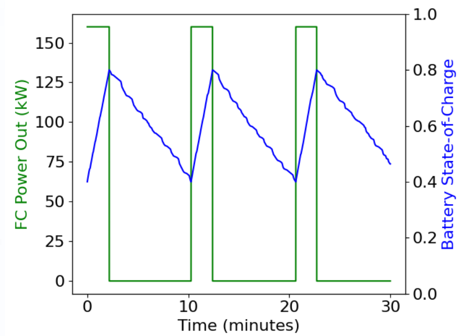


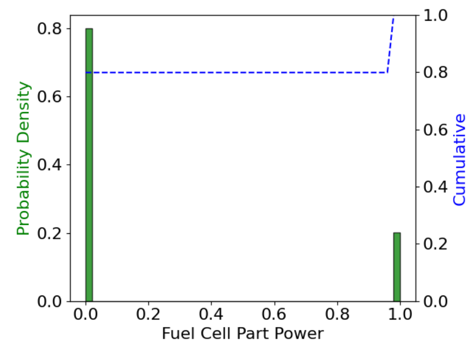


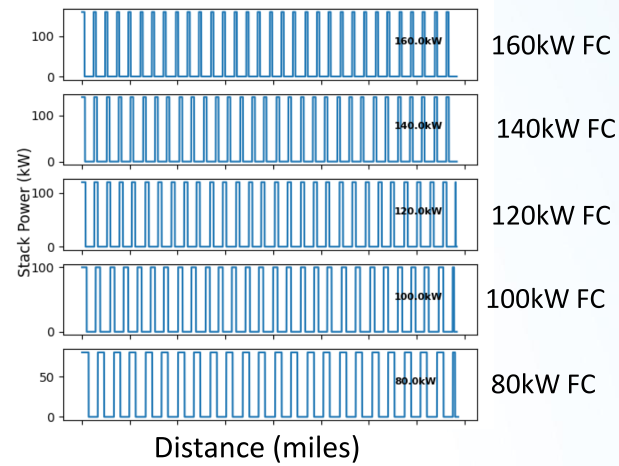


- Bus is idle a significant fraction of the time and the fuel cell sits at or near 0 kW for ~50% of cycle.
- Minor change in fuel economy over single drive cycle at various stack sizes (Preliminary Results).

FC Hybrid Systems: On/Off mode







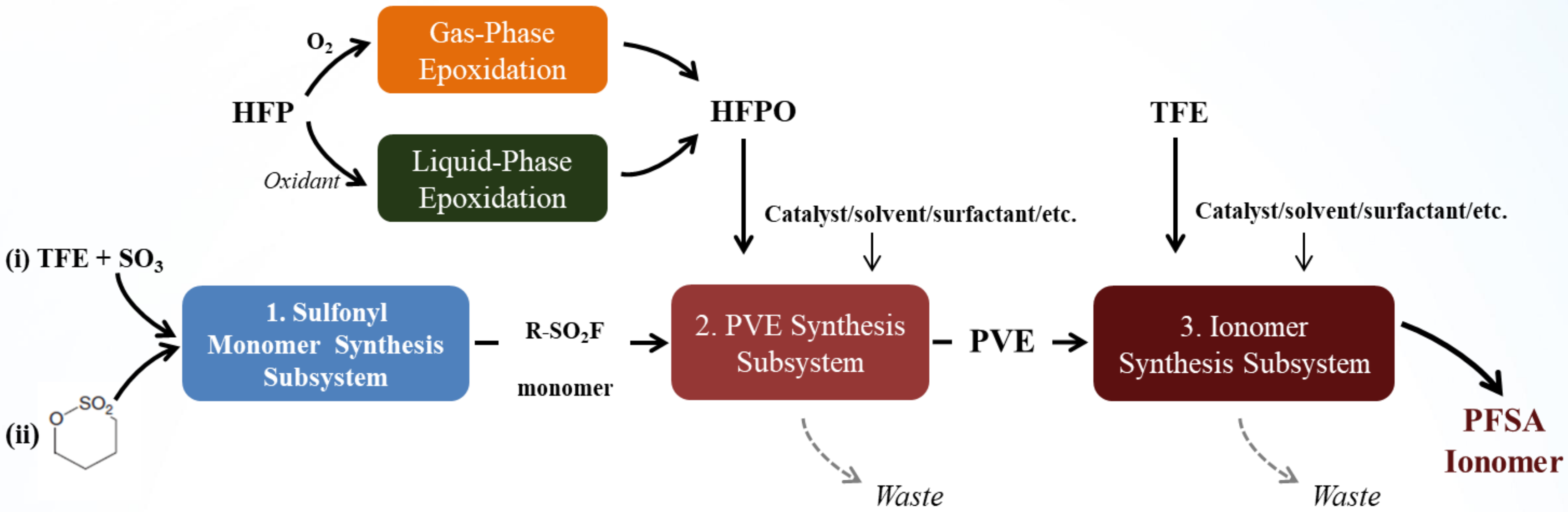
- 160kW Fuel cell sits at 0 kW for ~80% of cycle.
- Tight controls on start-up/shut-down are needed to realize fuel cell lifetime gains
- Future models to incorporate operating conditions to limit ECSA loss and impose fuel economy degradation over vehicle life.

Hybridization strategy to also be applied to LDV, MDV, and HDV Truck

Accomplishments and Progress:

Ionomer Cost Analysis

- Two previous reports by GM (Xie, 2010)[1] and Roland Berger (Bernhardt, 2013)[2] analyzed the cost of PFSA production by estimating the CAPEX/OPEX of steps 1-3 and using market price HFPO as input
- <u>**HFPO and PVE synthesis (from HFPO) identified as major cost drivers**</u>
- Recent set of literature suggests that **gas-phase epoxidation** could produce cheaper HFPO than the liquid-phase epoxidation routes most commonly used

