STRATEGIC ANALYSIS

Fuel Cell Cost and Performance Analysis

2022 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting Presentation

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Project ID# FC353
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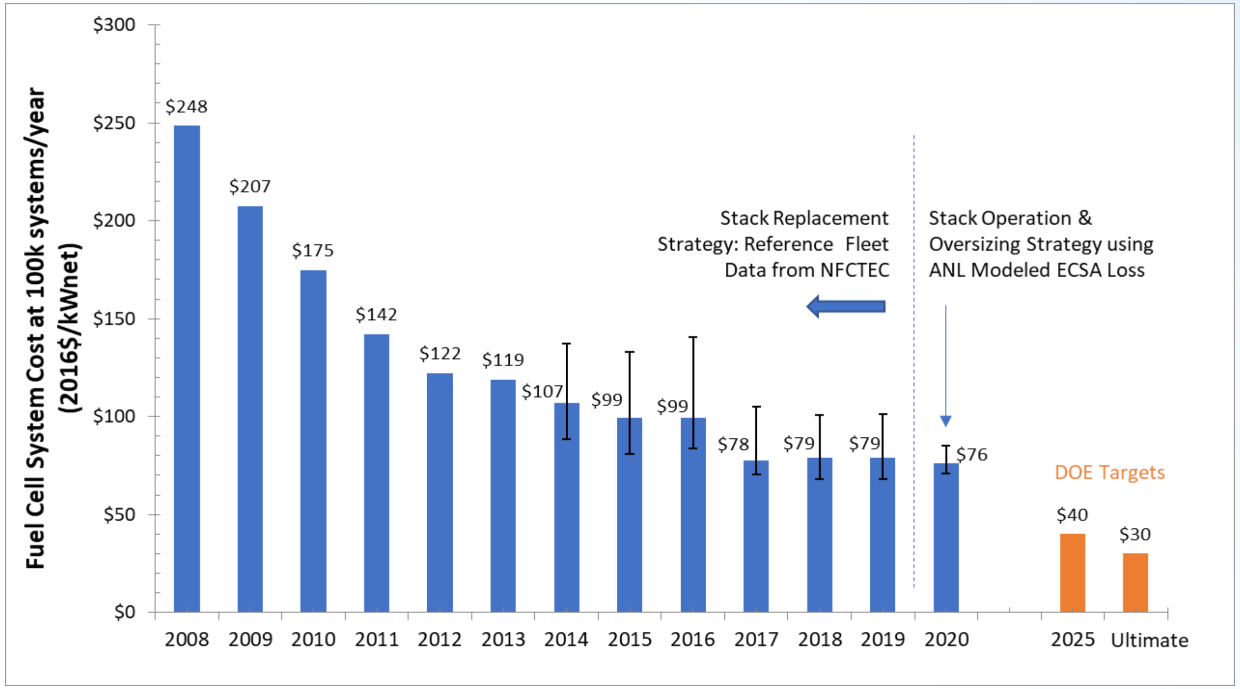
Project Goal

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



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

Overview

Timeline

- Project Start Date: 10/01/21
- Project End Date: 9/30/25
- % complete: ~13% of four-year project (in Year 1 of 4)

Barriers

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

Budget

- Total Funding Spent
  - ~$88k (through March 2022, SA only)
- Total DOE Project Value
  - $1.26M (over 4 years, excluding Labs)
  - 0% Cost share

Partners

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

Relevance

Overall Project Objectives:

- Project current (2022) and future (2025 and 2030) cost of automotive, truck, rail, and marine fuel cell systems at high manufacturing rates.
- Project impact of technology improvements on system cost
- Identify low-cost pathways to achieve the DOE target values
- Benchmark against production vehicle power systems
- Identify fuel cell system cost drivers to facilitate HFTO programmatic decisions.
- Quantify the cost impact of components that improve durability.

Preliminary Cost Estimates

Systems Evaluated for 2022	Units (2016$)	Project Status 2022	2025	2030	DOE Targets	DOE Ultimate Target
Cost of LDV FC Power Systems	$\$/kW_{net}$	$60 @500k sys/yr	$50 @500k sys/yr	$45 @500k sys/yr	40 (2025)	30
Cost of MDV FC Power Systems	$\$/kW_{net}$	$216@ 100k sys/yr	$177@ 100k sys/yr	$157@ 100k sys/yr	NA	NA
Cost of HDV FC Power Systems	$\$/kW_{net}$	$182@ 100k sys/yr	$145@ 100k sys/yr	$107@ 100k sys/yr	80 (2030)	60 (2050)

Relevance: Timeline of Analyses

Year	Project Year	Technology	Proposed Analyses
2022	1	$275kW_{net}$ HDV	Current, 2025, 2030
		$70kW_{net}$ MDV	Current, 2025, 2030
		$80kW_{net}$ LDV Light Update	Current, 2025, 2030
2023	2	Rail	Current, 2025, 2030
		HDV Update	Current, 2025, 2030
		MDV Light Update	Current, 2025, 2030
2024	3	Marine	Current, 2030
		HDV Update	Current, 2030
		LDV Light Update	Current, 2030
2025	4	HDV, MDV, LDV Update	Current, 2030
		Rail, Marine Update	Current, 2030

Year 1: 2022 Analyses

- Three system technology years for each application
- Prioritize HDV and MDV system analyses
- Light update of LDV baseline systems

Future Year Analyses: 2023-2025

- **2023: Prioritize Rail** system analyses
  - Three technology years for each application
- **2024: Prioritize Marine** system analyses
  - Two technology years for each application
- **2025: Update to all systems** previously analyzed
  - Two technology years for each application

Task	Description	Completed for 2022 Analysis?
1	Manufacturing Process and Technology Review	Ongoing
2	System Definition and Bill of Materials	Milestone 1 submitted in October 2021
3	Techno economic Analysis	Milestone 2 submitted in March 2022
4	Project Reporting	Milestone 3: Response to Reviewer Feedback (In Process) Milestone 4: Final Annual Report (to be submitted in September 2022 (Go/No-Go decision metric))

Approach: Topics Examined for 2022

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

2022/2025/2030 Light-Duty Automobile Systems (Light Update)

