2021 DOE Hydrogen and Fuel Cells Program Review Presentation

Fuel Cell Systems Analysis

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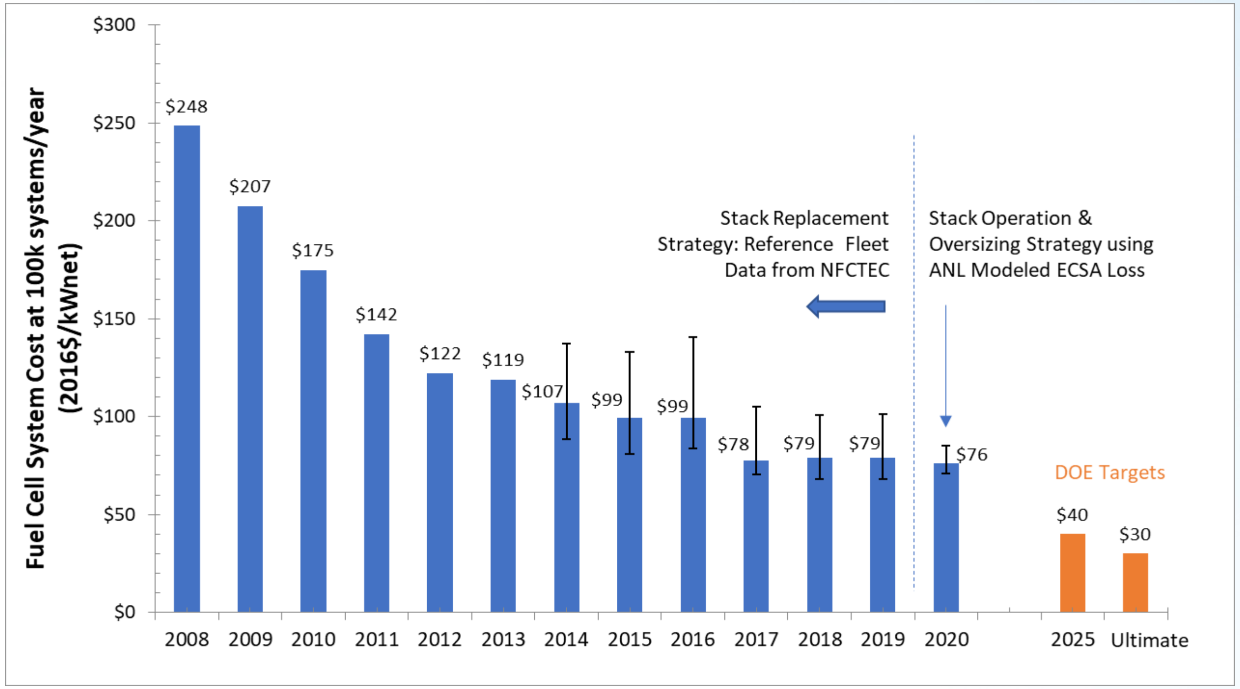
June 9, 2021

Project ID# FC163

Contract No. DE-EE0007600

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: 9/30/16
- Project End Date: 9/30/21
- % complete: 90% of five-year project (in Year 5 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
  - ~$1.06k (through March 2021, 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)

Relevance

Overall Project Objectives:

- Project current (2021) 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 2021	Project Status 2025	DOE Near-Term Target	DOE Ultimate Target
Cost of LDV FC Power Systems [a, b]	$\$/kW_{net}$	76	57	40 (2025)	30
Cost of LDV FC Stacks [a, b]	$\$/kW_{net}$	31	22	20	15
Cost of LDV Bipolar Plates [a]	$\$/kW_{net}$	7[b]	5[b]	3	NA
Air Compression System Cost [a]	$/system	832	780	500	NA
Cathode Humidifier System Cost [a]	$/system	60	60	100	NA
Cost of HDV FC Power Systems [a, c]	$\$/kW_{net}$	185	129	80 (2030)	60

[a] Based on high production volume (100,000 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	275kW HDV Class 8 Long-Haul Truck	Current (2021), 2025
		160kW MDV Class 4 Delivery Truck	Current (2021), 2025

Final results for 2020 LDV system will be highlighted

Impact since 2020 analysis final results:

- Incorporating ANL durability modeling of LDV system increased cost $24/kW
- Incorporating durability aspects to the HDV system increased cost $76/kW
- Addition of voltage monitoring system, stack active area oversizing, & higher Pt loading (LDV).

Approach: Topics Examined Since 2020 AMR

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

2020/2025 Light-Duty Automobile Systems

- **Impact of Durability on Cost:** Optimal operating conditions to extend life and amount of stack active area oversizing to meet 8,000 hour life, based on ANL durability modeling effort (Completed)
- **Addition of Cell Voltage Monitor and Dummy Cells:** stack durability improvements

2021/2025 Medium-Duty and Heavy-Duty 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 60% electrochemical surface area (ECSA) loss after 25,000 hours (SA cost modeling completed for 2021 HDV System, In Process for 2021 MDV System)
- **Addition of Cell Voltage Monitor and Dummy Cells:** stack durability improvements (In Process/Completed)
- **Re-evaluation of stack sizing/config.:** Maintain max 400 cells/stack and increase system voltage 600-800V (Completed)
- **Update QC equipment:** specific to MDV/HDV manufact. (in collaboration with NREL) (In Process)

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

***Milestone 2,5,8,11,14: System Definition* – Completed for 2021/2025 MDV and HDV Systems**

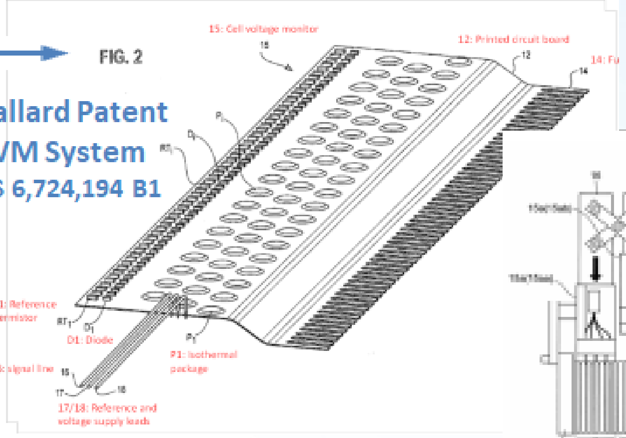
***Milestone 3,6,9,12,15: DFMA® Cost Analysis* – Completed for 2021/2025 MDV and HDV Systems**

***Milestone 4,7,10,13: Reporting of Cost Results* – (due Sept 2021) => End of project**

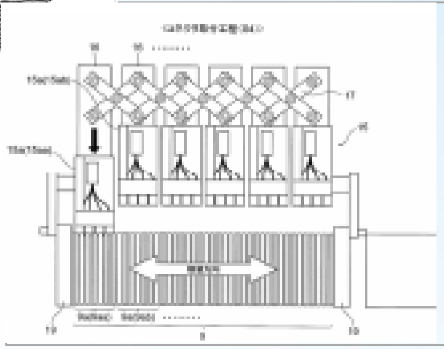
Accomplishments and Progress:
Evaluation of FC Stack Monitoring Systems

- Investigated three main continuous, real-time FC stack monitoring system types
  1. **Cell Voltage Monitoring (CVM)** (Incorporated in baseline systems)
     - Cell-by-cell monitoring (cell reversals)
  2. **High Frequency Resistance Measurement (HFR):**
     - 2-3kHz to measure membrane humidity
  3. **Total Harmonic Distortion (THD)**
     - Sample 4-5 frequencies between 1-1kHz
     - Indication of:
       - membrane dry out, flooding of electrodes, & media/gas starvation

Ballard Patent
CVM System
US 6,724,194 B1



Toyota Patent
CVM Process
JP 2019-79643 A



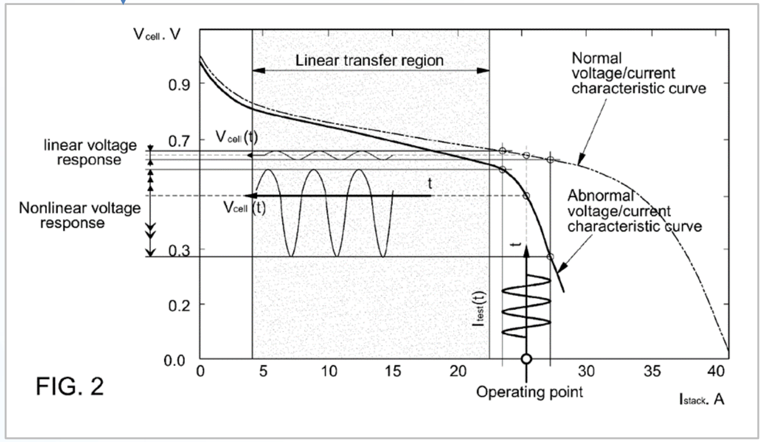


FIG. 2

Hyundai Patent THD System
US 8,906,568 B2

Stack Monitoring Systems	CVM	HFR	THD
Complicated to incorporate into design	Yes	No	No
Detects cell reversals on specific cell or group of cells	Yes	No	No
Detects cause or source of change	No	Yes	Yes
Cost	High: \$3-\$10/kW	TBD	Med: \$3/kW from parasitic load
Parasitic Load	Low	TBD	High: 10% of gross power
Known use of system in production vehicles	Yes: Toyota/Hyundai	Yes: Toyota	Unknown: (Hyundai/AVL patents)

- Highly customized systems unique to FC stack/system/controller design
- None of the monitoring systems are ideal from a cost or parasitic load perspective
- CVM cost roughly based on \$2-3/cell from BMS and SA summation of only physical components (w/out assembly). Full DFMA planned for 2021 activities.
- Initial assessment:
  - **Current systems use CVM or combination of CVM and HFR**
  - **Future robust system may only require THD (beyond 2025 or 2030)**

Accomplishments and Progress:
FCS-LDV Degradation Adjusted Stack Size: Modeling Conducted by ANL