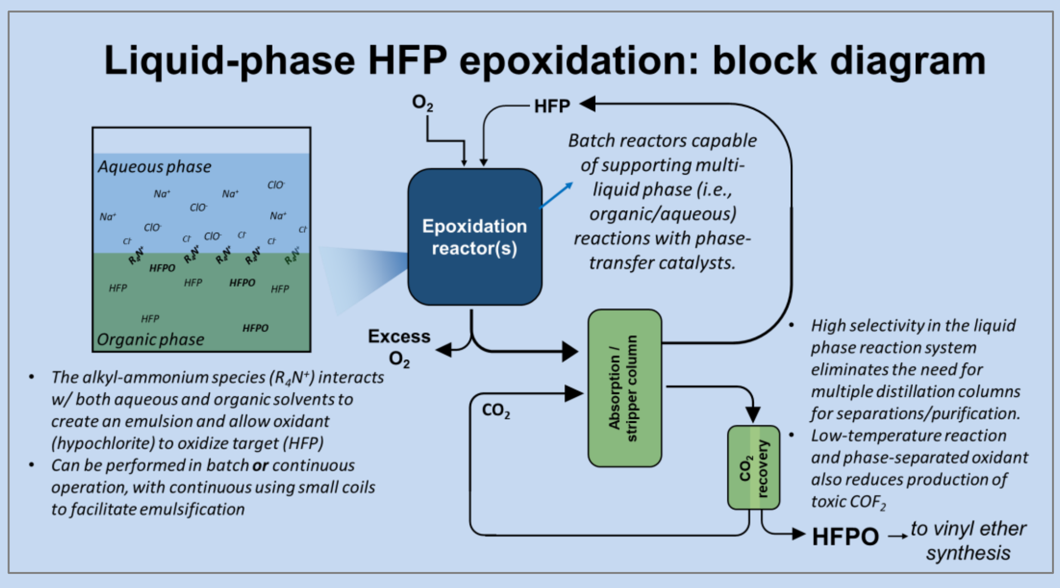


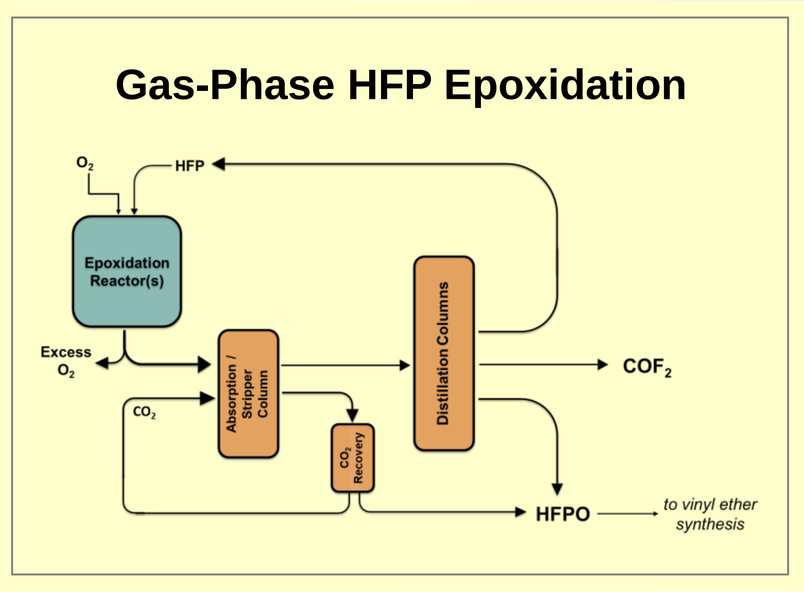
PFSA Ionomer Production

(1) Xie, T.; Mathias, M. F.; Gittleman, C.; Bell, S. L. High Volume Cost Analysis of Perfluorinated Sulfonic Acid Proton Exchange Membranes; Fuel Cell Activities; General Motors: Honeoye Falls, NY, 2010.

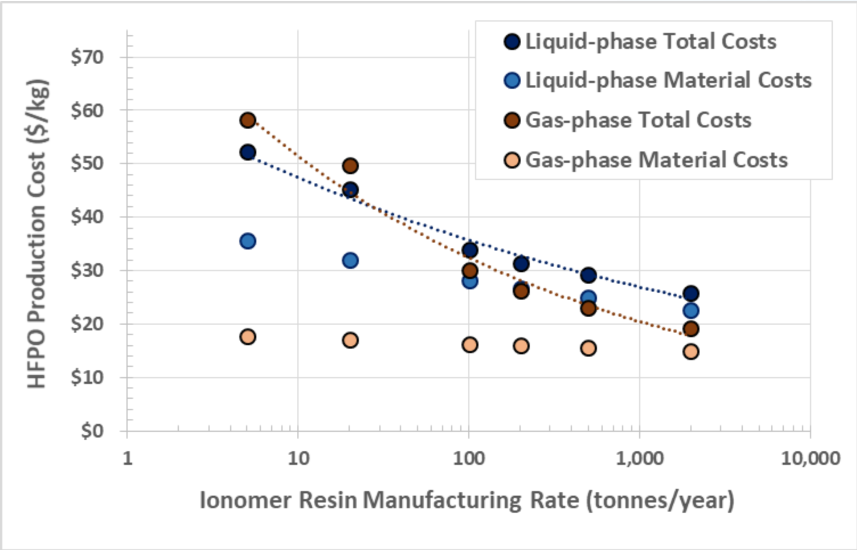
(2) Bernhardt, W.; Riederle, S.; Yoon, M. Fuel Cells--A Realistic Alternative for Zero Emission?, 2013.

Accomplishments and Progress: Focus on Estimating HFPO Cost





- SA performed a detailed DFMA® analysis of <u>liquid-phase and gas-phase epoxidation</u>
- At low production rates, liquid-phase HFPO production is cheaper by ~10%.
  - The lower reaction selectivity of the gas-phase approach necessitates higher capital expenditures for separations and waste handling
- At high production rates, gas-phase synthesis is ~20 – 30% less expensive due to lower **Materials** costs:
  - Cheap oxidant (O_2)
  - Inexpensive catalyst/initiator (copper tubes)
  - No liquid solvent(s)



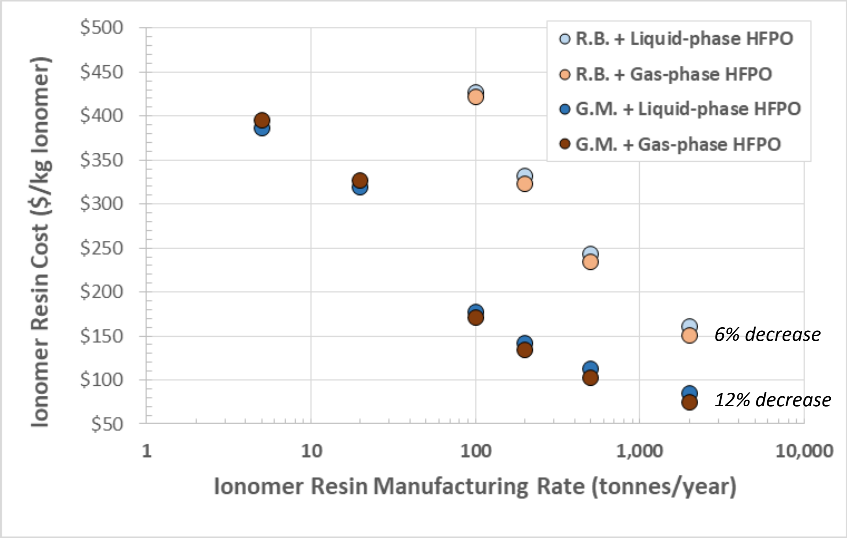
Accomplishments and Progress:
Gas- vs. Liquid-Phase HFPO Effect on Ionomer Costs

- The decrease in HFPO costs from gas-phase synthesis at high production rates results in a **6% (R.B. estimate) to 12% (G.M. estimate) decrease in total ionomer costs**
  - If gas-phase reaction selectivity can be improved to 90% (without major cost increase), the decrease in ionomer costs would be 10% - 19%
  - HFPO is a significant cost input for PFSA ionomers, but one of many factors

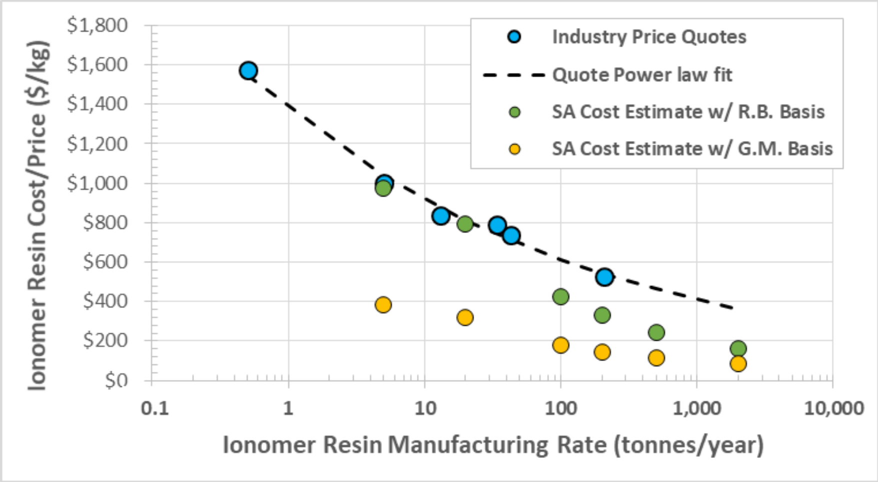
- The Industry **Price** Quotes (max. production rate ~200 tonnes/year) were extrapolated to 2,000 tonnes/yr or 10M veh/yr). At this production rate, industry pricing of ionomer could still exceed **$350/kg**

- High-volume ionomer **cost estimates** (based on liquid-phase HFPO syn. utilizing G.M. and R.B. assumptions) are:
  - **G.M.: $85/kg$_{ionomer}$ @ 2,000 tonnes/yr**
  - **R.B.: $160/kg $_{ionomer}$ @ 2,000 tonnes/yr**
  - These preliminary cost estimates would allow for significant sales margins at high volume.