- **Projection of Performance and Durability for future systems:** Utilized ANL 2020 analysis of LDV modeling (Preliminary)
- **Improvement in Cell Voltage Monitoring (CVM) System:** Cost modeled a detailed CVM assembly process (Preliminary)

2022/2025/2030 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 69% electrochemical surface area (ECSA) loss after 25,000 hours (Preliminary for HDV, In Process for MDV)
- **Improvement in Cell Voltage Monitoring System:** Cost modeled a detailed CVM assembly process (Preliminary)
- **Update Automated MEA and Cell Stacking:** Re-evaluate assumptions for demonstrated equipment (Preliminary for HDV)
- **Alternative HDV Humidifier Designs:** Investigate available types of humidifiers (added to 2022 HDV system) (In process)

Side studies not affecting baseline system analysis

- **Cell Reversal Tolerant Anode (RTA) Catalyst:** Estimate the cost trade-off for 1-to-1 replacement of CVM (In process)
- **Phase Change Material (PCM) for Heat Rejection in HDV system:** Evaluate the cost of hybrid fan/radiator and PCM systems (In process)
- **MEA roll-to-roll manufacturing approaches:** Evaluate CCM vs. GDE, and direct coat vs decal transfer (Future study)

Accomplishments and Progress:

Projecting Performance and Durability of LDV FCS

Modeling Conducted by ANL in 2020

Cathode Pt Loading mgPt/cm²	Lifetime	PD (mw/cm²) BOL / EOL	Cell Voltage (mV) BOL/EOL	EOL ECSA Loss %	Baseline Systems Selections
0.15	8k hrs	**1107 / 911**	705/650	69%	**2020/2022 system**
	5k hrs	1205 /1062	685/657	53%	
0.1	8k hrs	996/803 1196 / 964 (2025)	710/649	69%	2025 system: 2020 Model Basis plus 20% PD improvement
	5k hrs	1104 / 959 1325 / 1151 (2030)	688/656	53%	2030 system: 2020 Model Basis, 20% PD improv., and achieving 8kh)

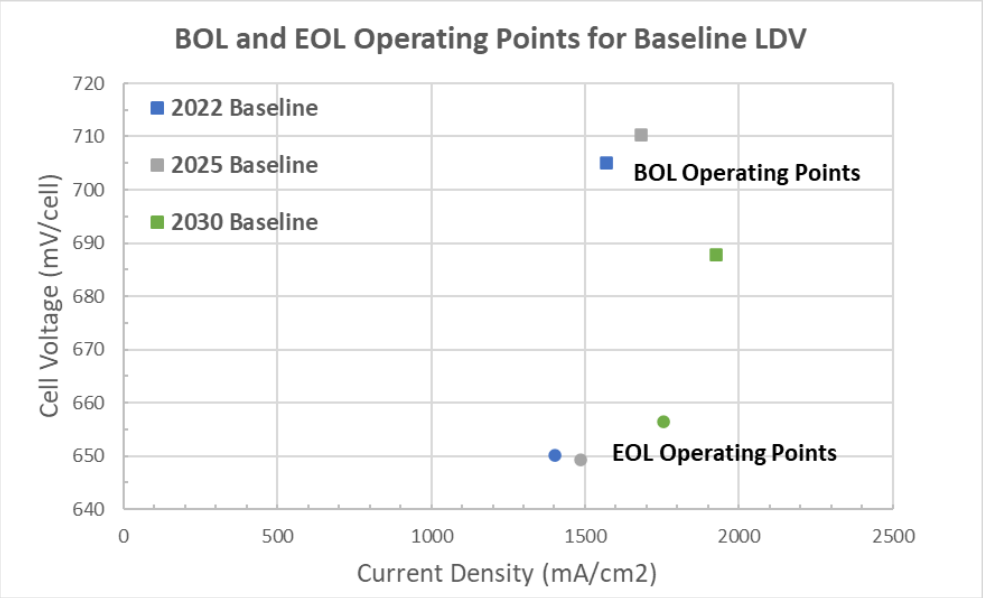
Yellow text signifies deviation from ANL 2020 modeling

- **2020 ANL Modeling used as basis for 2022 LDV System Operating Conditions**
  - ANL provided results for 8k and 5k protocol at 0.1 and 0.15mgPt/cm^2 cathode loading:

2022 operation: Unchanged from 2020/2021

2025 operation:
- Based on 2020 modeling for 8hrs, 0.10mgPt/cm^2 but:
  - increase PD by 20%

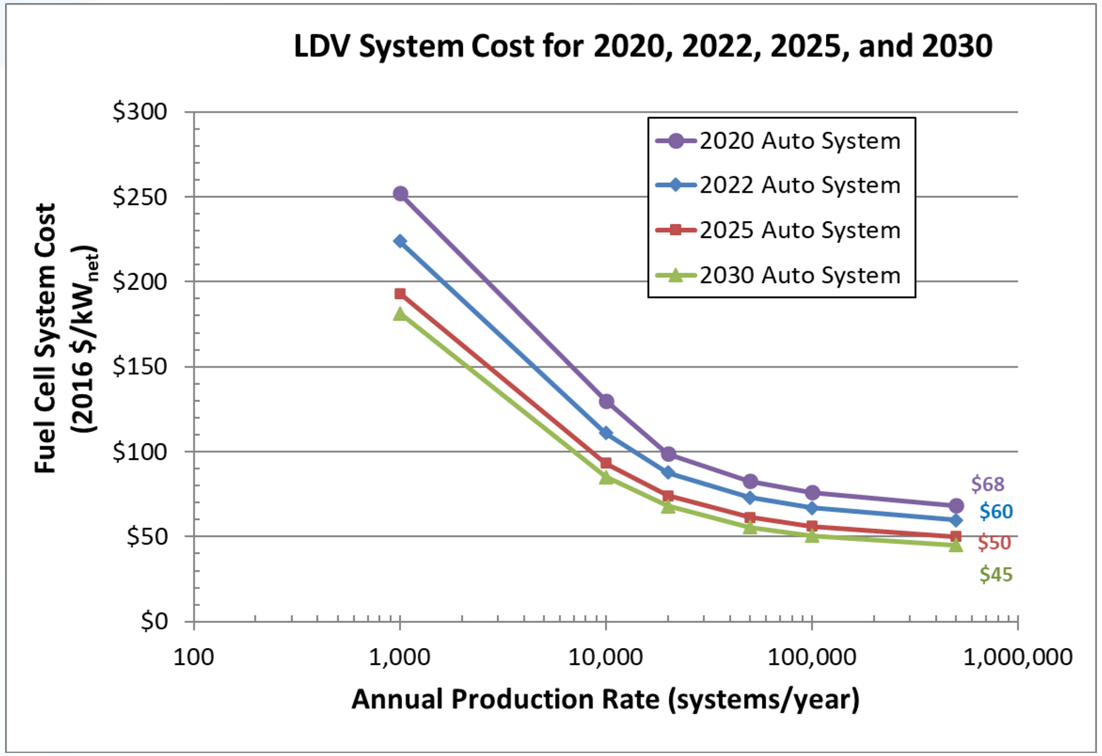
2030 operation
- Based on 2020 modeling for 5khrs, 0.10mgPt/cm^2 but:
  - increase PD by 20%
  - Increase hours to 8k