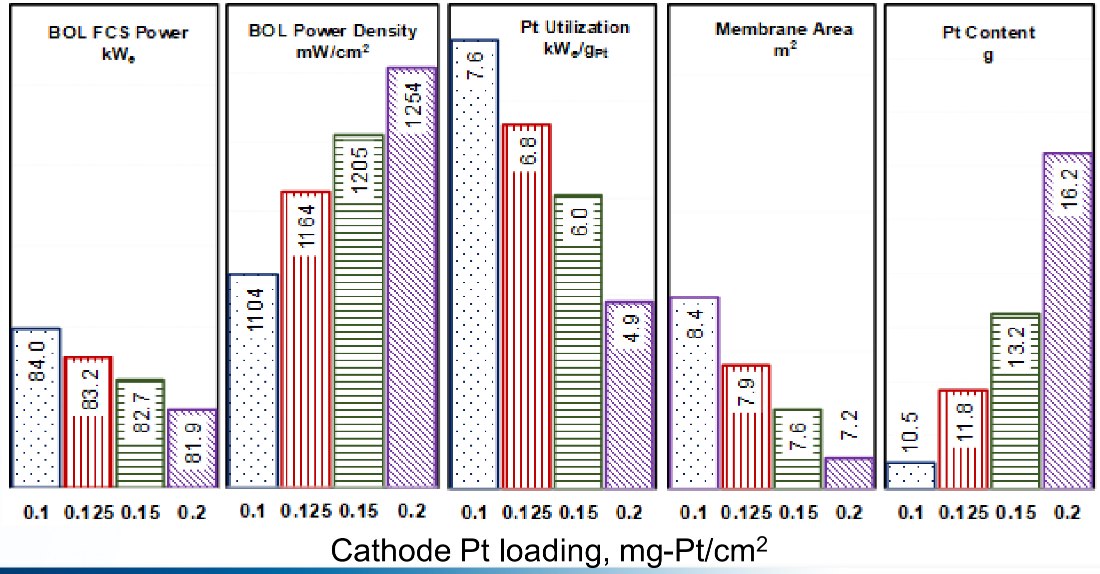
Durability Model

- Catalyst AST data on 5- and 50-cm^2 cells, FC017-FCPAD-FC156 collaboration: trapezoidal wave, 0.6-V LPL, 0.85-0.95 V UPL, 350 mV/s scan rate, 30-60,000 cycles, 55-95°C, 1-5 s hold at UPL, 40-100% RH, Journal paper under preparation.
- Pt dissolution model from on-line ICP-MS data in aqueous media at room temp. (RT): R.K. Ahluwalia et al, JECS 165(6) F3024-F3035 (2018)
- FCS simulations on EPA HWFET and UDDS using power demand from Autonomie: Determine idle power, coolant temperature, CEM turndown, RH, voltage clipping to reach target electrode lifetime; R.K. Ahluwalia, X. Wang, J-K Peng, V. Konduru, S. Arisetty, N. Ramaswamy, and S. Kumaraguru, "Achieving 5,000-h and 8,000-h Low-PGM Electrode Durability on Automotive Drive Cycles," JECS (2021)

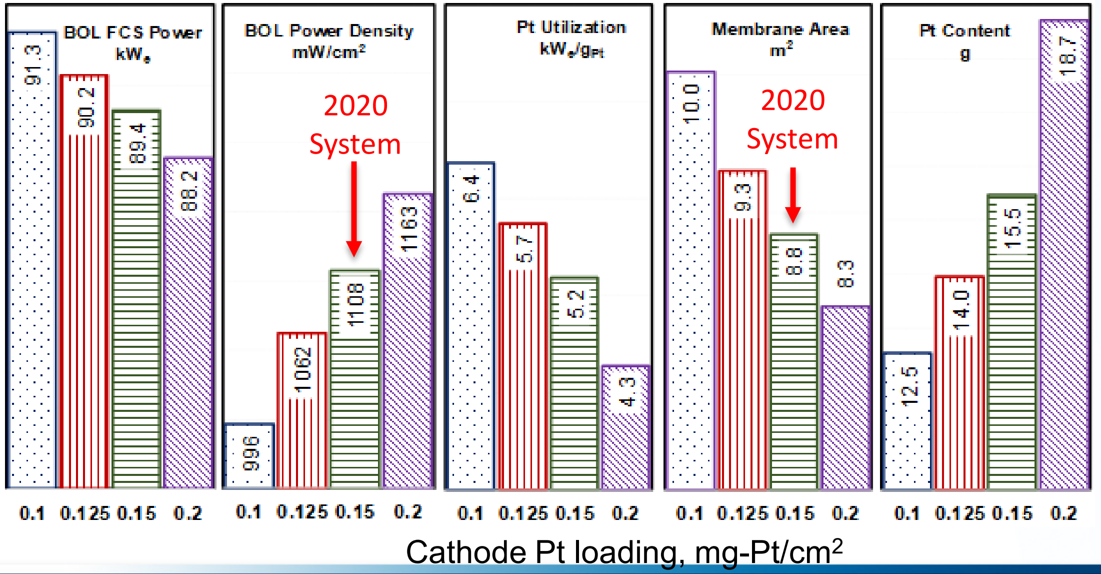
Mismatch in allowable and actual ECSA losses

- Allowable degradation to limit power loss at EOL to 10% depends on cathode Pt loading:
  - 44.9% with 0.1 mg-Pt/cm^2
  - 49.6% with 0.2 mg-Pt/cm^2
- Actual cell degradation:
  - 55.3% for 5,000-h life
  - 69% for 8,000-h life

Stack sizing to produce 72 kW_e after 5,000 h (5k Protocol)

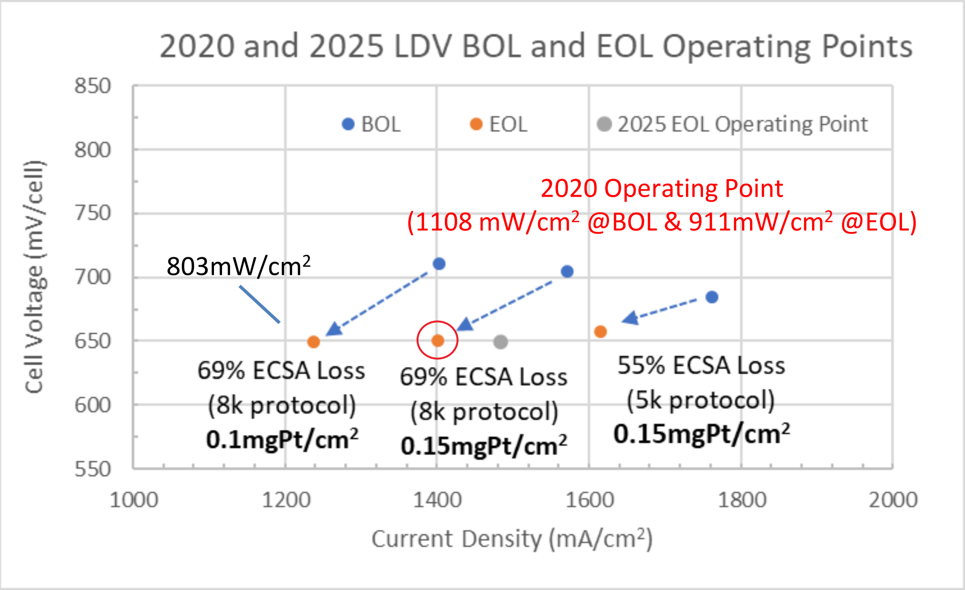


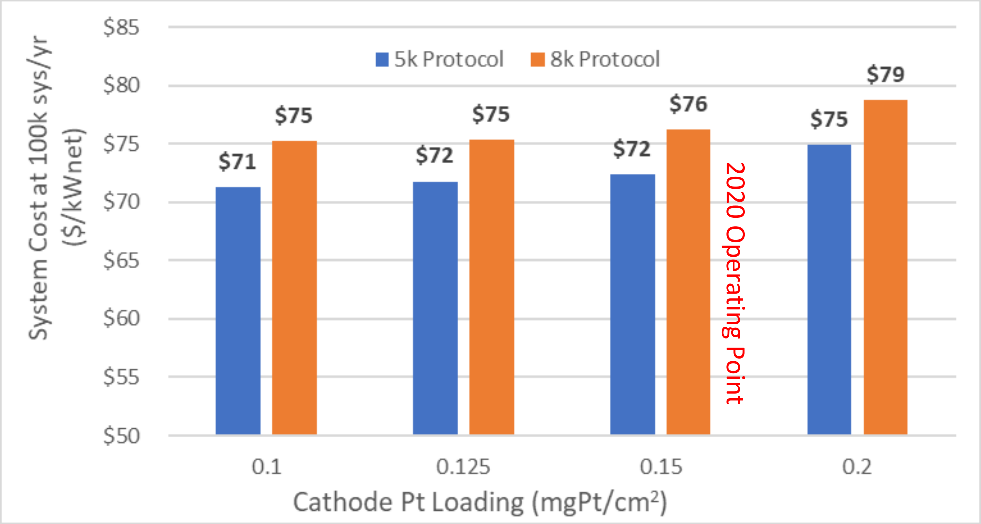
Stack sizing to produce 72 kW_e after 8,000 h (8k Protocol)



Accomplishments and Progress:

2020 LDV Durability-Optimized Operating Conditions





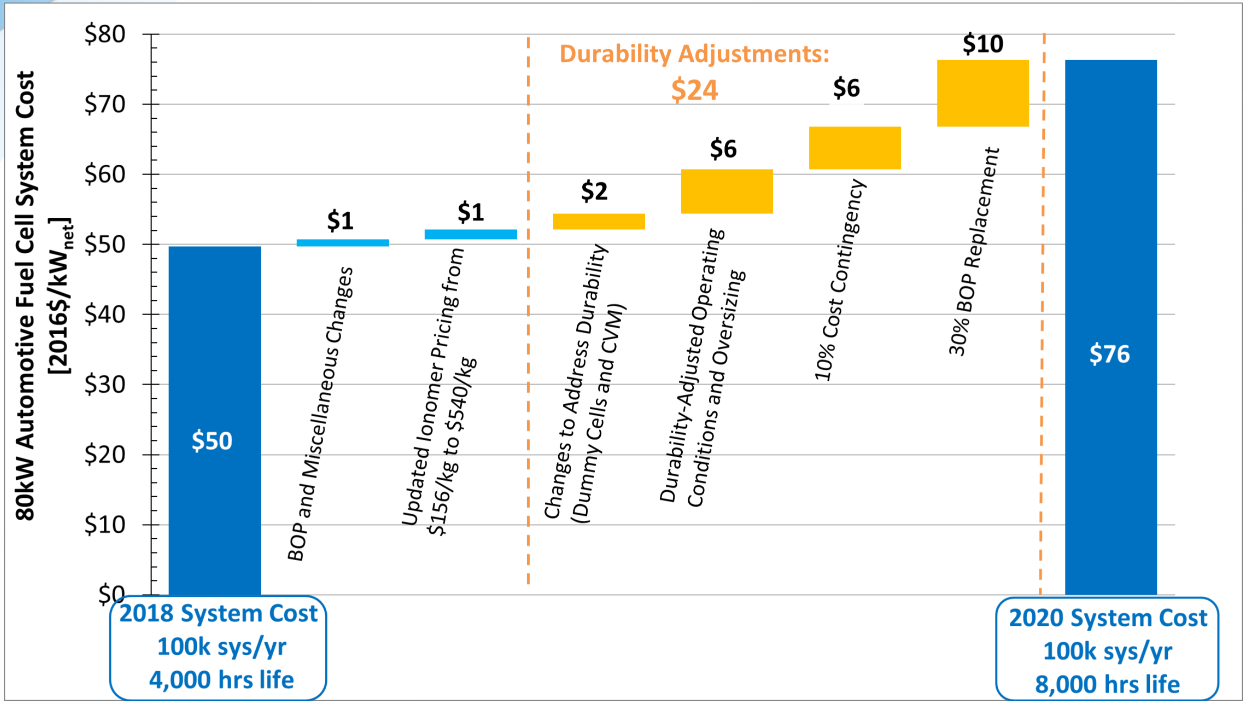
Cost Estimates Based on ANL Results

EOL LDV Conditions (8k Protocol)	2020	2025
Power Density (mW/cm²)	911	803*1.2 = 964
Cell Voltage (V)	0.65	0.65
Total Pt Loading (mgPt/cm²) Cathode Pt Loading (mgPt/cm²)	0.175 0.15	**0.125** **0.10**
ECSA Loss over 8k hrs	69%	**69%**
Coolant Exit Temp (C)	92	92
Membrane Thickness (μm)	14	14
Gross System Power (kW)	81	81
Net System Power (kW)	72	72
Membrane Active Area (m²)	8.8	8.4