Manufacturing Cost Estimates comparing HFPO Synthesis Methods



Ionomer Resin Manufacturing Cost w/ Industry Quotes



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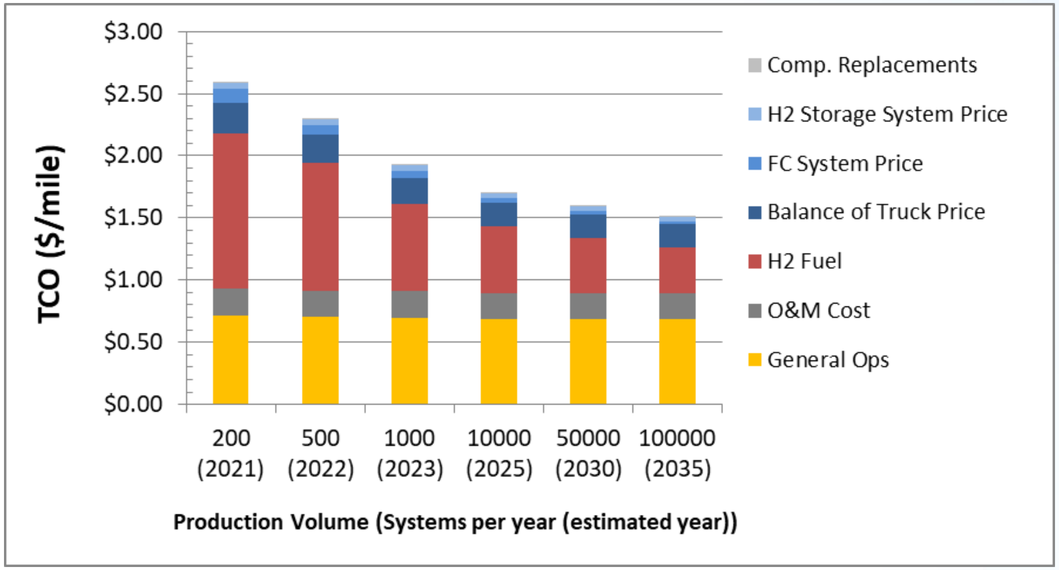
Accomplishments and Progress:

Class 8 Long-Haul Total Cost of Ownership (TCO)

- Discounted cash flow (DCF) analysis of total cost of ownership for Class 8 long-haul truck
- Truck power system design based on ANL modeling
- Other than General Operation costs (driver wages, insurance, permits, tolls, and tires), fuel cost has potentially greatest impact on TCO in future
- Need for systems with high fuel economy and low-cost H_2 fuel
- Reduction in TCO between current 2021 and 2035 is a combination of increased production volume, minor system improvements, increase in fuel economy, and reduction in fuel price

PEM FC Dominant System	HDV Design Value
Vehicle Test Weight (US tons)	35
Percentage of cargo mass to Test Weight	62%
Fuel Economy (miles/kg)	9.4 - 12
Fuel Cost ($/kg)	$6-16
Range (miles)	750
On-Board Fuel Storage (kg)	63-80
Fuel Cell Power net/gross (kW)	275/346
Motor Peak Power (kW) Motor Cont. Power (kW)	600 350
Battery Power (kW peak) Battery Energy (kWh, 100% DOD/Usable)	112 37.5/26.3



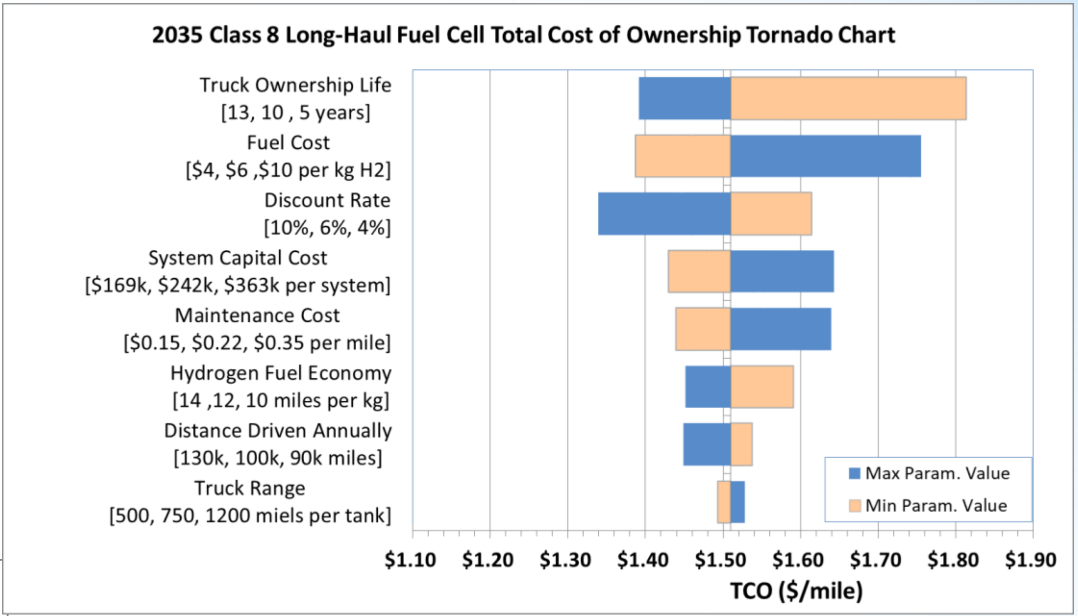
Infrastructure cost and payload opportunity cost not included in TCO

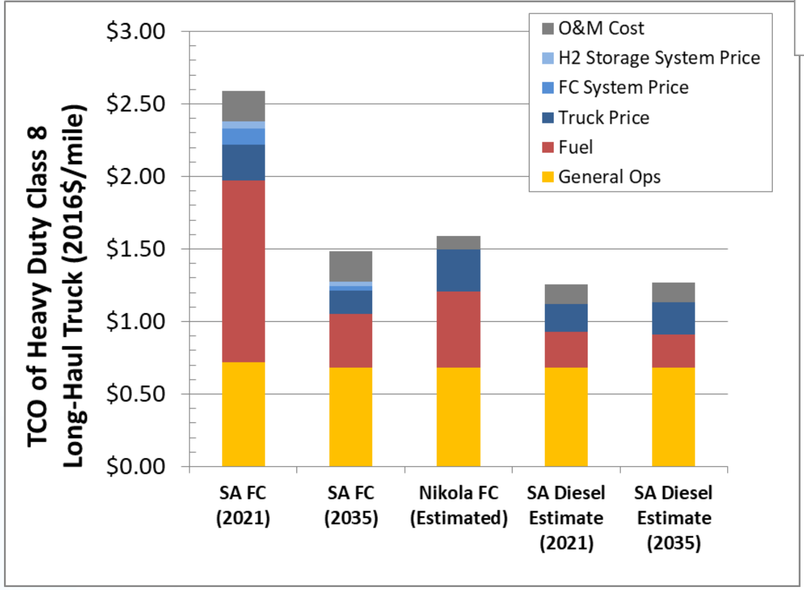
Accomplishments and Progress:

TCO Sensitivity Analysis

Single Variable Sensitivity at 100k sys/yr

- Estimate 100k sys/yr production in 2035
- TCO most sensitive to truck ownership lifetime and fuel cost
- Impact of truck range only affects capital cost of fuel tank





FC System Compared to Diesel Truck

- SA estimate for 2021 and 2035 FC truck TCO
- General Ops constant across all estimates
- SA estimate of Nikola cost breakdown based on $6/kg H_2 price[1]
- SA estimate for diesel truck increases slightly due to capital cost. Fuel cost contribution about even between 2021 and 2035 due to increase in both fuel economy and fuel pricing.
- FC Trucks have slightly higher TCO than diesels but are clean