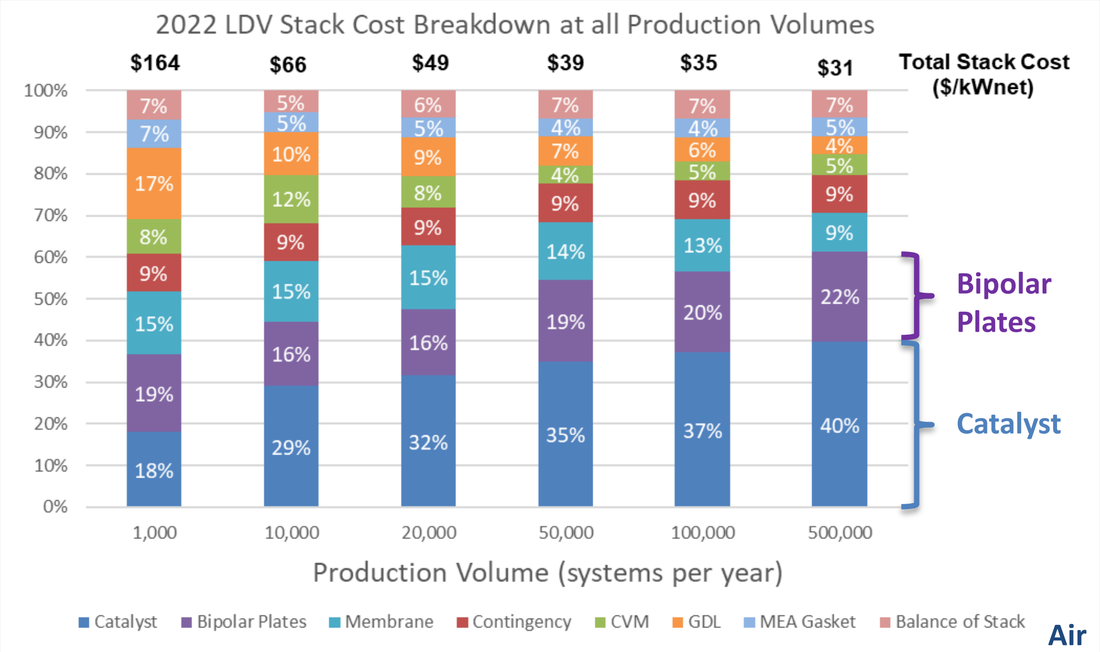


EOL LDV Conditions (8k hrs)	2022	2025	2030
Power Density (mW/cm^2)	911	803*1.2 = 964	959*1.2 = 1151
Cell Voltage (V)	0.65	0.65	0.656
Total Pt Loading (mgPt/cm^2) Cathode Pt Loading (mgPt/cm^2)	0.175 0.15	**0.125** **0.10**	**0.125** **0.10**
ECSA Loss over 8k hrs	69%	**69%**	**53%**
Coolant Exit Temp (C)	92	92	90
Membrane Thickness (µm)	14	10	10
Gross System Power (kW)	81	81	78.5
Net System Power (kW)	72	72	72
Membrane Active Area (m^2)	8.8	8.4	6.8

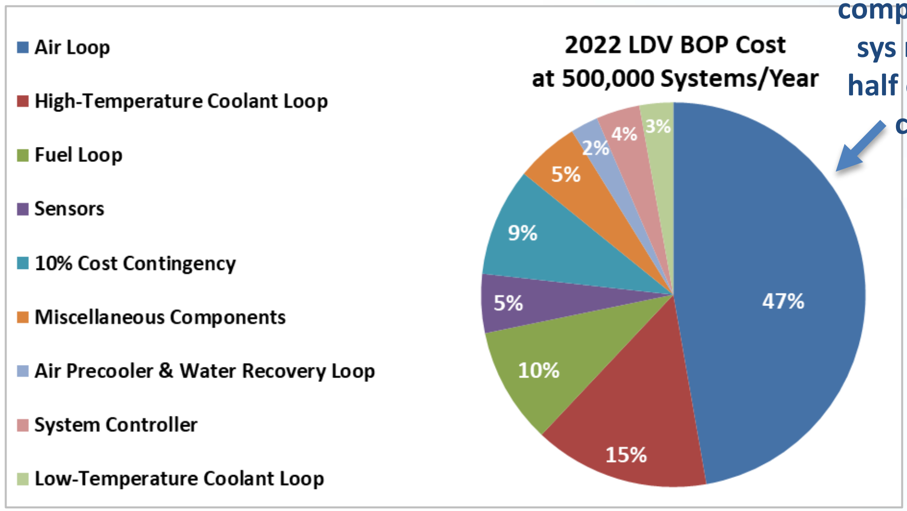
Accomplishments and Progress:

Preliminary Cost Results for 2022 LDV Systems





Air compression sys nearly half of BOP cost



- LDV system cost reduced by $8/kW between 2020 and 2022 analyses
  - $7/kW reduction due to removal of BOP replacement cost (Fuel Cell Technical Team recommendation)
  - ~$1/kW reduction for CVM assembly re-evaluation and miscellaneous changes
- Future 2025 and 2030 systems would improve in both durability (lower Pt loading to reach 8k hrs) and performance (20% improvement between design cycles)