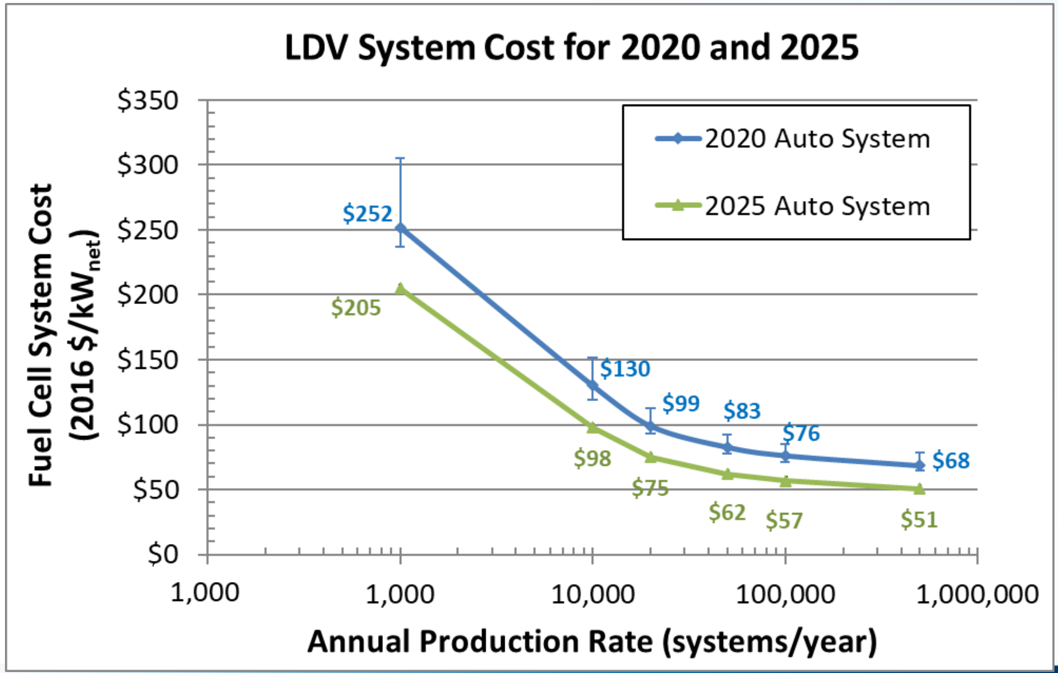
- 2020 Stack oversizing: $\frac{\text{Active Area@ 69\%ECSA loss}}{\text{Active Area@ 0\% ECSA loss}} = 24\%$
- BOP sized for $80kW_{net}/89kW_{gross}$ at BOL
- 2025 system assumes achievement of 8khr at lower cathode Pt loading (0.1mgPt/cm²) & 20% power density improvement (increase 803mW/cm² to 963mW/cm² at constant cell voltage)

Accomplishments and Progress:

Durability Adjusted Cost Results for 2020 LDV System



- Minor cost impact due to BOP changes and increased ionomer pricing ($156/kg to $540/kg at high volume)
- Durability adjustments include:
  - Dummy cell and cell voltage monitoring (CVM) addition
  - ANL's durability optimized operating conditions (includes active area oversizing)
  - 10% cost contingency for non-enumerated costs for 8khr life
  - 30% BOP replacement costs (includes labor installation)



Fuel Cell Technical Team Review

- **Consensus that the BOP replacement costs should not be included in the system cost (to be removed in future analysis)**
  - **Equate to $66/kW at 100k sys/yr**
- **Future 2025 system would improve in both durability (lower Pt loading to reach 8k hrs, no BOP replacement) and performance (10-20% improvement between design cycles)**

Documentation for durability adjusted cost for LDV system: 2021 DOE Record #21001 , 2020 Final Report

Summary of Truck Enhanced-Durability Measures
(as modeled in 2021 cost assessment)

System-Design Choices

- Increased Pt loading (0.4 Pt/cm^2)
- CeO_2 radical scavengers
- Graphite Bipolar Plates
- Choice of catalyst (annealed Pt/HSC)
- Thicker membrane (20 vs. 14 micron)
- Dummy cells (to maintain temp. uniformity)
- Extra valving (for stack isolation on shutdown)
- Cell Voltage Monitoring (CVM)

Operational Measures (not vetted, subject to change, but conceptually included in cost model)

- Limit max cell temperature to <90°C (other than hill climb at EOL)
- Limit max cell voltage to <0.85 volts
- Limits on cell relative humidity
- => ANL Stack Operating Protocols (in process)
  - Minimize ECSA loss rate (from Pt dissolution) by controlling
    - Temperature, air flow (relative humidity & cell voltage)
- Currently assume only 60% ECSA loss over 25khrs operation (to be confirmed by future ANL modeling)

Stack Oversizing

- Increase stack total active area to compensate for performance degradation and achieve end-of-life (EOL) power requirement (275kW_{net} continuous at EOL)

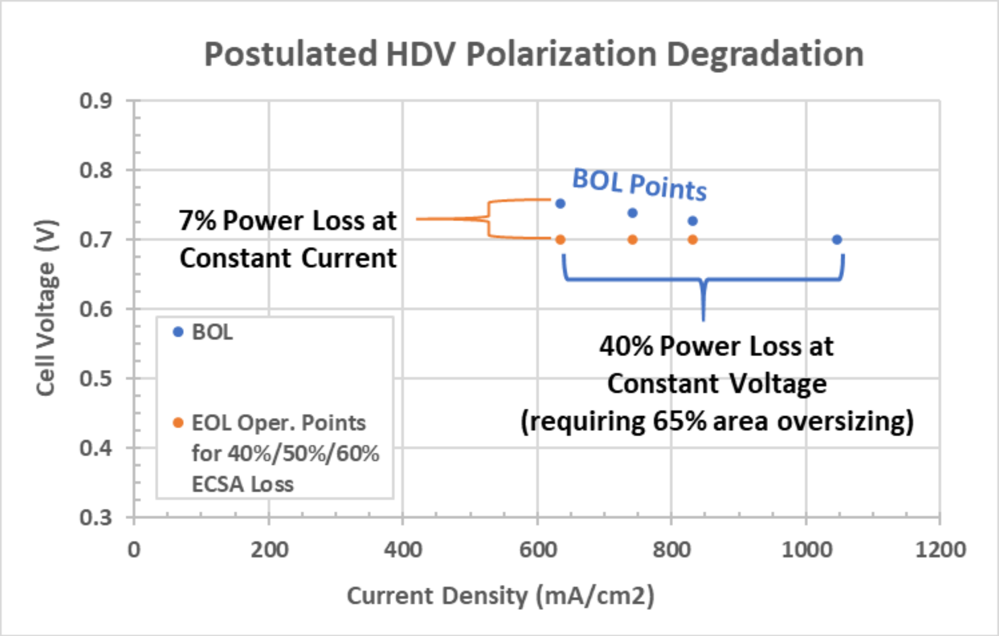
EOL Definition (and allowable cell voltage)

- 2021 system: 275kW_{net} at 0.7V/cell
- 2025 system: 275kW_{net} at 0.66V/cell

Accomplishments and Progress:

Durability Adjusted Operating Conditions for HDV System

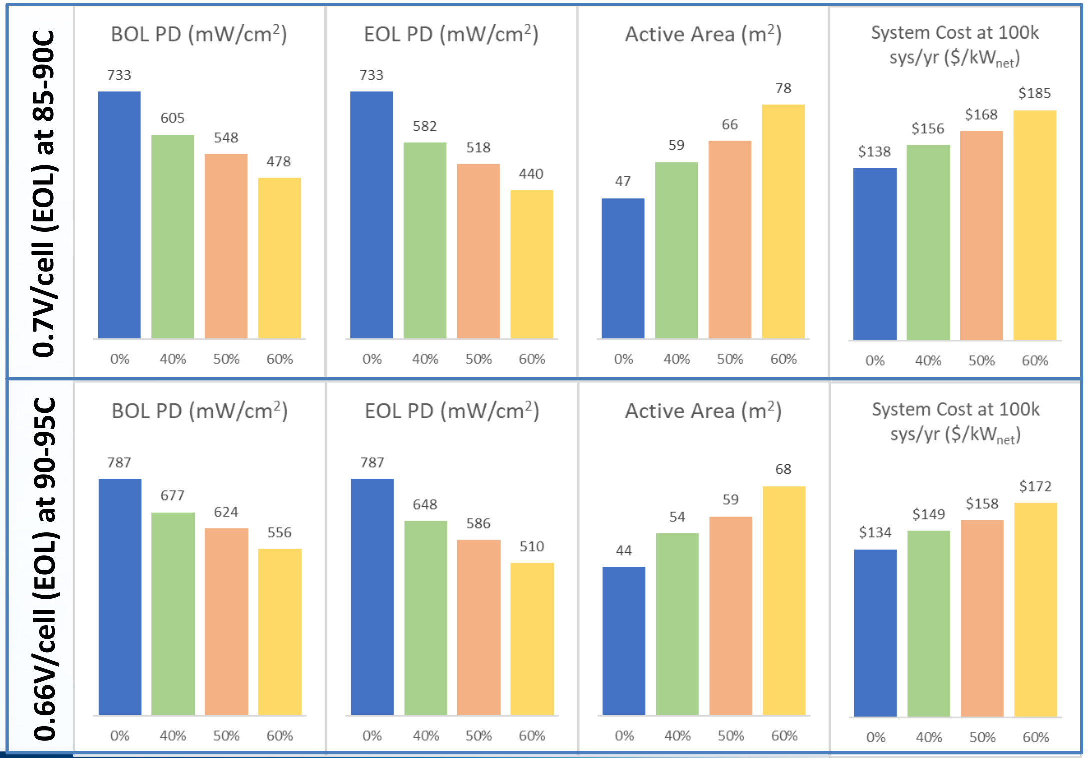
- **<u>Data not yet available</u>** for ANL to complete HDV durability modeling: not optimal operating conditions or ECSA loss over drive cycle
- ANL conducted parametric study over range of possible ECSA loss
- Currently assuming 60% ECSA loss after 25k hrs operation for 2021