[1] https://www.ccjdigital.com/nikola-discusses-hydrogen-infrastructure-its-class-8-and-total-cost-of-ownership/

Accomplishments and Progress:

Responses to Previous Year's Reviewers' Comments

2018 Reviewer's Comments	Response to Reviewer's Comment
"There should be a stronger focus on the TCO for HDVs."	SA conducted a TCO analysis for long-haul Class 8 trucks and will continue to refine this analysis in future work (pending time and funding available).
"There should be a sensitivity analysis on the level of hybridization between the fuel cell and battery on the MDV/HDV TCO. "	SA conducted a preliminary analysis on different levels of hybridization and duty cycle for fuel cell within a bus. This analysis will be further evaluated for a delivery truck and long-haul Class 8 HDV.
"It could be relevant to assess the impact of operation modes such as start-up and shutdown in terms of "penalty" on durability and cost, as this is part of the real operation of a system.	As part of system mitigation strategies for durability, SA is investigating best practices for startup/shutdown and the component costs added to the system to prevent significant degradation: 1. Maintain voltage below 0.85V as much as possible 2. Monitor cell voltage to detect increase in degradation 3. Consume gases upon shutdown to prevent gas cross-over leakage or cathode oxidation
"It will be informative to further understand if LDV manufacturing can be leveraged for MDVs/HDVs."	SA presented on this topic at the 2017 and 2019 Fuel Cell Seminar. At low volumes, pooling of LDV (1k sys/yr) and HDV (200 sys/yr) stack orders can reduce capital costs by almost 30%.

Collaboration & Coordination

*Additional Collaborations Listed in Reviewer Slides

Partner/Collaborator/Vendor	Project Role
National Renewable Energy Laboratory (NREL) (sub on contract)	• Provided knowledge and expertise on QC systems for FC manufacturing lines. • Reviewed and provided feedback on SA's assumptions for MEA & R2R processing and techniques. • Provided feedback on current 2020 and 2025 analysis systems and manufacturing processes. • Participates in researching the affect of durability on cost.
Argonne National Laboratory (ANL) (sub on contract)	• Supplied detailed modeling results for optimized fuel cell operating conditions (based on experimental cell data). • Provided SA with model results for system pressure, mass flows, CEM η, and membrane area requirements for optimized system. • Provided modeling data on durability for various operating conditions. (2020) • Modeled HDV cooling system requirements and optimized FC operating conditions
2019/2020 Collaborators	• Chad Hunter (NREL) reviewed SA's HDV TCO analysis. • Mann + Hummel provided information on air management system components and pricing • Aeristech provided information on air compression technology • Norbek provided BPP and cell leak testing system costs
Vendors/Suppliers	See back-up material for list of ~30 other companies with which we have consulted.

Remaining Barriers and Challenges

- PFSA ionomer cost uncertainty: Some in industry suggest ionomer cost may be ~$500/kg even at high production volumes. Alternative formulation or fabrication process may be required.
- 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.
- Gasket material cost: Low-cost PET material degrades under FC conditions. Polyethylene Naphthalate (PEN) is a recommended alternative, but may lead to ~$5/kW cost increase.

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: While the 2025 projected systems meets the $40/kW DOE LDV cost target, it requires substantial performance improvements to do so.
- $30/kW DOE target even harder to achieve: Projections for 2025 analysis suggest the DOE ultimate target of $30/kW may be difficult to achieve and will require much lower material costs.
- 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 nor modeled.
- Hybridization: Better understanding of the FCV truck preferred operating mode is needed i.e. how much hybridization is cost and durability optimal.

Proposed Future Work

Near-Term Future Work

- Incorporate durability into cost modeling for system capital cost and TCO
    1. Voltage Control: cell-by-cell monitoring and power electronics design
    2. Oversizing stack: impact on fuel economy
    3. Hybridization: Battery/FC sizing impact on fuel economy
- Evaluate a Class 4 delivery truck and Class 8 Long-Haul truck as part of the hybridization study
- Conduct sensitivity analyses for LDV, MDV and HDV systems
- Document in 2020 Final Report: Report due September 2020

Far-Term Future Work

- Further investigate synthesis cost of PFSA or other ionomer chemistries
- Continue to investigate ways to incorporate durability into cost modeling

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

Technology Transfer Activities

Not applicable for SA's Cost Analysis

Summary of Findings

- **LDV 80kW$_{net}$ System**
  - Interim results: ~$46/kW$_{net}$ (current 2020) and ~$39/kW$_{net}$ (2025) at 500k sys/year
- **MDV/Bus 170kW$_{net}$ System**
  - Interim results: ~$94/kW$_{net}$ (current 2020) and ~$83/kW$_{net}$ (2025) at 100k sys/year
- **HDV Long-Haul 275kWnet System**
  - Interim results: ~$84/kW$_{net}$ (current 2020) and ~$71/kW$_{net}$ (2025) at 100k sys/year
- **Impact of Durability on Cost**
  - Material and System Solutions (qualitative and quantitative) incorporated into system cost models
  - Preliminary ANL results of quantifying the ECSA loss allowable for 8,000 hrs in LDV systems may not have a significant impact to FC cost
- **Hybridization Study**
  - Preliminary results of FC bus drive cycle analysis suggests a minor impact to fuel economy between different size hybrid FC systems in on/off mode
  - Greater trade-off in TCO observed between fuel cost and ownership life
- **Ionomer Cost Study**
  - At low production rates, liquid-phase HFPO production is cheaper by ~10% (than gas-phase synthesis)
  - At high production rates, gas-phase synthesis is ~20 – 30% less expensive due to lower Materials costs: cheap oxidant (O_2), inexpensive catalyst/initiator (copper tubes), and no liquid solvents
- **Class 8 Long-Haul Truck Total Cost of Ownership**
  - In the near-term (2021) at low production volume (200 sys/yr) and high H_2 pricing ($16/kg), the interim TCO value for FC trucks is roughly twice the estimated value for diesel trucks.
  - By 2035, at high production volume (100k sys/yr) and low H_2 pricing ($6/kg), TCO comes down to ~$1.50/mile (~18% higher than estimated diesel truck).

Project Summary

- **Overview**
  - Exploring subsystem alternative configurations and benchmark cost where possible
  - In year 4 of 5 year project
- **Relevance**
  - Cost analysis used to assess practicality of proposed power system, determine key cost drivers, 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 and open discussion of assumptions and results
- **Accomplishments**
  - 2019 MDV and HDV analysis documented (report coming soon)
  - LDV, MDV/Bus and HDV 2020 & 2025 fuel cell systems analysis results
  - Analyses:
    - Impact of Durability on Cost
    - Hybridization Study
    - Ionomer Cost Study: Gas and liquid phase epoxidation of HFP
    - Long-Haul HDV Total Cost of Ownership (TCO)
- **Collaborations**
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
  - Extensive discussions, interviews, feedback with 30+ industry vendors/suppliers
- **Future Work**
  - Continue to incorporate durability into cost analysis, evaluate additional hybridization cases for different types of vehicles, and draft 2020 final report.

Technical Back-up Slides

Approach: DFMA® methodology used to track annual cost impact of technology advances

What is DFMA®?