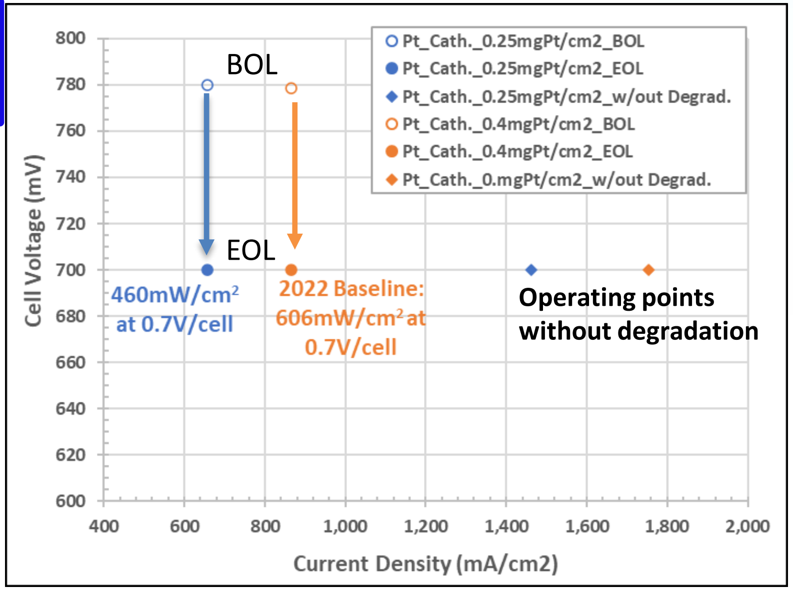
Documentation for durability adjusted cost for LDV system: 2021 DOE Record #21001 , 2020 Final Report

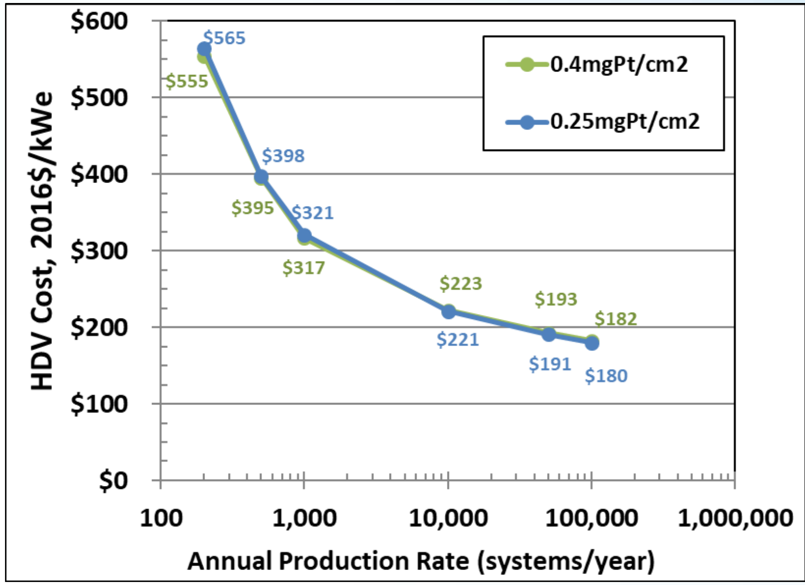
Accomplishments and Progress:

Durability Adjusted Operating Conditions for HDV System

Two optimized data sets provided by ANL

	Data Set 1	Data Set 2
Cathode Pt Loading (mgPt/cm²)	**0.25**	**0.4**
EOL Power Density (mW/cm²) @ 0.7V	460	606
Durability	25k hrs	25khrs
ECSA Loss at EOL	56.5%	56.5%
Active Area Oversizing	120%	100%
Total Active Area per System (m²)	73.3	55.6
Stack Volumetric Power Density (kW_{gross}/L)	1.44	1.84
Stack Specific Power (kW_{gross}/kg)	1.27	1.64
System Cost ($/$kW_{net}$) @ 100k sys/yr	**$180**	**$182**





- Durability estimates currently only includes data based on electrode degradation
  - Membrane mechanical and chemical degradation to be included in future analysis by ANL
  - Data used in ANL models at 0.25mgPt/cm² (cathode) but 0.4mgPt/cm² (cathode) loading results are projections
  - ECSA loss estimated over Class 8 Long-Haul highway drive cycle
  - Very large (~2x) increase in active area required to achieve 25k hours of operation
- EOL cell voltage is set to 0.7V (based on DOE target), however, current systems are unable to meet this EOL voltage

Accomplishments and Progress:
Durability Adjusted Operating Conditions for Future HDV Systems

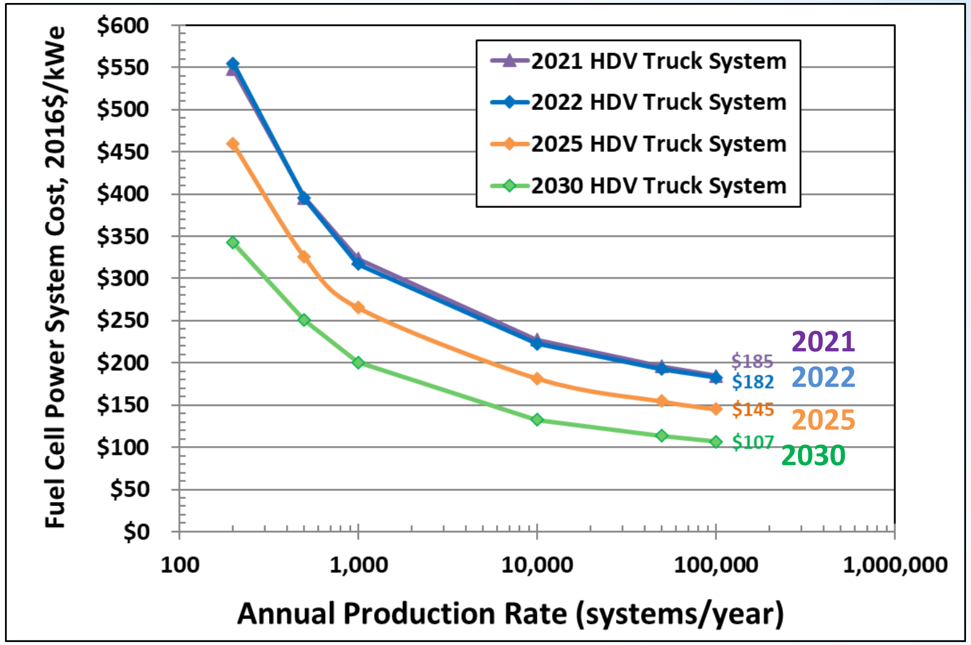
Primary variables adjusted: catalyst loading, temp., air stoic. rate