ANL parametric study over range in ECSA Loss %

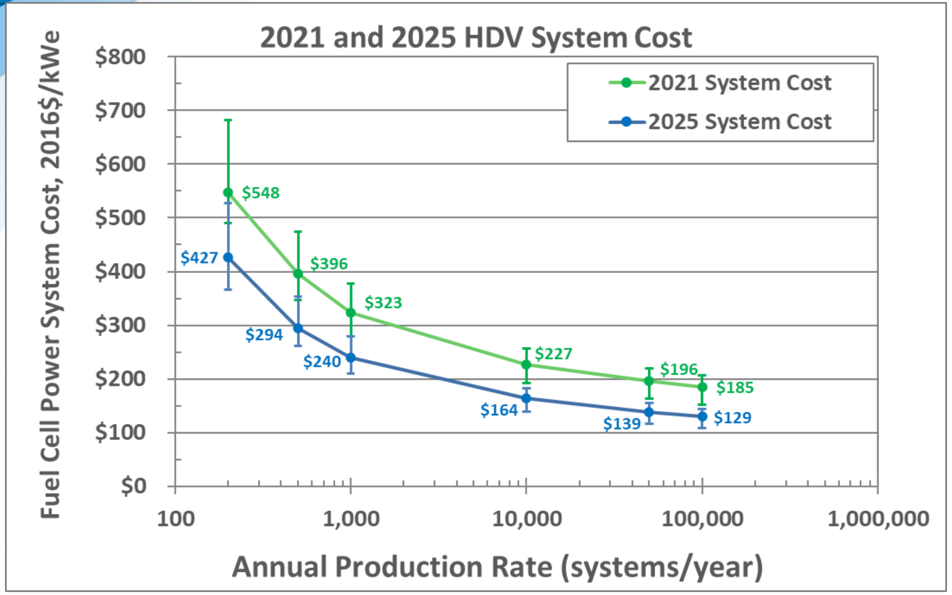
275kW at 2.5atm, 1.5SR(c), 0.3mgPtc/cm² total Pt loading, a-Pt/HSC catalyst

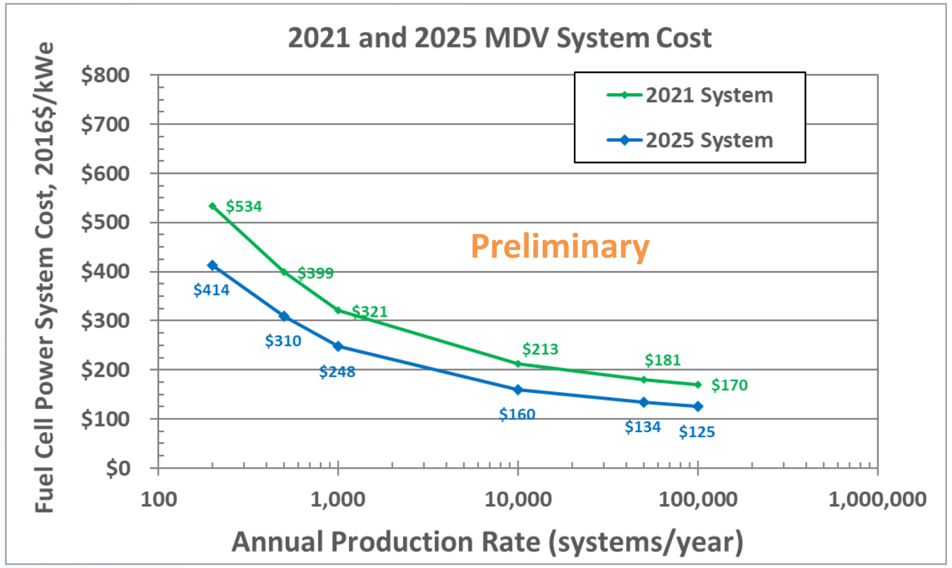
Assumption: no power de-rating over 25khr life



- Cost modeled as 0.4mgPt/cm² (0.35mg/cm² on cathode)
- **Initial feedback from HDV industry:**
  - **Currently unable to meet 0.7V/cell at EOL**
    - **<u>0.7V at EOL is "conservative" for stack oversizing & cost</u>**
  - **Design for efficiency or low cost**
  - **Postulated value of 2mV/1khrs may be too aggressive**
  - **Perf. degradation may not determine EOL**

Accomplishments and Progress: 2021 and 2025 HDV and MDV System Cost Results





Error bars based on Monte Carlo analysis

EOL Conditions	2021 HDV	2025 HDV	2021 MDV	2025 MDV
Power Density (mW/cm^2)	440	586*1.1 = 644	518	648*1.1 = 713
Cell Voltage (V)	0.70	**0.66**	0.7	**0.66**
Total Pt Loading (mgPt/cm^2)	0.4	**0.35**	0.4	**0.35**
ECSA Loss over 25k hrs	60%	**50%**	50%	**40%**
Coolant Exit Temp (C)	88	94	88	94
Membrane Thickness (µm)	20	15	20	15
Gross System Power (kW)	346	348	191	192
Net System Power (kW)	275	275	160	160
Membrane Active Area (m^2)	78	54	37	27

Preliminary MDV

2025 HDV System Assumptions:

- ANL modeled results for 50% ECSA loss: 586mW/cm^2 at 0.66V/cell at EOL
- 0.66V/cell EOL is minimum voltage to maintain heat rejection and 275kW$_{net}$
- Assume 10% improvement on power density
- Reduced membrane thickness

MDV System Assumptions (Preliminary)

- Currently using ANL's HDV data with lower ECSA loss assumptions than HDV system (50% ECSA loss for 2021 and 40% ECSA loss for 2025).

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Accomplishments and Progress:

Responses to 2019 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 however, SA has more recently been supporting NREL on their TCO studies for HDV systems instead of conducting a separate TCO study.
"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. As there are other studies being conducted under DOE funding, SA has discontinued this hybridization study so as to focus on other technoeconomic analyses.
"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%.

No Review in 2020, so these are 2019 Review comments

Collaboration & Coordination

*Additional Collaborations Listed in Reviewer Slides

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 SA's assumptions for MEA & R2R processing and techniques. • Provided feedback on current 2021 & 2025 analysis systems & 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
2020/2021 Collaborators	• Celeroton provided information about compressor systems and estimated lifetimes • Formal Review on HDV system operation and components: Daimler, GM, Ford, Cummins • Orchid Technologies is building CVM systems and commented on components and cost • AVL provided technical details on total harmonic distortion (THD) systems • Fuel Cell Powertrain reviewed and commented on FC stack cost for 30kW system • Gannon & Scott commented on recycle of Pt and FC stack disposal processes • Cell Centric Canada (JV of Daimler and Volvo) provided feedback on HDV tech challenges
Vendors/Suppliers	See back-up material for list of ~30 other companies with which we have consulted.

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.
- 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: 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 $57/kW compared to $40/kW DOE target).
- $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, 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. how much hybridization is cost and durability optimal.
- $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

- Complete more detailed cost model for cell voltage monitoring system
- Update manufacturing quality control processes for stack MDV/HDV systems (with NREL)
- Obtain feedback and re-evaluate BOP component costs for HDV systems
- Continue to investigate ways to incorporate durability into cost models
- Complete sensitivity analysis on MDV and HDV Systems
- Document MDV and HDV systems in 2021 Final Report: Report due September 2021

Future Work for Side Studies

- Conduct cost analysis of Aluminum BPPs with advanced coatings (based on work by PNNL)
- In collaboration with NREL, investigate the performance and cost trade-offs for a variety of deposition techniques to manufacture MEAs

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

Summary of Findings

- **LDV 80kW$_{net}$ Automotive System**
  - Final 2020 cost results: ~\$76/kW$_{net}$ (current 2020) and ~\$57/kW$_{net}$ (Future 2025) at 100k sys/year
- **MDV 170kW$_{net}$ Delivery Truck System**
  - Preliminary results: ~\$170/kW$_{net}$ (current 2021) and ~\$125/kW$_{net}$ (2025) at 100k sys/year
- **HDV 275kW$_{net}$ Long-Haul Truck System**
  - Final 2021 cost results: ~\$185/kW$_{net}$ (current 2021) and ~\$129/kW$_{net}$ (2025) at 100k sys/year
- **Cell Monitoring System Study**
  - Evaluated three real-time monitoring systems (cell voltage monitor, HFR, and THD)
  - CVM and HFT currently used in multiple systems while THD tends to be a possible future option
- **Impact of Durability on Cost**
  - Material and System Solutions (qualitative and quantitative) incorporated into system cost models
  - Increased active area to meet 8k hrs for LDV and 25k hrs for HDV
  - Addition of durability cost contingency
  - Addition of BOP cost replacements
  - LDV system cost increased by \$24/kW due to durability adjustments
  - HDV system cost increased by \$76/kW due to durability adjustments

Project Summary

- **Overview**
  - Exploring subsystem alternative configurations and benchmark cost where possible
  - In year final year of 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, open discussion of assumptions and results, extensive briefing to industry/researchers for validation
- **Accomplishments**
  - **Documented durability-adjusted cost for LDV system: 2021 DOE Record #21001**
  - 2020 LDV Annual Report (coming soon)
  - 2021 DOE Record on HDV System Cost (coming soon)
  - MDV and HDV 2021 & 2025 fuel cell systems analysis results
  - Analyses:
    - Cell Monitoring System Analysis
    - Impact of Durability on Cost: stack oversizing, cost contingency and BOP replacement costs
- **Collaborations**
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
  - Extensive discussions, interviews, feedback with 30+ industry vendors/suppliers
- **Future Work**
  - Finalize MDV system design, complete sensitivity analyses, and draft 2021 final report.

Technical Back-up Slides

Technology Transfer Activities

Not applicable for SA's Cost Analysis

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

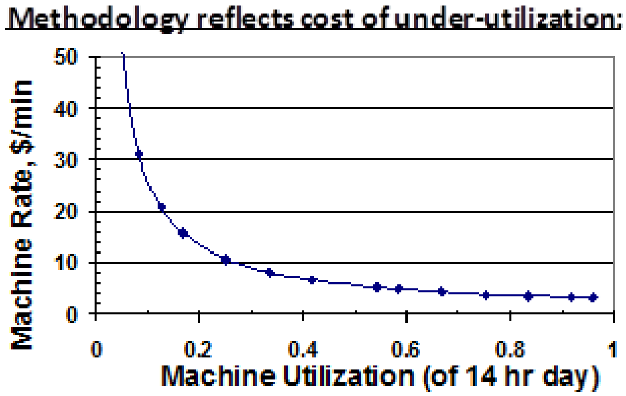
What is DFMA® ?