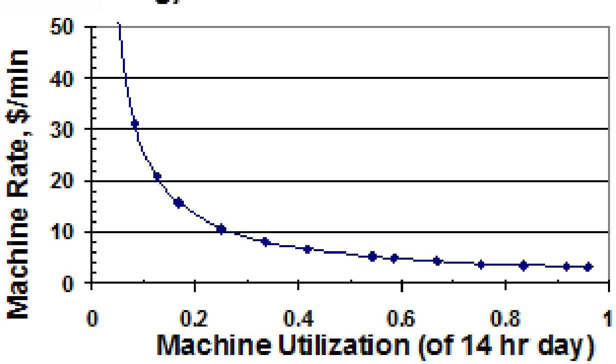
- DFMA® = Design for Manufacture & Assembly = Process based cost estimation methodology
  - Registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Company (Ford) design/costing method for the past 20+ years
- SA practices are a blend of:
  - "Textbook" DFMA®, industry standards and practices, DFMA® software, innovation, and practicality

Estimated Cost = (Material Cost + Processing Cost + Assembly Cost) x Markup Factor

Manufacturing Cost Factors:

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

Methodology reflects cost of under-utilization:



Methodology Reflects Cost of Under-utilization:

Capital Cost
Installation
} **Initial Expenses** → **Used to calculate annual capital recovery factor based on:**

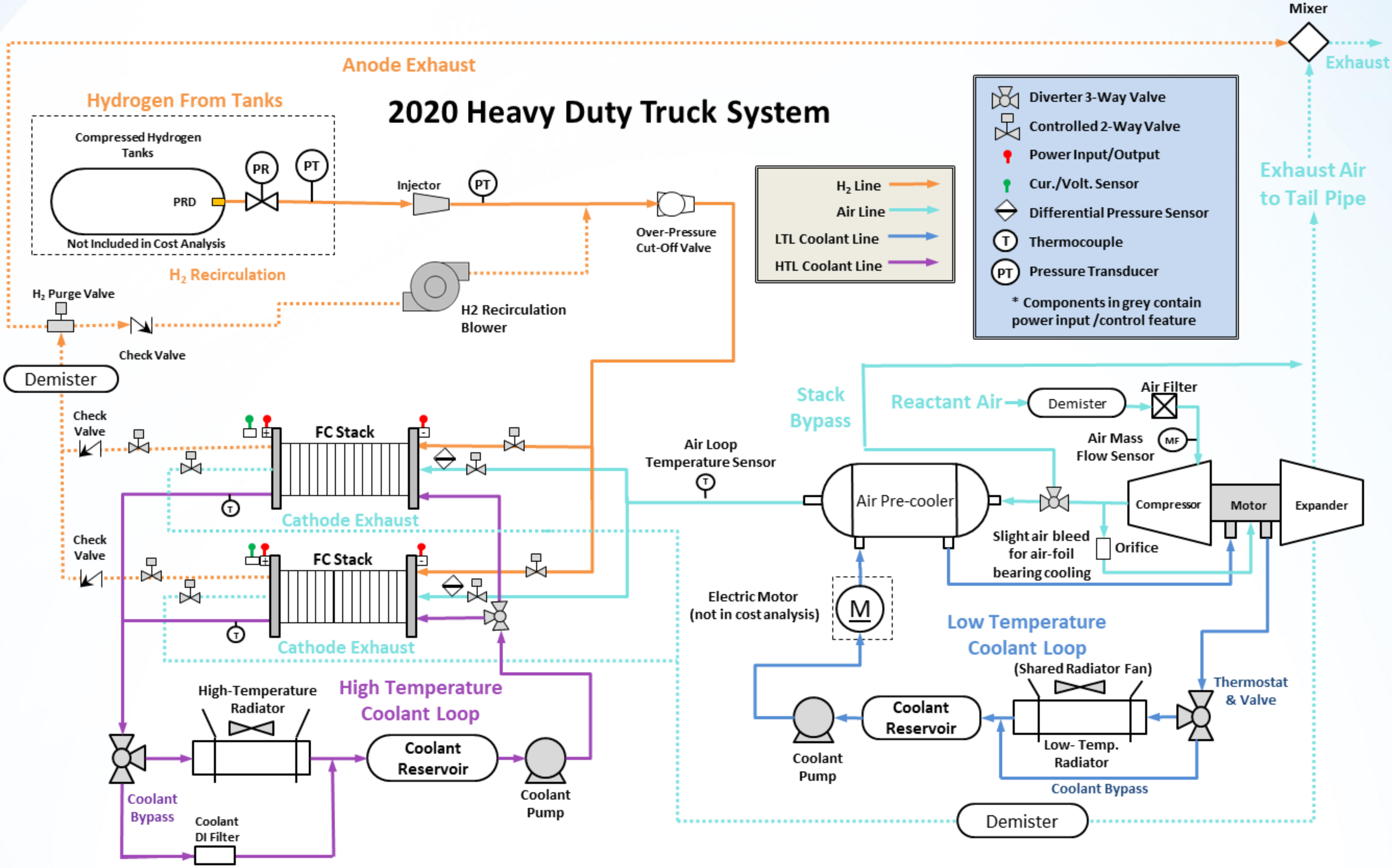
- Equipment Life
- Interest Rate
- Corporate Tax Rate

Maintenance/Spare Parts Utilities
Miscellaneous
} **Operating Expenses**

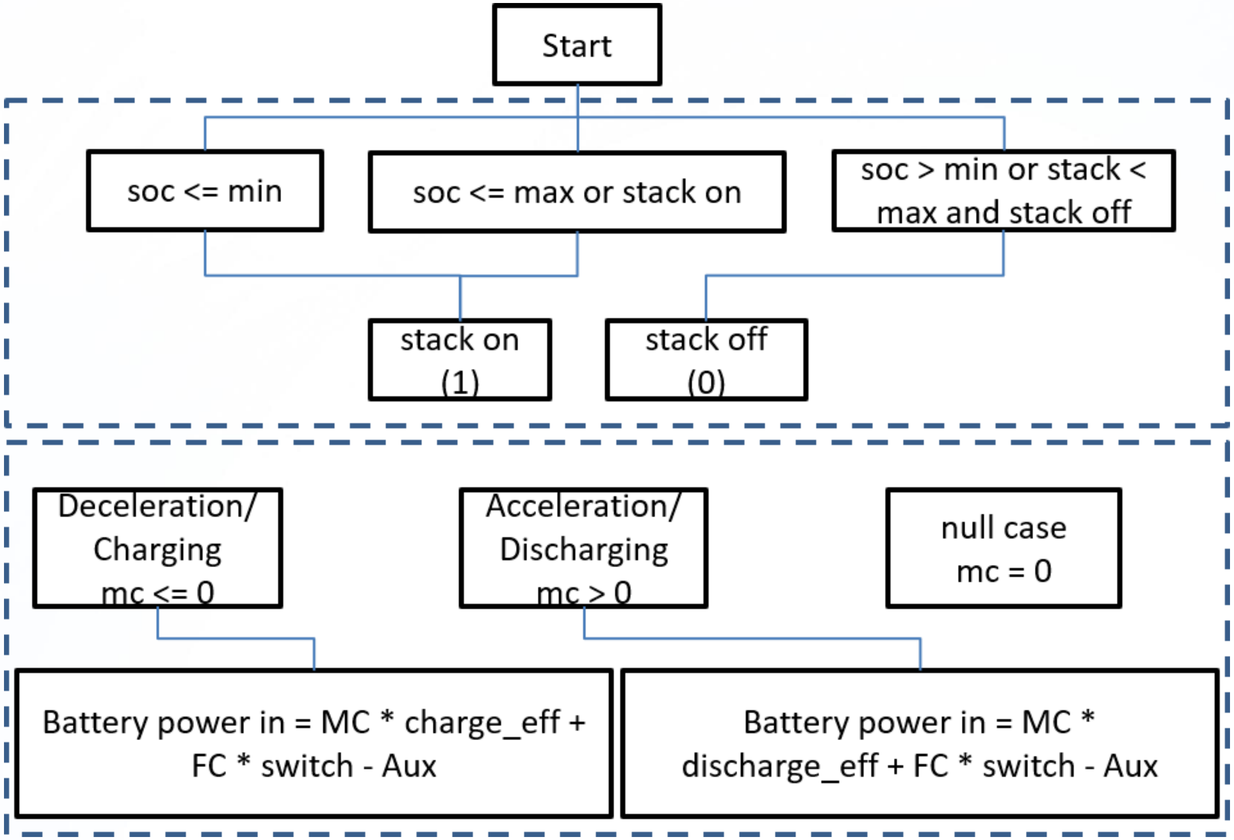
$$\frac{\textbf{Annual Capital Repayment} + \textbf{Annual Operating Payments}}{\textbf{Annual Minutes of Equipment Operation}} = \textbf{Machine Rate (\$/min)}$$