	2022 HDV Technology System	2025 HDV Technology System	2030 HDV Technology System	Notes
Net Rated Power (kWnet)	313 (BOL), 275 (EOL)	313 (BOL), 275 (EOL)	313 (BOL), 275 (EOL)	
Gross Power (kW_{gross})	373 (BOL), 335 (EOL)	370 (BOL), 333 (EOL)	360 (BOL), 323 (EOL)	Assume no air bleed loss for air compressor motor cooling/bearing for 2030
CEM Efficiencies	72%C., 75%Exp., 84.3%M/MC	72%C., 75%Exp., 84.3%M/MC	75%C., 80%Exp., 92%M/MC	Assume more efficient CEM for 2030
Net CEM Input Power Parasitic (kW)	27	27	19	
Radiator Fan Power Parasitic(kW)	28	25	22	10% reduction in radiator fan power between technology years
Cell Voltage (V)	0.779 (BOL), 0.70 (EOL)	0.779 (BOL), 0.70 (EOL)	0.779 (BOL), 0.70 (EOL)	
Stack Power Density @ Rated Power (mW/cm^2 active area)	674 (BOL), 606 (EOL)	808 (BOL), 726 (EOL)	970 (BOL), 872 (EOL)	Assume increased power density by 20% between technology years
Total Pt loading ($mgPt/cm^2_{total\ area}$)	0.45 (0.4 cath,0.05 anode)	0.35 (0.3 cath,0.05 anode)	0.3 (0.25 cath,0.05 anode)	Assume reduction in Pt loading down to $0.25mgPt/cm^2$ on cathode for 2030
Pt Group Metal (PGM) Total Content (g/kW_{gross})	0.743	0.482	0.344	
Catalyst Durability(ANL modeling): ECSA loss after 25k hours operation	57%	57%	57%	Assume the same ECSA loss but at lower Pt loadings for future years
Operating Pressure (atm)	2.5	2.5	2.5	
Stack Temp. (Coolant Exit Temp) (°C)	90	90	90	
Air Stoichiometry	1.5	1.5	1.5	
H2 Stoichiometry	2	2	2	
Active Cells per system	1600	1600	800	Reduces from 4 to 2 stacks in 2030
Cell Active Area (cm^2)	346	287	464	
Active to Total Area Ratio	0.625	0.65	0.65	
Stacks per System	4 (2 parallel strings of 2 stacks electrically in series)	4 (2 parallel strings of 2 stacks electrically in series)	2 stacks electrically in series	
Total System Voltage	560	560	560	
Stack Oversizing	100%	100%	100%	Values may change with further investigation of membrane degradation.
Total Active Area per System (m^2)	55.3	45.9	37.1	
FC BOP Replacement Cost Over Vehicle Life (% of Total BOP Cost)	40%	40%	30%	Addition of humidifier raises replacement cost by 10% in 2022. 2030 system assume humidifier and air bearings in air compressor motor only need single replacement over life, reducing BOP replacement cost from 40% to 30%.

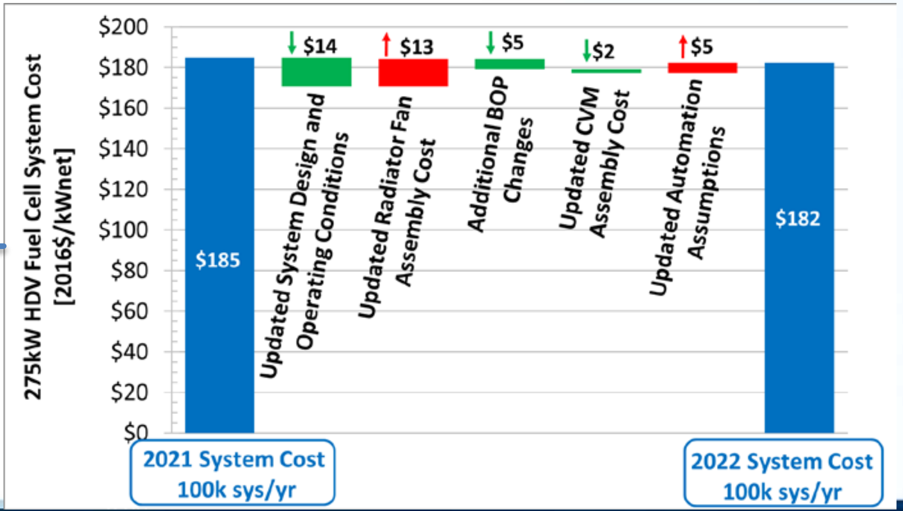
Values in green are a change from the previous year

Accomplishments and Progress:
2022 HDV System Design and Preliminary Cost Results

- Other HDV System Assumptions
  - Addition of a humidifier is crucial for durability of the membrane and enables a wider range of operation for the FC stack
  - Air compression system (CEM) is sized based on conditions for instantaneous peak load on flat highway driving at lower elevation
    - 40°C ambient temp with lower radiator fan power (enough ram-air intake for cooling)
    - Do not currently account for lower ambient air pressure at higher elevations
    - **27kW max air compressor motor power**
  - High Temp Loop radiator and fan size based on 20 min hill climb (6.5% grade) continuous peak power load ($335kW_{gross}$)
    - 25°C ambient temp with max radiator fan power required **(28kW max fan power)**
  - Fuel cell stack sized based on gross power for continuous power load ($335kW_{gross}$)