- 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:

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

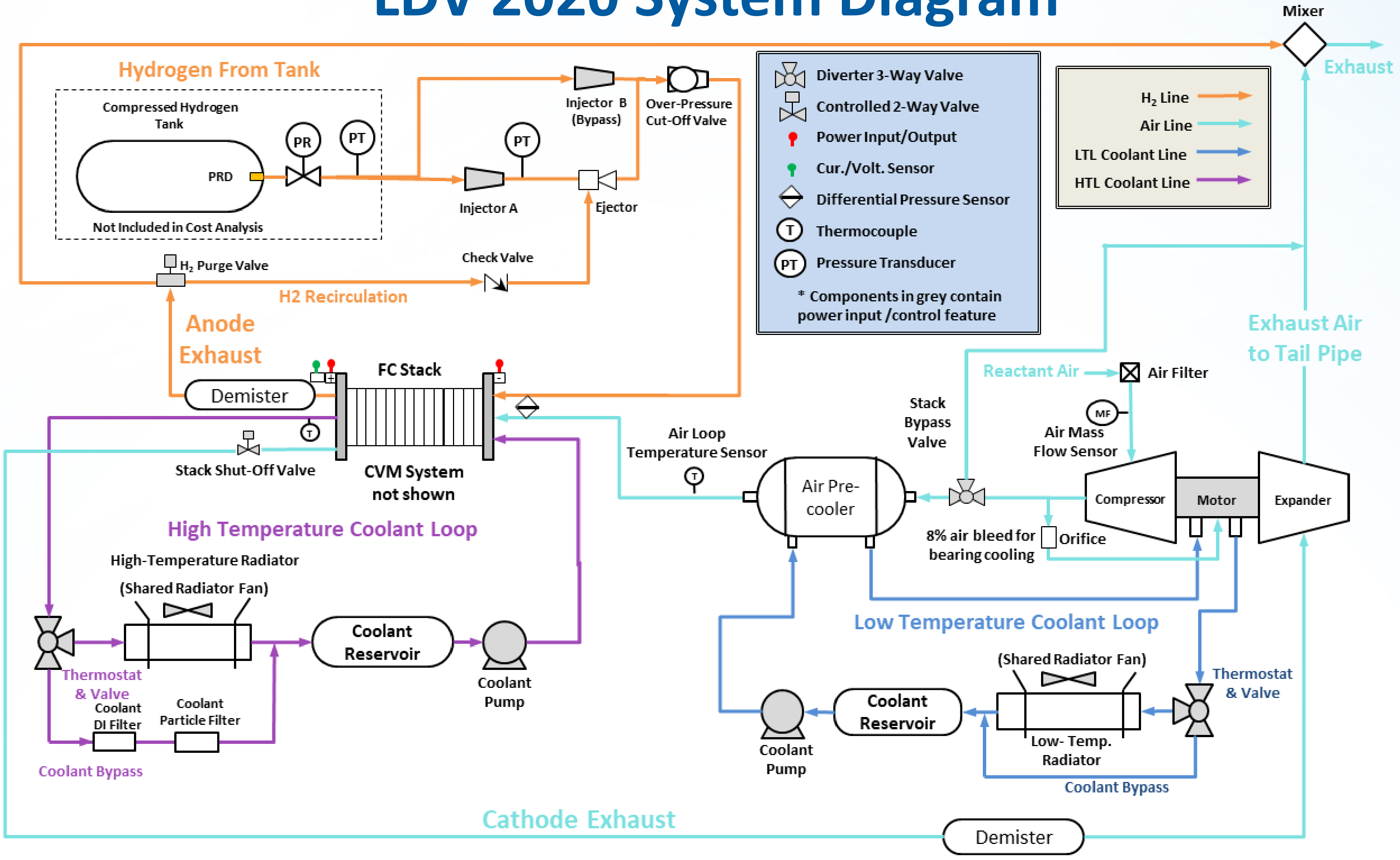
- Equipment Life
- Interest Rate
- Corporate Tax Rate

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

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

All values in 2016$

Accomplishments and Progress:
LDV 2020 System Diagram



2020 LDV System Assumptions

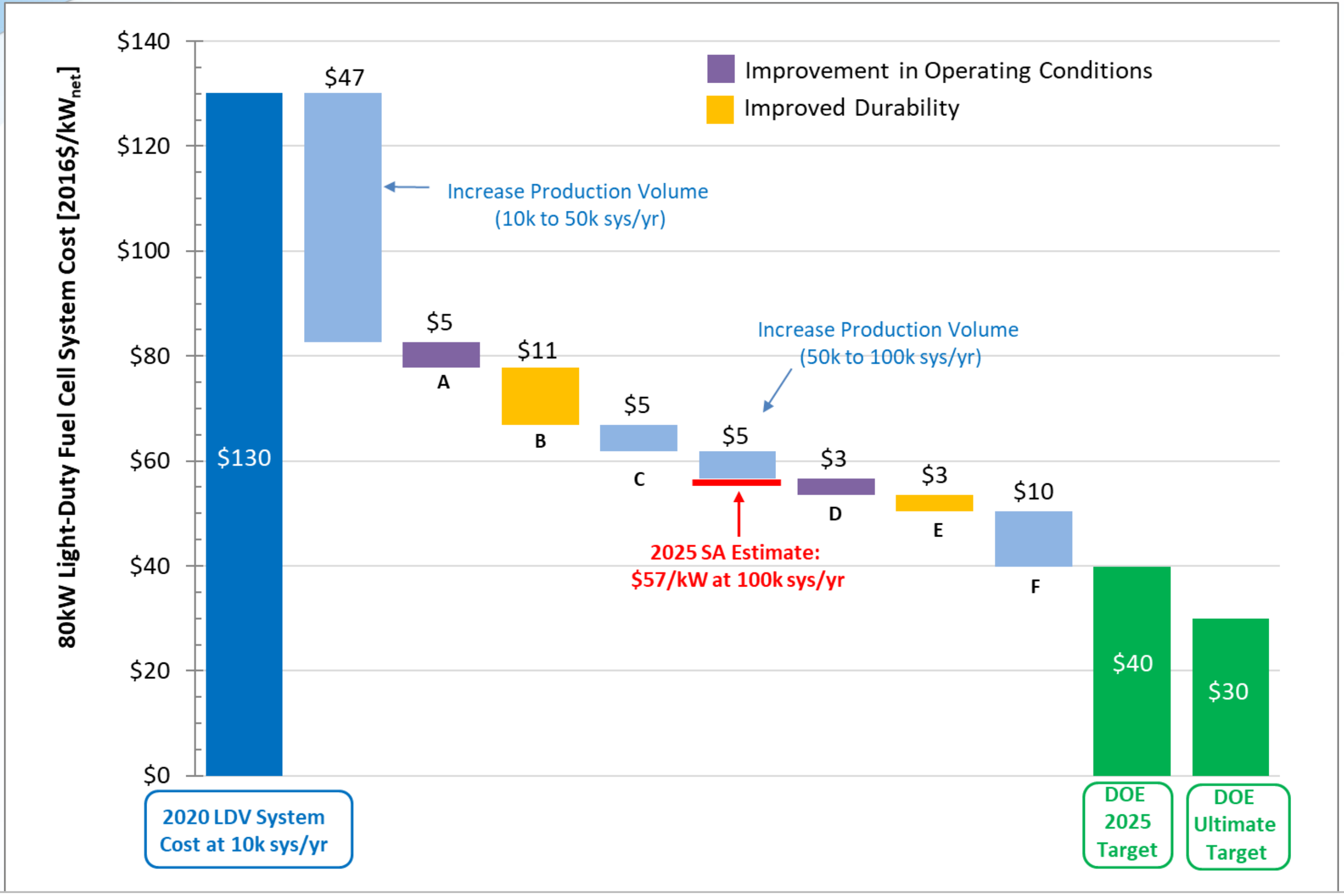
Red: Values changed from previous year

	2018 Auto Technology System	2020 Auto System (EOL)	2025 Auto System (EOL)
Power Density (mW/cm^2)	1,183	911	803
Total Pt loading ($mgPt/cm^2$)	0.125	0.175	0.125
Pt Group Metal (PGM) Total Content (g/kW_{gross})	0.106	0.206	0.167
Net Power (BOL) (kW_{net})	80	80	80
Net Power (EOL) (kW_{net})	80	72	72
Gross Power (kW_{gross})	88.4	89.2	89.2
Cell Voltage (V)	0.657	0.650	0.650
Operating Pressure (atm)	2.5	2.5	2.5
Stack Temp. (Coolant Exit Temp) (°C)	95	92	92
Air Stoichiometry	1.5	1.5	1.5
$Q/\Delta T$ (kW_{th}/°C)	1.45	1.45	1.45
Active Cells	380	307	346
Cell Active Area (cm^2)	197	290	292
Active to Total Area Ratio	0.625	0.625	0.65
Stack Specific Power (kW_{gross}/kg)	3.70	3.25	3.06
System Specific Power (kW_{gross}/kg)	0.96	1.14	1.12
Stacks per System	1	1	1
Total System Voltage (V)	250	200	225
BOP Replacement (% of BOP Cost)	0%	30%	0%
Cost Contingency (%)	0%	10%	10%

2020 LDV Component Assumptions

	2018 Auto Technology System	2020 Auto System	2025 Auto System (High Innovation)
Membrane Material	14-micron Nafion® (850EW) supported on ePTFE	14-micron Nafion® (850EW) supported on ePTFE	High performance membrane (cost based on 10 mm Nafion® supported on Electrospun PPSU) (Giner DSM)
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	SS 316L with TreadStone LIteCell™ Coating (Dots-R)	SS 316L with TreadStone LIteCell™ Coating (Dots-R)	SS 304L with TreadStone TIOX coating
BPP Forming/Joining	Progressive Stamping/Welding	Progressive Stamping/Welding	Hydroforming/Welding
Air Compression	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, Radial-Inflow Expander (with adv. mech. design)
Air Humidification	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	None	None
Gas Diffusion Layers	150 microns (105 mm GDL, 45 mm MPL, uncompressed)	150 microns (105 mm GDL, 45 mm MPL, uncompressed)	150 microns (105 mm GDL, 45 mm MPL, uncompressed)
Catalyst & Application	Slot Die Coating of: Cath.: Dispersed 0.1 mgPt/cm^2 PtCo/HSCAnode: Dispersed 0.025mgPt/cm^2 Pt/C	Slot Die Coating of: Cath.: Dispersed 0.150 mgPt/cm^2 d-PtCo/HSC Anode: Dispersed 0.025mgPt/cm^2 Pt/C	Slot Die Coating of advanced performance catalyst. Cost modeled as: Cath.: Dispersed 0.100 mgPt/cm^2 d-PtCo/HSC Anode: Dispersed 0.025mgPt/cm^2 Pt/C (Assume catalyst cost still dominated by Pt price and no major improvements in application)
CCM Preparation	Gore Direct-Coated Membrane with dual-side slot-die coated electrodes, acid washing	Gore Direct-Coated Membrane with dual-side slot-die coated electrodes, acid washing	Gore Direct-Coated Membrane with dual-side slot-die coated electrodes, acid washing
Air Compressor/Expander/ Motor Efficiency	Compressor: 71% Expander: 73% Motor/Controller: 80%	Compressor: 71% Expander: 73% Motor/Controller: 85%	Compressor: 71% Expander: 73% Motor/Controller: 85%
Hydrogen Humidification	None	None	None
Anode Recirculation	Pulse ejector with bypass	Pulse ejector with bypass	Pulse ejector with bypass
Exhaust Water Recovery	None	None	None
MEA Containment	R2R sub-gaskets, GDL hot-pressed to CCM	R2R sub-gaskets, GDL hot-pressed to CCM	R2R sub-gaskets, GDL hot-pressed to CCM
Coolant & End Gaskets	Laser Welded(Cooling)/ Screen-Printed Polyolefin Elastomer (End)	Laser Welded(Cooling)/ Screen-Printed Polyolefin Elastomer (End)	Laser Welded(Cooling)/ Screen-Printed Polyolefin Elastomer (End)
Freeze Protection	Drain Water at Shutdown	Drain Water at Shutdown	Drain Water at Shutdown
Hydrogen Sensors	0 for FC System	0 for FC System	0 for FC System
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