All values in 2016$

Accomplishments and Progress:
2020 Long-Haul HDV System
(Diagram shows system components included in baseline cost analysis model)



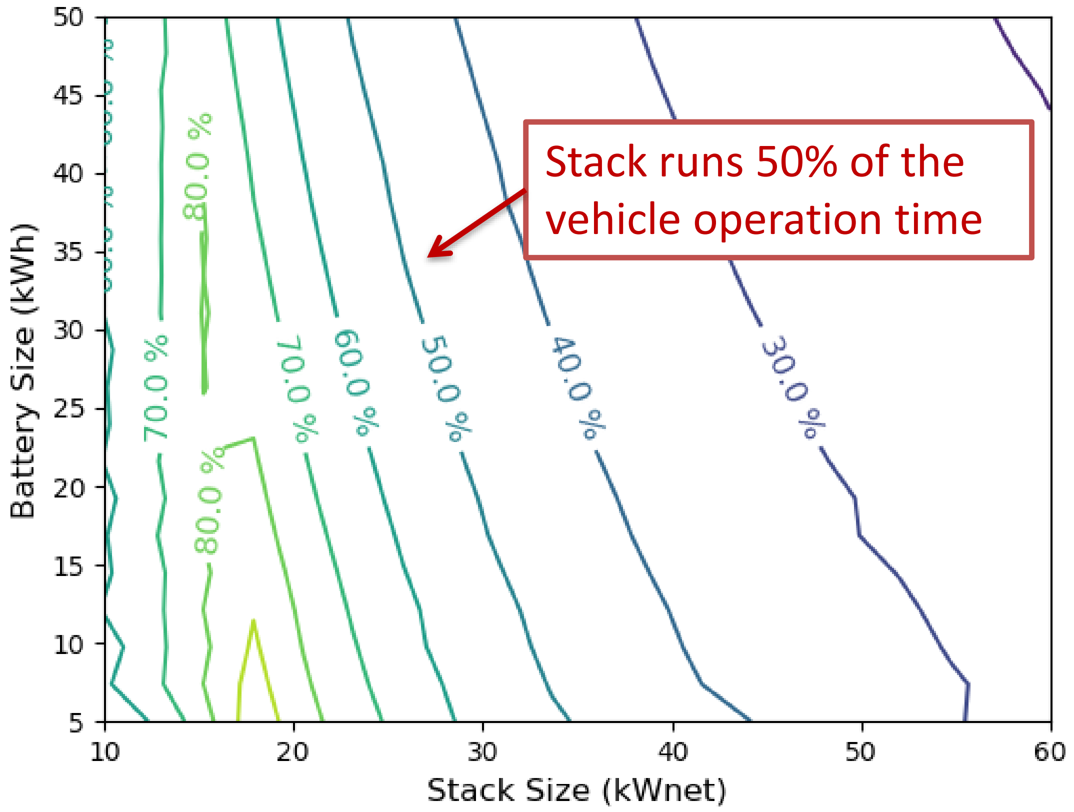
Logic Structure for Hybridization Model



Stack on/off controlled by current battery state-of-charge

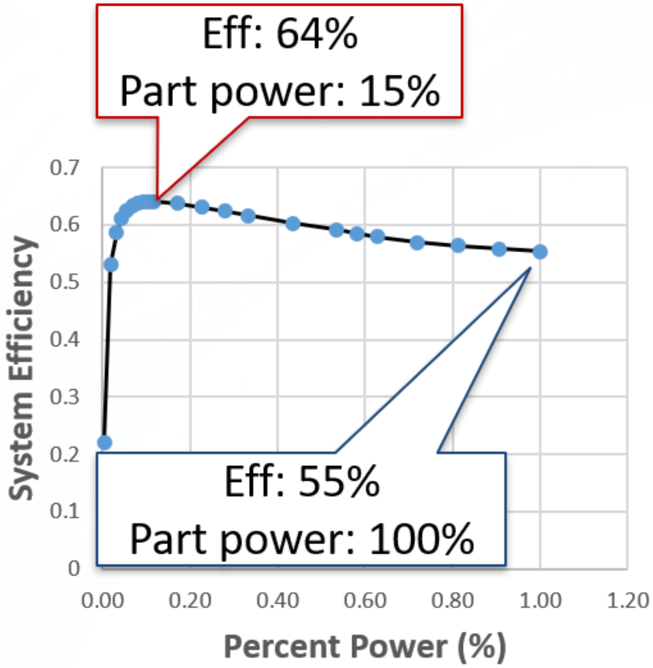
This logic loop is required by difference in charge/discharge efficiencies

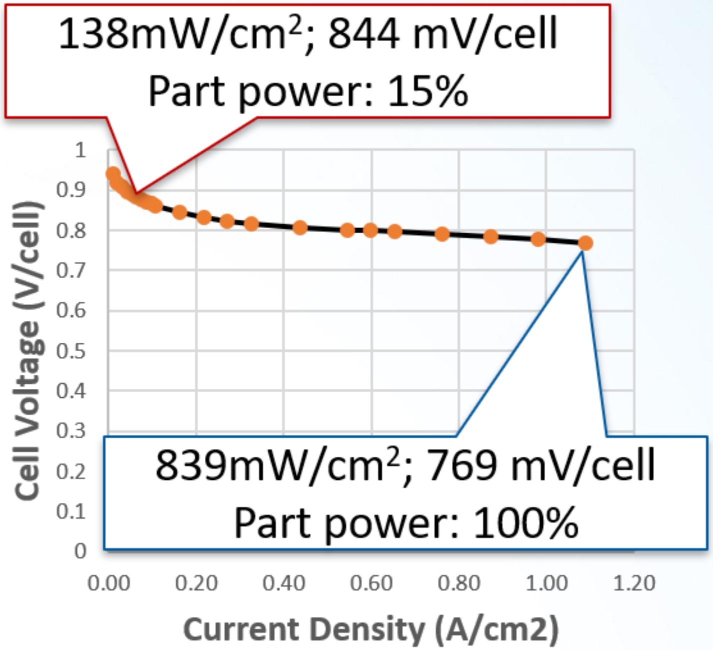
‘Durability’ hybridization could improve fuel cell system effective lifetime by a factor of 2



- LDV fuel cell duty cycle for the US06 drive cycle
- Duty-cycles for vehicles with intermediate battery and fuel cell sizes are 40%-50%

Hybridization Model Assumptions for System Efficiency and Performance at Part Power





Ionomer Cost Analysis Assumptions/Inputs

Reaction Material Inputs

Liquid Phase

Oxidant: sodium hypochlorite
Catalyst: Tri-octylmethylammonium chloride
Organic solvent: R-113A
Stripping Agent: CO_2

Gas Phase

Oxidant: O_2
Catalyst: Copper / HFP oligomer formed *in situ*
No solvents
Heat transfer fluid: R-113A
Stripping Agent: CO_2

Key Cost Inputs

- Producing enough HFPO for 5 – 2,000 tonnes/year ionomer production at **850 g equivalent weight**

- HFP Cost *(low production)* = **$14.25/kg**
  - PVE monomer length = 2 x HFPO
- Liquid-phase selectivity = **92%**
- **Gas-phase selectivity = 60%**

A more selective gas-phase process would reduce costs even further!