- HDV system cost reduced by $3/kW from 2021 analysis (previous project)
  - $14/kW reduction due to updated performance (440 to 606mW/cm^2), offset by added humidifiers and increased Pt loading 0.4 to 0.45mgPt/cm^2 total
  - $13/kW addition for updated HTL radiator fan, fan motor, and motor controller costs
  - $5/kW reduction due to reduced number of controllers from (4 to 2), added coolant particle filter, updated CEM efficiencies, sizing the CEM based on 40°C ambient temp, and update to pressure drop within air loop components.
  - $2/kW reduction for updated CVM assembly re-evaluation
  - $5/kW addition for MEA, cell stacking, and conditioning automation assumptions



Accomplishments and Progress: Alternative HDV Humidifier Designs

- Current HDV design (2022) has **one humidifier per single stack or two stacks** (100-150kW FC power)
- Ammonia is a humidifier membrane degradation mechanism
  - Can be mitigated/eliminated via an up-stream activated carbon air filter (as is modeled in current baseline system)
- ANL estimate for humidifier membrane area sizing based on ~90°C FC operating temp: **1.5 m^2 per system**
  - SA assumes 25% membrane area oversizing for degradation: **1.88m^2 total per system**
- Humidification adds ~$2/kW at 100k sys/yr (excludes improvement to power density)
- Assume lifetime of about 10,000 hrs (Fumatech), two humidifier replacements over lifetime
- **Future years 2025 and 2030 could assume cost reduction strategies:**
  - Reduce number of humidifiers per system by increasing the length of the stacks (only possible with improved sealing down length of stack)
    - 2025 assume two humidifiers can feed 4 stacks
    - 2030 system only has 2 FC stacks and thus has two humidifier stacks
  - Alternative to ion-conducting membrane material
  - Lower pressure drop
  - Reduced membrane area required
  - Increase humidifier lifetime (fewer replacements)
  - Use a plastic frame/housing
    - Lighter weight, greater design freedom, no/less machining (possible future analysis)

Vendor	Type	Material	FC Power Sizing
Perma Pure	Tube-style	Nafion™	Gas-to-gas: up to 50kW Water-to-gas: up to 100kW
DPoint	Planar membrane humidifier	PFSA/ePTFE	110kW
Mann + Hummel	Plate frame membrane humidifier	PFSA/ePTFE	100-150kW
Fumatech	Plate frame membrane humidifier	Hollow fiber polyimide/PSU	110kW

Accomplishments and Progress:
Update to Automated MEA and Cell Stacking Assumptions

- Numerous recent discussions with automation suppliers
- Key processes re-visited:
  - **7-layer MEA ("Gasketed MEA", UMEA)**
    - Roll-to-Piece line
    - Input: rolls of CCM, Gasket, GDL
    - Output: discretized UMEA
  - **Cell Stacking**
    - Robotic assembly of repeat cells (UMEA & Bipolar Plate Assembly (BPA)
    - Sub-stack or full-stack leak test
    - Assembly of endplates, current collectors, tie-rods, etc.
    - Compression and banding
  - **Stack Conditioning**
    - Electrical Continuity/Factory-Acceptance-Test(FAT)
    - "Conditioning" with steam and electrical load bank
    - (Optional) Stack Leak Test

Gasketed MEA Assembly (Pick & Place or R2R) Example

	"New" (2022 Analysis) Values								
Year	2022			2025			2030		
Production Rate (Systems/Year)	Low1	Med1	High1	Low2	Med2	High2	Low3	Med3	High3
Stacking Method	P&P	P&P	P&P	P&P	P&P	R2R	P&P	P&P	R2R
Line Speed (m/min)						15			25 (vendor target)
Max Width (mm)						650 (vendor spec.)			650
Max Parts Across Width						1			2
Effective Time Per Cell (sec/cell)	15 (vendor spec.)	5 (vendor spec.)	5	15	5	0.71	12	4	0.27
Capital Cost ($/line)	$1.7M (~vendor spec.)	$3.1M (~vendor spec.)	$3.1M (= Med1)	$1.4M (= Low1 −15%)	$2.6M (= Med1 −15%)	$9.4M (~vendor spec.)	$1.2M (= Low2 −15%)	$2.2M (= Med2 −15%)	$8.7M (= High2 −6.5%)

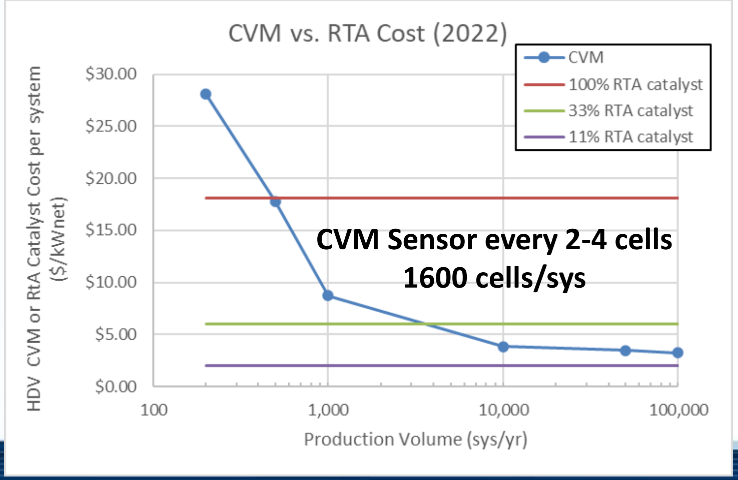
Conclusion:
- Numerous vendors with varied current status but common goals
- **Substantially higher equipment capital cost for R2R than previously estimated by SA**
- Further mid-volume production solutions to be explored (e.g., simplified R2R)
- Total HDV Cost Impact from 2021 to 2022
  - ~$5/kW @100k sys/yr