Progress Toward DOE Targets for LDV Systems



- Majority of cost reduction initially due to economies of scale
- Estimate assumes substantial improvement between now and 2025 based on improved durability and compression & air management systems
- Assume improvement in power density from both tech advances in catalyst and reduction in stack active area oversizing

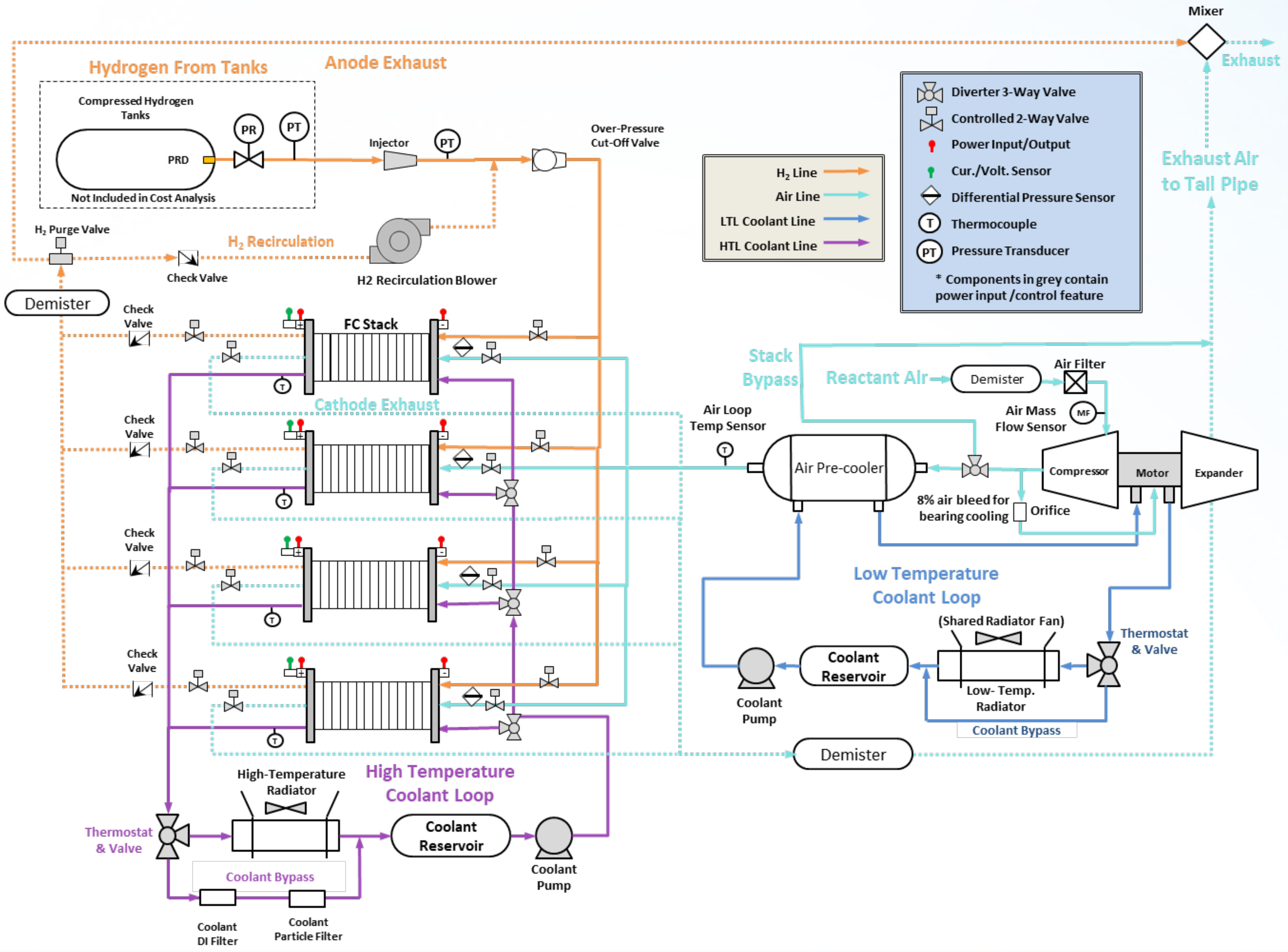
A Improvement in operating conditions: Increase in Power Density (911 to 964 mW/cm2), reduction in total Pt loading from 0.175 to 0.125 mgPt/cm2.
B Improved Durability: reduction in membrane thickness from 14 to 10microns, increase the number of cells per sensing unit in CVM (from 4 to 8 cells), and removal of BOP replacement cost.
C Misc. Technical Advances: Switch from ePTFE to alternative low-cost membrane support material, increase active to total area ratio, switch from stamped SS316 to hydroformed SS301 bipolar plates with TIOX coating, and improvemnet in CEM design.
D Improvement in operating conditions: Increase in Power Density (964 to 1156 mW/cm2).
E Improved Durability: remove stack oversizing, (increase power density from 1156 to 1394mW/cm2), removal of BOP replacement cost, reduction in cost contingency from 10% to 8%.
F Misc. Technical Advances: Improvement in CEM (improvement in efficiencies and no air bleed), reduce from two to one coolant loop, reduction in BPP and coolant sealing cost to $2.50/kW, removal of air precooler and demisters.

Accomplishments and Progress:
2021 Long-Haul HDV System
(Diagram shows system components included in baseline cost analysis model)

System design in collaboration with ANL

4 Stacks:
2 parallel strings of 2 stacks electrically in series
-Gas manifolds in parallel

System Voltage: 560-760V
Limit 400 cells/stack
Cell Active Area: 490cm^2



2021 HDV System Assumptions

Red: Values changed from previous year

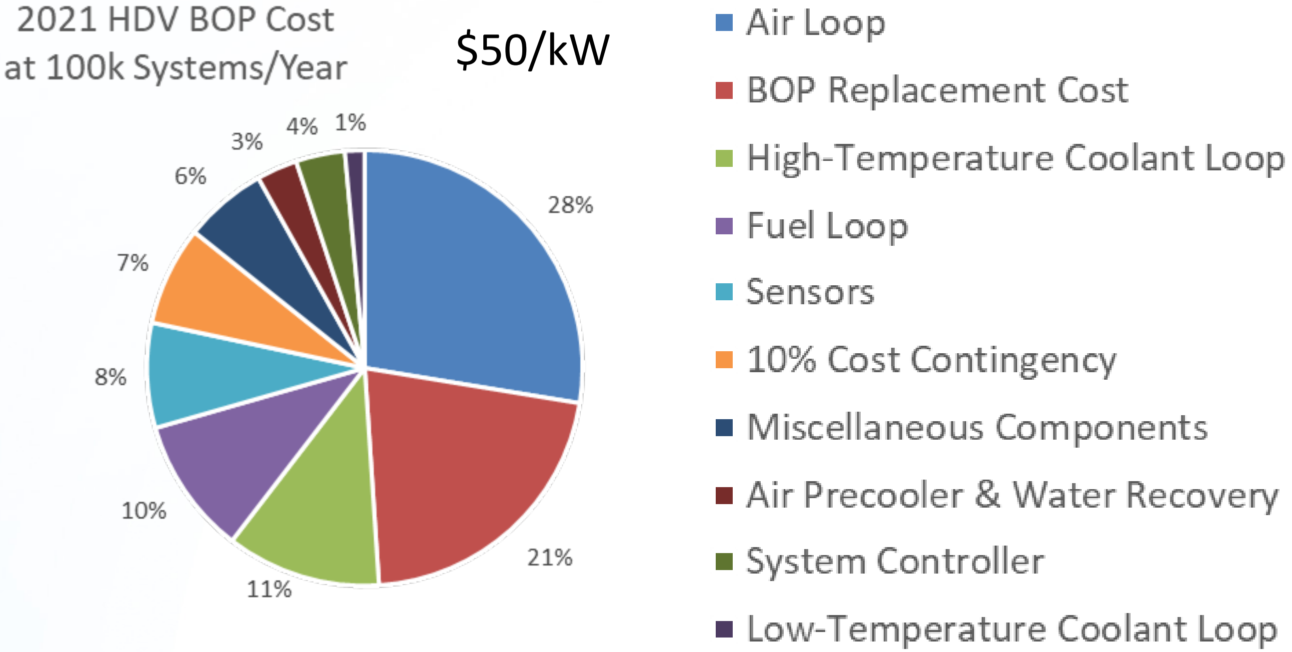
	2020 HDV Technology System	2021 HDV System (EOL)	2025 HDV System (EOL)
Power Density (mW/cm^2)	1050	440	644
Active Area Oversizing	0%	66%	43%
Total Pt loading ($mgPt/cm^2$)	0.4	0.05(a)+0.35(c)= 0.4	0.05(a)+0.30(c)= 0.35
Pt Group Metal (PGM) Total Content (g/kW_{gross})	0.407	0.96	0.58
Net Power (kW_{net})	275	275	275
Gross Power (kW_{gross})	346	346	348
Cell Voltage (V)	0.70	0.70	0.66
Operating Pressure (atm)	2.5	2.5	2.5
Stack Temp. (Coolant Exit Temp) (°C)	88	88	94
Air Stoichiometry	1.5	1.5	1.5
H2 Stoichiometry	2	2	2
$Q/\Delta T$ ($kW_{th}/°C$)	4.38	4.31	4.51
Active Cells	1,144	1,600	1600
Cell Active Area (cm^2)	362	491	338
Active to Total Area Ratio	0.625	0.625	0.65
Stacks per System	2 in parallel	4 (2 parallel strings of 2 stacks in series)	4 (2 parallel strings of 2 stacks in series)
Total System Voltage (V)	350	560-760	560-760
Lifetime before stack replacement (hrs)	25,000	25,000	25,000
BOP Replacement (% of BOP Cost)	0%	30%	15%
System Cost Contingency	0%	10%	10%