Gas-Phase HFP Epoxidation References:

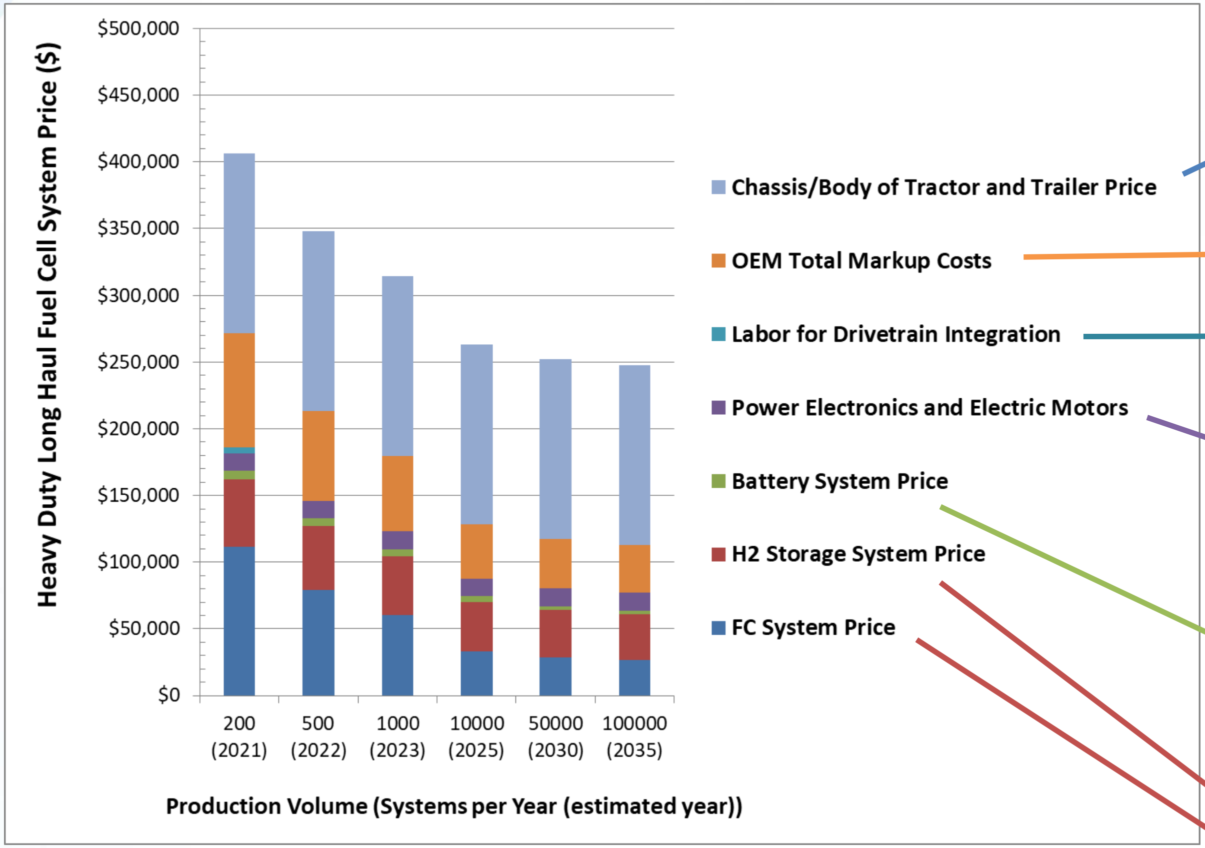
(1) Lokhat, D.; Singh, A.; Starzak, M.; Ramjugernath, D. Design of a Continuous Gas-Phase Process for the Production of Hexafluoropropene Oxide. Chem. Eng. Res. Des. 2017, 119, 93–100. https://doi.org/10.1016/j.cherd.2017.01.017.

(2) Lokhat, D.; Starzak, M.; Ramjugernath, D. Production of Hexafluoropropylene Oxide. 9073883, July 7, 2015.

(3) Ramjugernath, D.; Naidoo, P.; Subramoney, C.; Nelson, M. Recovery of Components Making Up a Liquid Mixture. 8299280, October 30, 2012.

Accomplishments and Progress:

Class 8 Long-Haul Truck Capital Cost Assumptions



100k sys/yr Assumptions

$50k Trailer
+$125k Diesel Tractor
-$40k Diesel Engine
$135k

Non-recurring Engineering Cost

~$4k (only needed at low volume)

Motor & Power Electronics[1]:
$21.70/kW$_{peak}$ x P_m + $425
P_m = peak motor power = 600kW
$13,445/system

Battery System:
$20/kW for 255kW
~$5,000

Contain 36-56% markup for warranty and profit

[1] O'Keefe, M., Brooker, A., Johnson, C., Mendelsohn, M., Neubauer, J., Pesaran, A., "Battery Ownership Model: A Tool for Evaluating the Economics of Electrified Vehicles and Related Infrastructure", Report by National Renewable Energy Laboratory, November, 2010.

Reference Table: 275kW HDV System Definition- Part 1

(Configuration, Operating, and Manufacturing Parameters)

	2019 HDV Truck System	2020 HDV Truck System	2025 HDV Truck System
Power Density (mW/cm^2)	840	**1,050**	**1,200**
Total Pt loading ($mgPt/cm^2$)	0.4	0.4	0.4
Pt Group Metal (PGM) Total Content (g/kW_{gross})	0.509	**0.407**	**0.358**
Net Power (kW_{net})	330	**275**	275
Gross Power (kW_{gross})	415	**346**	**342**
Cell Voltage (V)	0.769	**0.70**	0.70
Operating Pressure (atm)	2.5	2.5	2.5
Stack Temp. (°C) (Coolant Exit Temp)	85	**88**	88
Air Stoichiometry	1.5	1.5	1.5
$Q/\Delta T$ (kW_{th}/°C)	4.33	**4.38**	**4.33**
Active Cells	1,563	**1,144**	**1,000**
Total System Voltage	400	**350**	350
Active Area per cell (cm^2/cell)	316	**362**	**285**
Active to Total Area Ratio	0.625	0.625	**0.65**

Green Bold: Change from previous column.

Reference Table: 275kW HDV System Definition- Part 2

(Configuration, Operating, and Manufacturing Parameters)

	2019 HDV Truck System	2020 HDV Truck System	2025 HDV Truck System
Membrane Material	14-micron Nafion (850EW) supported on ePTFE	14-micron Nafion (850EW) supported on electrospun support	14-micron Nafion (850EW) supported on electrospun support
Radiator/ Cooling System	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler
Bipolar Plates and Coating	Flexible graphite with resin impregnation	Flexible graphite with resin impregnation	Flexible graphite with resin impregnation
BPP Forming/Joining	Embossed/Adhesive	Embossed/Adhesive	Embossed/Adhesive
Air Compression	Eaton-style compressor (no expander)	**Centrifugal Compressor, Radial-Inflow Expander**	Centrifugal Compressor, Radial-Inflow Expander
Gas Diffusion Layers	150 microns (105 μm GDL, 45 μm MPL, uncompressed)	150 microns (105 μm GDL, 45 μm MPL, uncompressed)	150 microns (105 μm GDL, 45 μm MPL, uncompressed)
Catalyst & Application	Slot Die Coating of: Cath.: Dispersed 0.35 mgPt/cm^2 a-Pt/HSC Anode: Dispersed 0.05mgPt/cm^2 Pt/HSC	**Slot Die Coating of: Cath.: Dispersed 0.35 mgPt/cm^2 a-Pt/HSC Anode: Dispersed 0.05mgPt/cm^2 Pt/HSC**	Slot Die Coating **of advanced perf. Catalyst** cost modeled as: Cath.: Dispersed 0.35 mgPt/cm^2 a-Pt/HSC Anode: Dispersed 0.05mgPt/cm^2 Pt/HSC
CCM Preparation	Gore Direct-Coated Membrane with dual-side slot-die coated electrodes	Gore Direct-Coated Membrane with dual-side slot-die coated electrodes	Gore Direct-Coated Membrane with dual-side slot-die coated electrodes

Green Bold: Change from previous column.