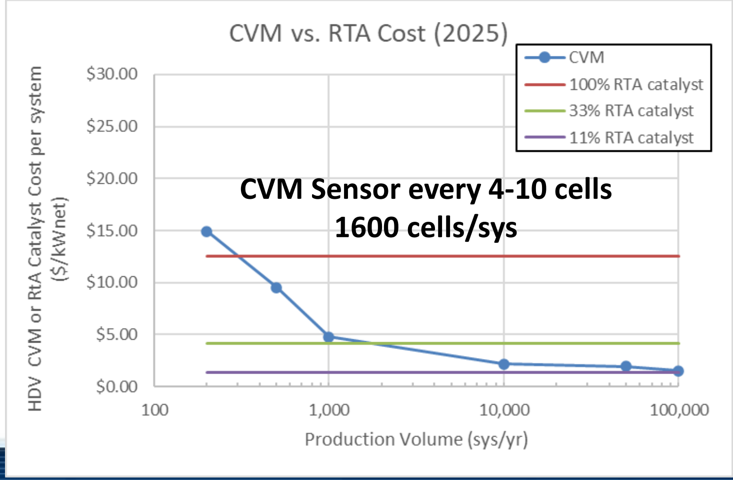
Accomplishments and Progress:
Side Study: Cell Reversal Tolerant Anode (RTA) Catalyst

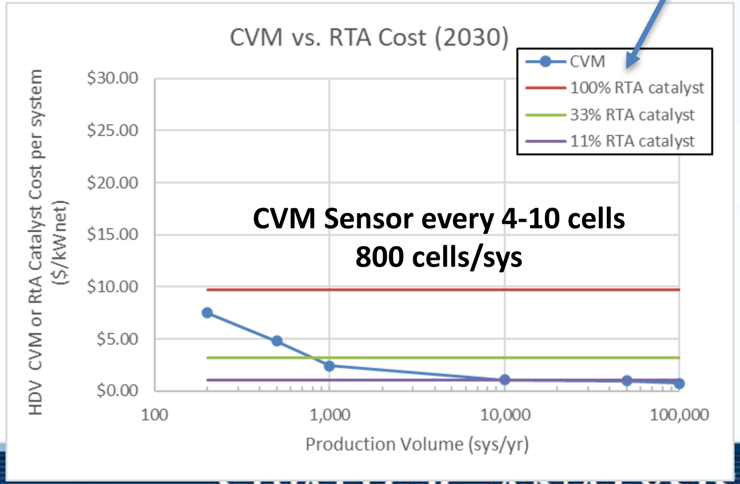
- Cell voltage reversals can occur during H_2 starvation (due to ice formation during startup, water flooding, etc.) and cause
  - Deterioration of FC performance from loss of catalyst particles through carbon catalyst corrosion
  - Overheating of the MEA and GDL leading to pin holes that can form electrical shorts
- Cell voltage reversal damage can be minimized by applying an RTA catalyst (water electrolysis catalyst such as IrO_2) in the anode to decompose water and supply H+ protons while also suppressing carbon corrosion
- Multiple sources suggest use of RTA catalyst in HDV systems (Hyundai Patent, Truck OEM, SinoHykey)
- Some FC systems avoid having a CVM by:
  - Stack operational protocols that avoid/minimize cell reversals during cold/freeze start
  - Use of an RTA catalyst
- SA estimated material cost for 0.05 mg IrO_2/cm^2 (0.04 mg Ir/cm^2) vs CVM cost for HDV system
  - Assume Ir cost of $6,000/tr.oz. and only additive to anode catalyst application active area %
  - Does not yet include IrO2 fabrication cost or added cost for additional electrical conductor (i.e., carbon nanotubes)

- Choice between RTA and CVM (or both) is not clear in industry
- RTA potentially adds ~$20/kW
- Selective application of RTA could signific. reduce cost
- Cost analysis currently includes only CVM

% of active area







Next steps: Add IrO_2 fabrication cost and additional application process cost for % of active area

Accomplishments and Progress:

Side Study: Phase Change Material (PCM) for Heat Rejection in HDV system

(Analyzed for 20-minute Hill Climb)

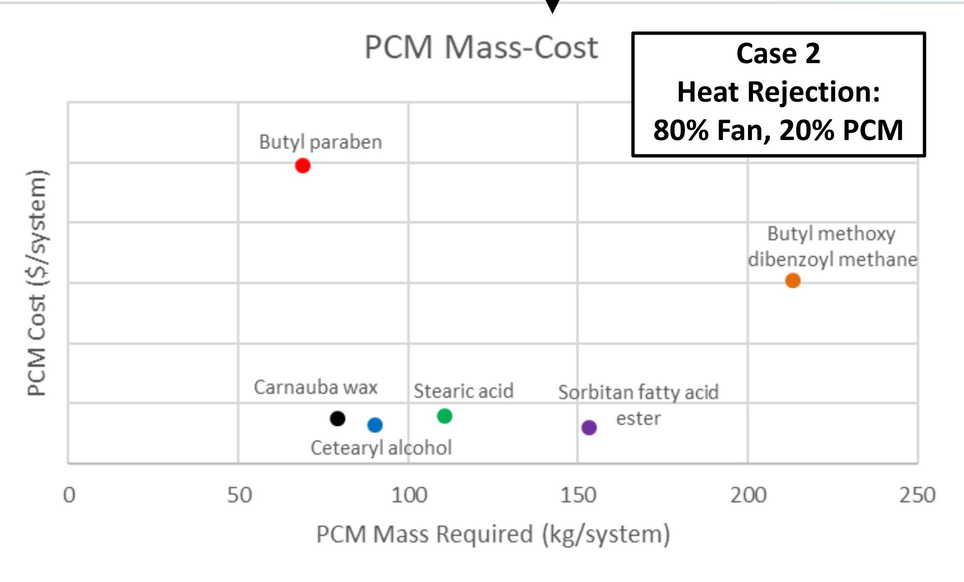
Heat Rejection Calculation

(Power data provided by ANL)

Ambient Temperature (°C)	25			
Coolant Temperature (°C)	88			
Case	**1 Heat Rejection: 100% Fan, 0% PCM**	**2 Heat Rejection: 80% Fan, 20% PCM**	**3 Heat Rejection: 60% Fan, 40% PCM**	**4 Heat Rejection: 0% Fan, 100% PCM**
Gross Power (kW)	335	315	309	305
Fan Motor Power (kW)	28	10	4	0
Stack Heat Duty (kW)	265	249	244	241
% Heat Rejected By Fan	**100%**	**80%**	**60%**	**0%**
Heat Rejected By Fan (kW)	265	199	146	0
% Heat Rejected By PCM	**0%**	**20%**	**40%**	**100%**
Heat Rejected By PCM (kW)	0	50	98	241
Time (min)	20			
Heat Rejected By PCM (kJ)	**0**	**60,000**	**117,600**	**289,200**