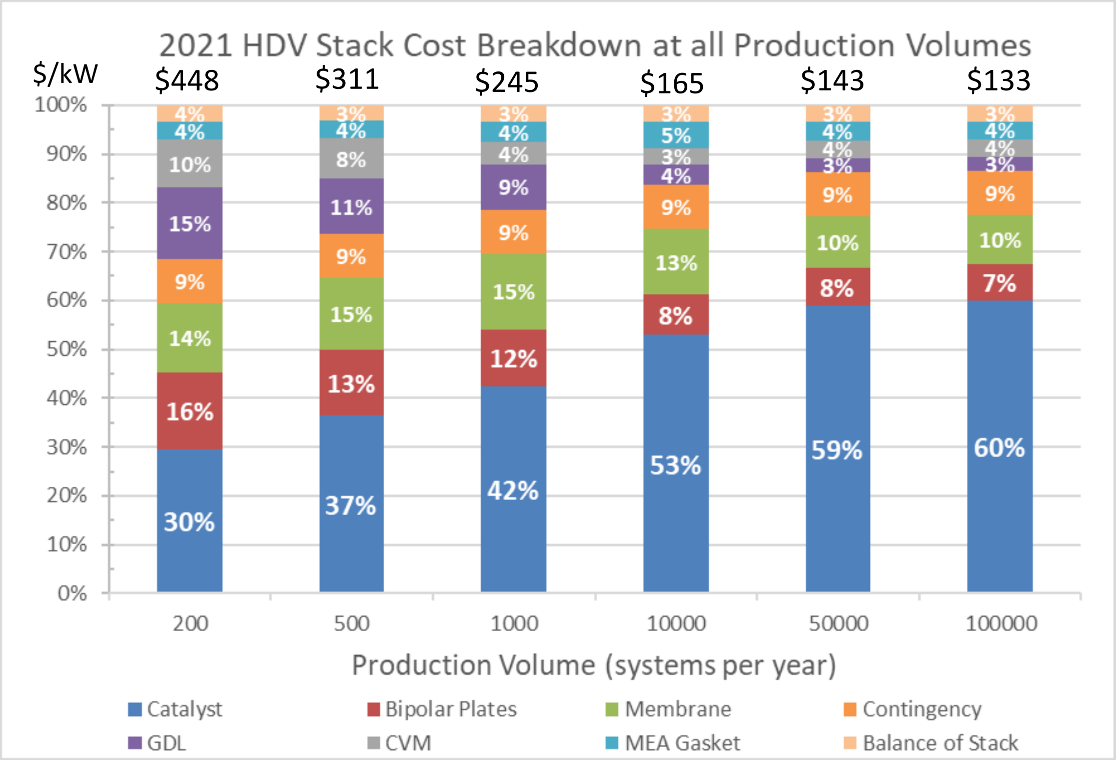
2021 HDV Component Assumptions

	2020 HDV Technology System	2021 HDV Technology System	2025 HDV Technology System
Membrane Material	14-micron Nafion® (850EW)	20-micron Nafion® (850EW)	15-micron Nafion® (850EW) supported on Electrospun PPSU
Membrane Support	ePTFE	ePTFE	
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
Gas Diffusion Layers	150 microns (105 mm GDL, 45 mm MPL, uncompressed)	150 microns (105 mm GDL, 45 mm MPL, uncompressed)	150 microns (105 mm GDL, 45 mm MPL, uncompressed)
Catalyst & Application	Slot Die Coating of: Cath.: Dispersed 0.35 mgPt/cm^2 annealed Pt/HSC (Performance based on alternative catalyst) Anode: Dispersed 0.05mgPt/cm^2 Pt/HSC	Slot Die Coating of: Cath.: Dispersed 0.35 mgPt/cm^2 annealed Pt/HSC (Performance based on alternative catalyst) Anode: Dispersed 0.05mgPt/cm^2 Pt/HSC	Slot Die Coating of: Cath.: Dispersed 0.30 mgPt/cm^2 annealed Pt/HSC (Performance based on alternative catalyst) Anode: Dispersed 0.05mgPt/cm^2 Pt/HSC
MEA Containment	R2R sub-gaskets, GDL hot-pressed to CCM	R2R sub-gaskets, GDL hot-pressed to CCM	R2R sub-gaskets, GDL hot-pressed to CCM
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
Air Compression	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, Radial-Inflow Expander
Air Compressor/Expander/ Motor Efficiency	Compressor: 72.5% (centrifugal) Expander: 72% Motor/Controller: 85%	Compressor: 72.5% (centrifugal) Expander: 72% Motor/Controller: 85%	Compressor: 72.5% (centrifugal) Expander: 72% Motor/Controller: 85%
External Air Humidification	None	None	None
External Hydrogen Humidification	None	None	None
Anode Recirculation	H_2 Recirculation Blower	H_2 Recirculation Blower	H_2 Recirculation Blower
Exhaust Water Recovery	None	None	None
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
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 Cells	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)	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 for FC System	1 for FC System
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	2

Accomplishments and Progress:
2021 HDV System Cost Breakdown

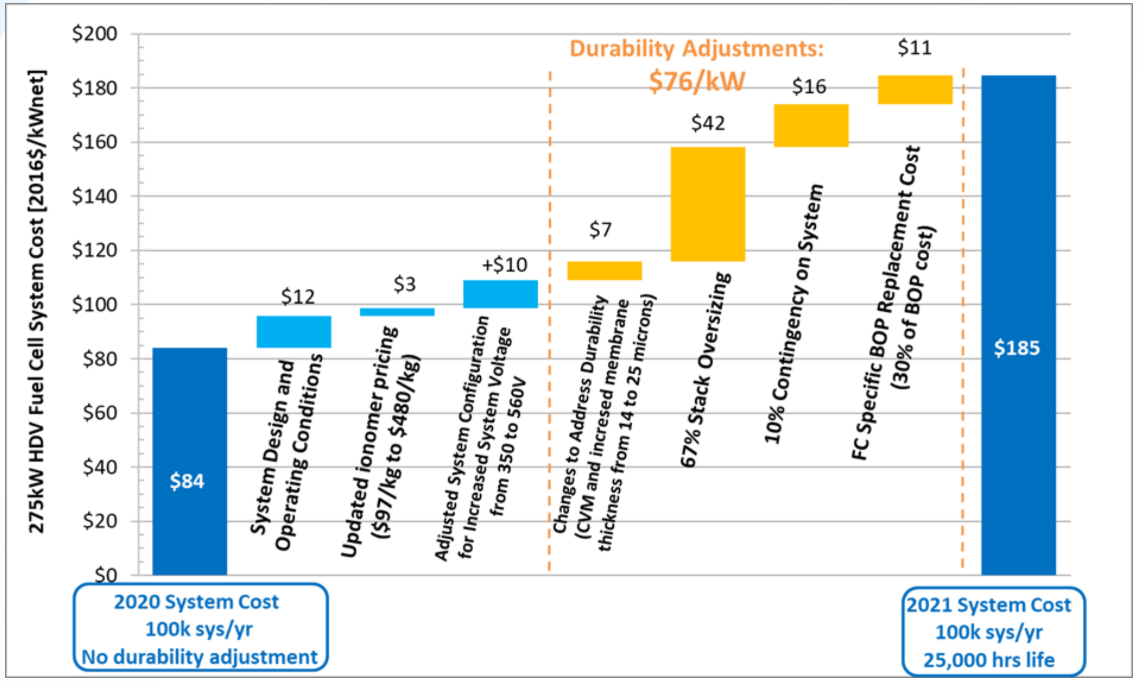
- HDV system cost dominated by stack cost
  - Requires high Pt loading
  - Operating conditions and durable catalyst contribute to lower power density than LDV application
- Air compressor/expander/motor (CEM) highest BOP component cost and assume can last 25,000 hr life

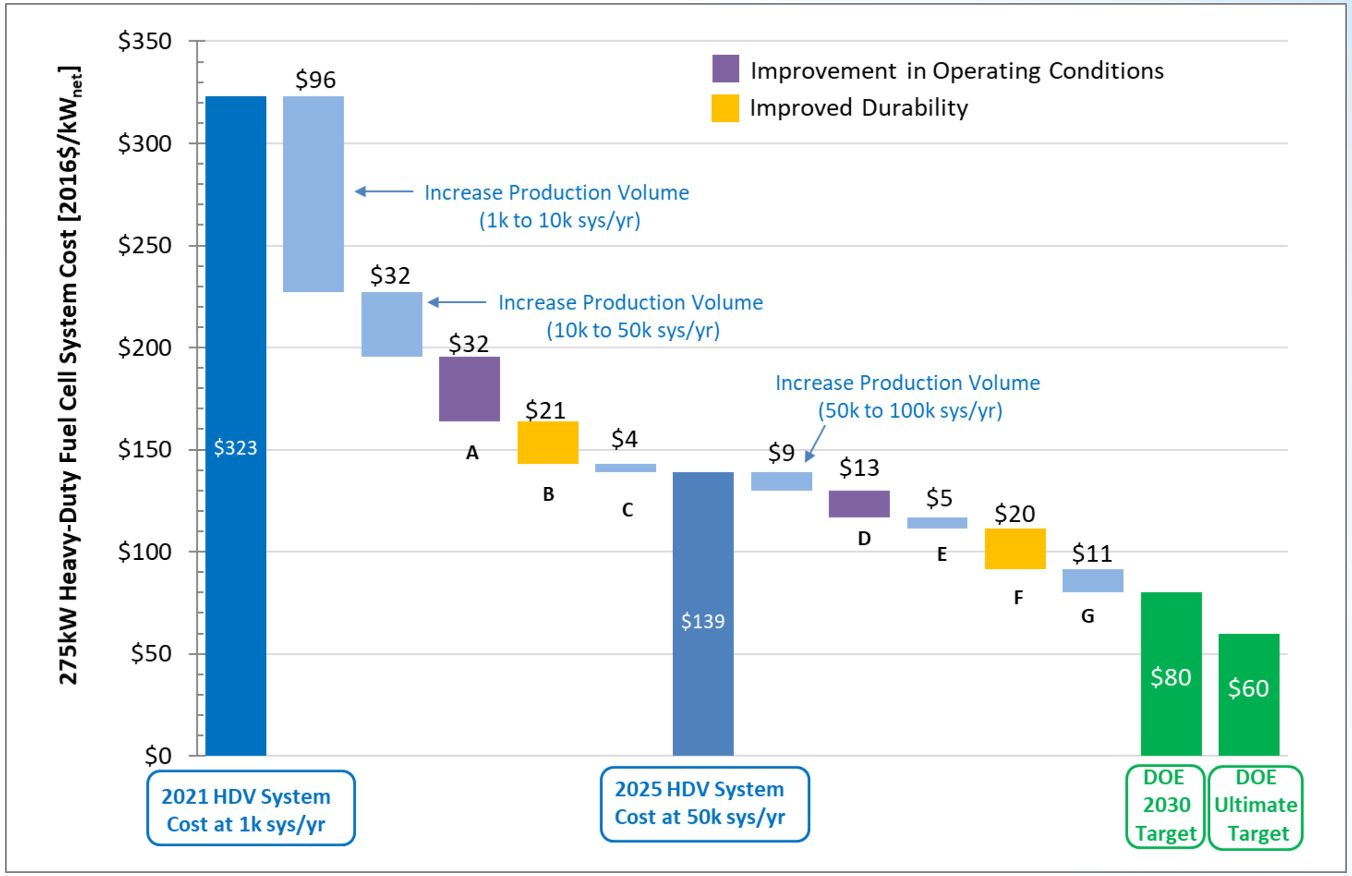




Progress Toward DOE Targets for HDV Systems

- Cost impact of $76/kW due to durability adjustments (below)
- Multiple levels of performance and durability improvements are needed to reach DOE targets for HDV (right)