Reference Table: 275kW HDV System Definition- Part 3

(Configuration, Operating, and Manufacturing Parameters)

	2019 HDV Truck System	2020 HDV Truck System	2025 HDV Truck System
Air Filtration	Standard Automotive Air Filter	**Activated Carbon Filter**	Activated Carbon Filter
Air Compressor/Expander/ Motor Efficiency	Compr.: 58% (multi-lobe) Motor/Controller: 95%	**Compressor: 73% (centrifugal) Expander: 72% (radial in-flow) Motor: 89%, Controller: 95%, Total: 84.6%**	Compressor: 73% (centrifugal) Expander: 72% (radial in-flow) Motor: 89%, Controller: 95%, Total: 84.6%
Air Humidification	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)
Hydrogen Humidification	None	None	None
Anode Recirculation	Pulse ejector with bypass	**H_2 Recirculation Blower**	H_2 Recirculation Blower
Exhaust Water Recovery	None	None	None
MEA Containment	R2R PET sub-gaskets, hot-pressed to CCM	R2R PET sub-gaskets, hot-pressed to CCM	R2R PET sub-gaskets, hot-pressed to CCM
Coolant & End Gaskets	Adhesive(Cooling)/ Screen-Printed Polyolefin Elastomer (End)	Adhesive(Cooling)/ Screen-Printed Polyolefin Elastomer (End)	Adhesive(Cooling)/ Screen-Printed Polyolefin Elastomer (End)
Dummy Cell at end of Stack	NA	**BPA and 4 GDLs encased in frame gasket (LIM hydrocarbon) and sealed with polyolefin elastomer (one at each end of stack)**	BPA and 4 GDLs encased in frame gasket (LIM hydrocarbon) and sealed with polyolefin elastomer (one at each end of stack)
Freeze Protection	Drain Water at Shutdown	Drain Water at Shutdown	Drain Water at Shutdown
Hydrogen Sensors	1 for FC System[1]	1 for FC System[1]	1 for FC System[1]
End Plates/ Compression System	Composite Molded End Plates with Compression Bands	Composite Molded End Plates with Compression Bands	Composite Molded End Plates with Compression Bands
Stack Conditioning (hrs)	2	2	**1**
Stack Lifetime (hrs) (before replacement)	25,000	25,000	25,000

[1] In the 2017 and 2018 auto cost analyses, the number of sensors in the fuel cell compartment of the automobile was reduced to zero (from a previous level of 2). Consequently, the HDV sensor estimate is one more than the auto and is thus set at one sensor (for all technology years).

Green Bold: Change from previous column.

2019/2020 Publications and Presentations

- James, B.D., Huya-Kouadio, J.M., Houchins, C., "Fuel Cell Systems Analysis", Presentation to the USDRIVE Fuel Cell Technical Team, February 12th, 2020.
- James, B.D., Huya-Kouadio, J.M., Murphy, B.M., Houchins, C., DeSantis, D.A., "Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2019 Update on Medium and Heavy-Duty Vehicles", Strategic Analysis, Inc., September 2019.
- James, B.D. Huya-Kouadio, J.M., Houchins, C., DeSantis, D.A., "Fuel Cell Systems Analysis", Hydrogen and Fuel Cell Technologies Office 2019 Annual Progress Report.
- James, B.D., "Making the Case for Graphite Bipolar Plates", Presentation at the 2019 Fuel Cell Seminar & Energy Exposition, November 2019.
- Huya-Kouadio, J.M., "Medium and Heavy Duty FCEV Design: Exploring Fuel Cell System Pathways to Lower Total Cost of Ownership", Presentation at the 2019 Fuel Cell Seminar & Energy Exposition, November 2019.
- Huya-Kouadio, J.M., "The Next Generation of Fuel Cell Fabrication Using Roll-to-Stack Automation" Presentation at the 2019 Fuel Cell Seminar & Energy Exposition, November 2019.
- Houchins, C., "Cost and Durability Tradeoff Analysis of Hybrid Fuel Cell Electric Vehicles", Presentation at the 2019 Fuel Cell Seminar & Energy Exposition, November 2019.

Additional Collaborations (Listed by Component)

System Component	Vendor/Partner	Project Role
Materials	ATI Metals	• Provide quotes and information on metal pricing
	Continental Steel	• Provide quotes and information on metal pricing
	AK Steel	• Provide quotes and information on metal pricing
Membranes	Elmarco	• Needless Electorspinning Machinery supplier
	Inovenso	• Electrospinning Machinery supplier
	Giner Technologies Inc.	• Developer for Dimensionally Stable Membranes (DSM™)
	General Electric	• Membrane supplier
	Donaldson	• Membrane supplier
	Philips Scientific	• Membrane supplier
Catalyst/Coating	W.L. Gore	• Manufacturer/Developer Direct-Coat CCM manufacturing process
	Johnson Matthey	• PtNi/C catalyst manufacturer provided process details
	Avcarb	• Catalyst manufacturer provided review of SA analysis
	3M	• Manufacturer of PtCoMn and PtNi NSTF catalysts
	Chemcut	• Provided process assumption of de-alloy machinery (for NSTF)
	B&W Megtec	• Slot die coating experience with fuel cell companies
	Coatema/Eurotech	• Slot die coating machinery expertise provided price quotes
	Faustel	• Non-Fuel Cell slot die coating, specialize in batteries
	Frontier Technologies	• Slot die coating experts with fuel cell pilot applications
	Los Alamos National Lab	• Non-PGM catalyst PANI catalyst development
	Fischer Technology	• Supplier for in-line XRF equipment
	Umicore	• Catalyst manufacturer provided review of Pt recycling
MEA/GDL	Ballard	• Provide information and cost of GDL
	Toray	• Manufacturer of GDL materials, currently in discussions
	Greenerity	• Manufacturer of CCM and MEAs
Bipolar Plates	Lincoln Electric	• Bipolar Plate welding station capital cost and station configuration
	American Trim	• Metal sheet stamping experience with auto BPPs
	Dana Reinz	• Metal sheet stamping/coating/sealing expertise
	Toyota Boshoku	• Supplier of Toyota Mirai BPPs using Fine Hold Stamping (FHS)
	Borit	• Hydroforming expertise with Hydrogate™ technology
	Graebener	• Hydroforming expert of BPPs
	Cell Impact	• BPP forming using High Velocity Impact Forming process
	TreadStone Technologies	• Developer of DOTS and TIOX coatings for BPPs
	Sandvik	• Supplier for In-Line PVD Coated materials (pre-coated) for BPPs
	Mustang Vacuum Systems	• Developer of in-line PVD and PECVD equipment for BPP coatings
	Precors	• Developer of pre-coating BPPs using non-vacuum , spray technique
Gaskets	3M	• Developer of PET sub-gasket roll-to-roll process
	Freudenberg Sealing	• BPP and MEA gasket supplier
Air Humidifier	Gore	• Membrane material manufacturer for plate frame humidifier
	Dpoint => Zehnder Group	• Manufacturer of plate frame membrane humidifier
	Perma Pure LLC	• Manufacturer of tubular membrane humidifier
	Mann + Hummel	• Manufacturer of air filtration, humidification, water separators, coolant ion exchange filter, piping/joints
Air Compressor/Expander/Motor	Honeywell	• Manufacturer of centrifugal compressor (baseline auto compressor)
	Eaton	• Roots compressor/expander (baseline bus compressor)
	Aeristech	• Manufacturer of centrifugal compressors
H2 Recirculation Blowers	Air Squared	• Manufacturer of scroll compressors used on material handling equip.
	Barber-Nichols	• Manufacturer of Centrifugal blowers for H2 recirculation
	Ogura-Clutch Ind. Corp.	• Manufacturer of Roots blowers (used on Ballard bus system)
H2 Sensors	NTM Sensors	• Manufacturer of ceramic H2 sensors (currently used on FC buses)
	Nissha	• Manufacturer of H2 sensors for Toyota Mirai
Additional Collaborators	Ford, Hyundai Nissan, Toyota US Hybrid, Loop Energy	Aalto University, Nolek Machine Works, Andritz Kusters FC Powertrain, Plug Power FFP Sys Inc. (press filter) Wisconsin Ovens, Tejin Films