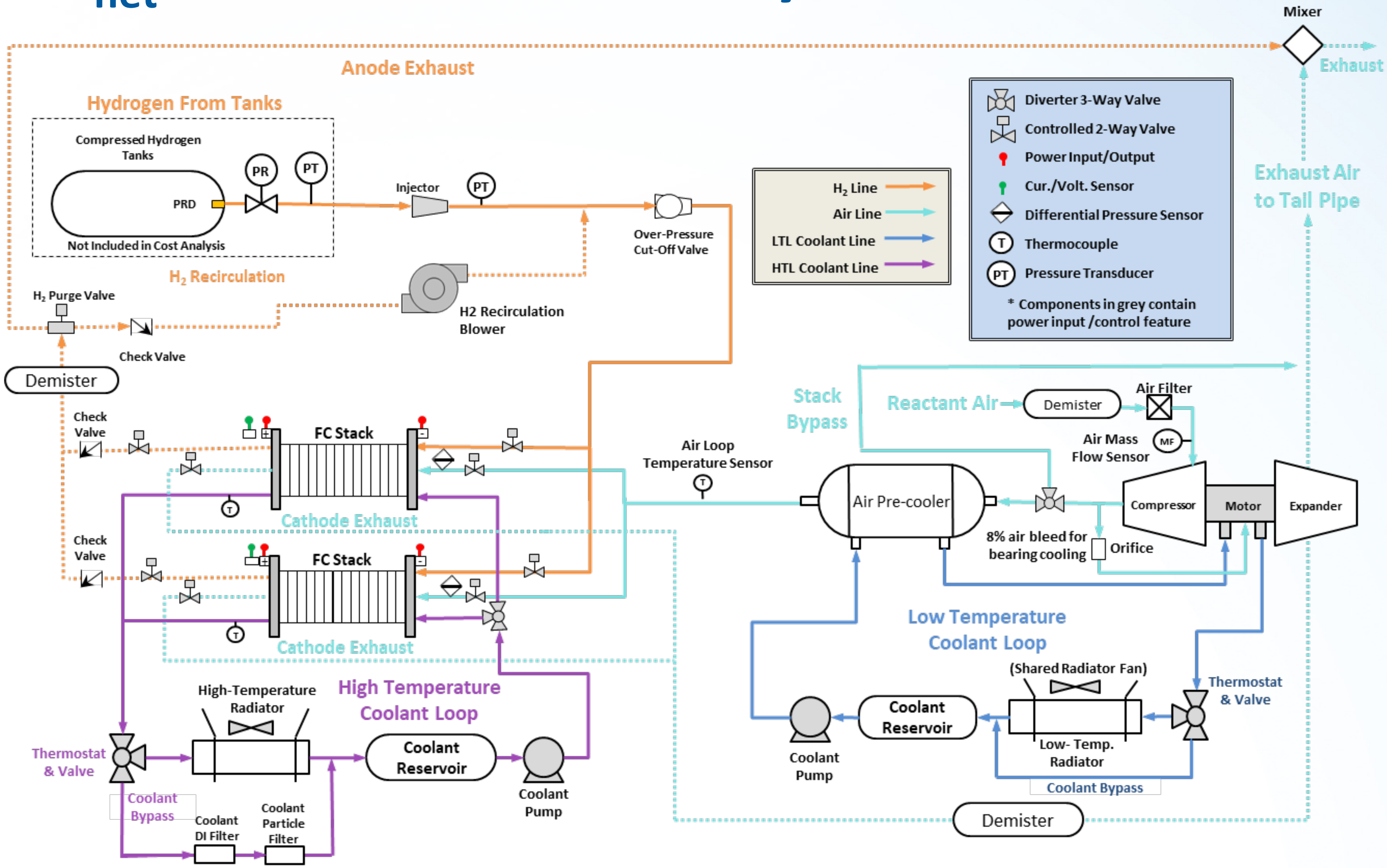


A Improvement in operating conditions: Increase power density from 440 to 553 mW/cm^2. Reduce EOL voltage from 0.7 to 0.66 V/cell, 88 to 94C. Reduce total Pt loading from 0.4 to 0.35 mgPt/cm^2
B Improved Durability: Reduce oversizing from 66% to 43% (increase power density 553 to 644 mW/cm^2), increase cells per sensor (4 to 8) for CVM, and reduce the BOP replacement from 30% to 15%.
C Misc.: Switch from ePTFE to alternative low-cost membrane support material, increase active to total area ratio, and reduce membrane thickness from 20 to 15microns.
D Improvements in operating conditions: increase power density from 644 to 708 mW/cm^2, reduce Pt loading from 0.35 to 0.3 mgPt/cm^2
E Improvements in air CEM: Increase in motor+controller efficiency from 85 to 92%, increase compressor efficiency from 72.5% to 75%, increase expander from 72 to 75%, remove 8% air bleed.
F Improved Durability: Reduce oversizing from 43% to 10% (increases power density from 708 to 921 mW/cm^2). Reduce BOP Replacement cost from 15 to 8%, Reduce cost contingency from 10% to 5%
G Reduce Number of Stacks from 4 to 2

Accomplishments and Progress: 2021 and 2025 System Configuration $160kW_{net}$ MDV Walk-in Delivery Truck

- 2 stacks electrically in series
- Gas manifolds in parallel

System Voltage: 560-760V
Limit 400 cells/stack
Cell Active Area: 460cm^2



2021 MDV System Assumptions

	2020 MDV Technology System	2021 MDV System (EOL)	2025 MDV System (EOL)
Power Density (mW/cm^2)	1050	518	713
Active Area Oversizing	0%	42%	22%
Total Pt loading ($mgPt/cm^2$)	0.4	0.05(a)+0.35(c)= 0.4	0.05(a)+0.30(c)= 0.35
Pt Group Metal (PGM) Total Content (g/kW_{gross})	0.408	0.817	0.524
Net Power (kW_{net})	170	160	160
Gross Power (kW_{gross})	205	191	192
Cell Voltage (V)	0.70	0.70	0.66
Operating Pressure (atm)	2.5	2.5	2.5
Stack Temp. (Coolant Exit Temp) (°C)	88	88	94
Air Stoichiometry	1.5	1.5	1.5
H2 Stoichiometry	2	2	2
$Q/\Delta T$ (kW_{th}/°C)	2.55	2.38	2.46
Active Cells	716	800	800
Cell Active Area (cm^2)	363	460	337
Active to Total Area Ratio	0.625	0.625	0.65
Stacks per System	2 electrically in parallel	2 electrically in series	2 electrically in series
Total System Voltage (V)	250	560-760	528-760
Lifetime before stack replacement (hrs)	25,000	25,000	25,000
BOP Replacement (% of BOP Cost)	0%	35%	20%
System Cost Contingency	0%	10%	10%

Red: Values changed from previous year

STRATEGIC ANALYSIS INC.

2021 MDV Component Assumptions

	2020 MDV Technology System	2021 MDV Technology System	2025 MDV Technology System
Membrane Material	14-micron Nafion® (850EW)	20-micron Nafion® (850EW)	15-micron Nafion® (850EW) supported on
Membrane Support	ePTFE	ePTFE	Electrospun PPSU
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
Gas Diffusion Layers	150 microns (105 mm GDL, 45 mm MPL, uncompressed)	150 microns (105 mm GDL, 45 mm MPL, uncompressed)	150 microns (105 mm GDL, 45 mm MPL, uncompressed)
Catalyst & Application	Slot Die Coating of: Cath.: Dispersed 0.35 mgPt/cm^2 annealed Pt/HSC (Performance based on alternative catalyst) Anode: Dispersed 0.05mgPt/cm^2 Pt/HSC	Slot Die Coating of: Cath.: Dispersed 0.35 mgPt/cm^2 annealed Pt/HSC (Performance based on alternative catalyst) Anode: Dispersed 0.05mgPt/cm^2 Pt/HSC	Slot Die Coating of: Cath.: Dispersed 0.30 mgPt/cm^2 annealed Pt/HSC (Performance based on alternative catalyst) Anode: Dispersed 0.05mgPt/cm^2 Pt/HSC
MEA Containment	R2R sub-gaskets, GDL hot-pressed to CCM	R2R sub-gaskets, GDL hot-pressed to CCM	R2R sub-gaskets, GDL hot-pressed to CCM
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
Air Compression	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, Radial-Inflow Expander
Air Compressor/Expander/ Motor Efficiency	Compressor: 72.5% (centrifugal) Expander: 72% Motor/Controller: 85%	Compressor: 72.5% (centrifugal) Expander: 72% Motor/Controller: 85%	Compressor: 72.5% (centrifugal) Expander: 72% Motor/Controller: 85%
External Air Humidification	None	None	None
External Hydrogen Humidification	None	None	None
Anode Recirculation	H_2 Recirculation Blower	H_2 Recirculation Blower	H_2 Recirculation Blower
Exhaust Water Recovery	None	None	None
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
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 Cells	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)	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 for FC System	1 for FC System
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	2

2020/2021 Publications and Presentations

- 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: 2020 Update on Light-Duty Vehicles", Strategic Analysis, Inc., May 2021.
- James, B.D., Huya-Kouadio, J.M., Houchins, C., "Fuel Cell Systems Analysis", Presentation to the USDRIVE Fuel Cell Technical Team, March 11th, 2021.
- Kleen, G., Padgett, E., "Durability-Adjusted Fuel Cell System Cost", US Department of Energy Hydrogen and Fuel Cells Technology Office Record#: 21001, January 8th, 2021.
- James, B.D., Huya-Kouadio, J.M., Houchins, C., "Rationale for Heavy Duty Truck Analysis", SA presentation at the M2FCT Meeting, December 3rd, 2020.
- James, B.D., Huya-Kouadio, J.M., Houchins, C., "Heavy Duty Fuel Cell Truck Cost Analysis", SA presentation at the 21st Century Truck Meeting, December 10th, 2020.

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/Garrett Motion	Manufacturer of centrifugal compressor (baseline auto compressor)
	Eaton	Roots compressor/expander (baseline bus compressor)
	Aeristech	Manufacturer of centrifugal compressors
	Celeroton	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	GM, Hyundai, Nissan, Toyota, US Hybrid, Loop Energy	Aalto University, Nolek, Machine Works, Andritz Kusters, FC Powertrain, Plug Power, Daimler (Cell Centric), Cummins, Ford, FFP Sys Inc. (press filter), Gannon And Scott, Wisconsin Ovens, Orchid Technologies, Tejin Films, AVL