PCM Candidates

Case	**2 Heat Rejection: 80% Fan, 20% PCM**	
Material	**PCM Mass Required (kg)**	**PCM Volume Required (L)**
Sorbitan fatty acid ester	153	153
Stearic acid	111	140
Cetearyl alcohol	91	105
Butyl paraben	69	65
Butyl methoxy dibenzoyl methane	214	194
Carnauba wax	**79**	**97**



- Preliminary cost analysis underway therefore exact PCM cost is not reported
- Best PCM option (Carnauba wax) has lowest mass-cost combination

Accomplishments and Progress:

Responses to 2021 Year's Reviewers' Comments

2021 Reviewer's Comments	Response to Reviewer's Comment
"The removal of a humidifier may not be the most cost-effective approach when looking at the cost tradeoff (assuming an impact on performance and durability)."	For the 2022 analysis, SA has incorporated the humidifier back into the MDV and HDV systems based on feedback from industry.
"The stack oversizing approach is one area that does not seem like the best approach. More model analysis is required to justify or change this approach."	The baseline systems assume stack oversizing as this is a practical approach to address durability without detailed durability data. The extent of oversizing is based on ANL modeling. There have also been suggestions that Pt loading has a greater affect on durability and may be a cost-optimal solution. SA hopes to incorporate this data when available.
"The modeling of the cell monitoring systems could also be very useful to manufacturers."	Cell monitoring systems are considered in-house proprietary systems making it difficult to define a representative system and manufacturing process to assemble. Although a specific design has been modeled, SA believes there are multiple design considerations that could ease the difficulties of assembly.
"…the team would benefit from greater feedback on durability, especially from fuel cell applications that have demonstrated high durability. "	Thus far, SA has obtained AST durability data only through M2FCT and published documentation. Many companies do not openly share their durability data unless conducted under a DOE funded project. This is further complicated by the different material designs and interactions between components during operation. SA welcomes any collaboration or specific feedback on durability should it become available.

Collaboration & Coordination

Partner/Collaborator/Vendor	Project Role
National Renewable Energy Laboratory (NREL) (sub on contract)	• Provided knowledge & expertise on QC systems for LDV and HDV FC manufacturing lines. • Reviewed and provided feedback on automation equipment for MEA manufacturing. • Provided feedback on current 2022, 2025, and 2030 analysis systems & manufacturing processes. • Participates in researching the affect of durability on cost. • Will be key reviewer of MEA coating methods analysis (CCM/GDE/Direct Coat/Decal Transfer)
Argonne National Laboratory (ANL) (sub on contract)	• Supplied detailed modeling results for optimized fuel cell operating conditions (based on experimental cell data) for HDV Class 8 long haul truck. • 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 two Pt loadings. • Modeled HDV cooling system requirements and optimized FC operating conditions.
2021/2022 Collaborators	• Mann+Hummel provided information on HDV membrane humidifiers • Formal Review on HDV system operation and components: CellCentric, GM, Cummins • MegTec/Durr provided helpful insight on R2R coating lines • Matthews International (formerly Terrella Energy Systems) confirmed plans for high production flexible graphite bipolar plate assemblies • Illuming Power commented on future advances in flexible graphite BPPs • Zeltwanger, Thyssenkrup (plus 3 others): Details on automated stacking, R2R MEA processing lines, leak check, stack conditioning

Remaining Barriers and Challenges

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

Automotive System

- BPP material cost: Base material 316SS contributes ~\$3/kW$_{net}$ making it difficult to reach DOE's 2025 LDV cost target of \$3/kW total BPP (material/forming/coating).
- \$40/kW DOE target difficult to achieve: With adjustments to the system to achieve 8k hrs, multiple rounds of performance and durability technical improvements must be made to achieve this target by 2025. SA status cost for 2025 system is \$50/kW compared to \$40/kW DOE target).
- \$30/kW DOE target even harder to achieve: Projections for 2030 analysis (\$45/kW) suggest the DOE ultimate target of \$30/kW may be difficult to achieve and will require much lower material costs, removal or consolidation of BOP components, and improvement in durability.
- Massively parallel BPP forming lines: Even with ~2 sec/plate forming speed, many parallel BPP production lines are needed for 500k systems/year. This presents part uniformity problems.

MDV/HDV Study

- Enhanced Durability: Durability of MDV/HDV systems is vital. Ballard buses have shown 25k+ hours durability but the exact "solution" to long life is not fully understood.
- Hybridization: Better understanding of the FCV truck preferred operating mode is needed (i.e., larger battery maybe cost and durability optimal).
- Stack cooling system: designs will need to improve as the fan motor electrical parasitic load is comparable to the air compression system (~27kW)
- \$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

- Re-evaluate MDV baseline operating conditions based on ANL 2022 HDV performance & durability modeling
- Incorporate automation into baseline systems: updated MEA automation, cell stacking, and conditioning assumptions for LDV and MDV
- Obtain feedback directly from companies in the Fuel Cell Technical Team and 21st Century Truck
- Complete sensitivity analysis on LDV, MDV, and HDV Systems
- Document LDV, HDV, and HDV systems in 2022 Final Report: Report due September 2022

Future Work for Side Studies

- Complete cell RTA catalyst analysis by including IrO2 fabrication cost and additional coating cost for partial active area coatings
- Complete PCM study by completing the cost comparison of a hybridized PCM/radiator fan system. Determine the PCM material qualities needed to be advantageous in HDV system cost, weight, and volume.

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

Summary of Findings

- **LDV 80kW$_{net}$ Automotive System**
  - Preliminary results: ~\$60/kW$_{net}$ (current 2022), ~\$50/kW$_{net}$ (2025), ~\$45/kW$_{net}$ (2030) at 500k sys/year
- **MDV 70kW$_{net}$ Delivery Truck System**
  - Preliminary results: ~\$216/kW$_{net}$ (current 2022), ~\$177/kW$_{net}$ (2025), ~\$157/kW$_{net}$ (2030) at 100k sys/year
- **HDV 275kW$_{net}$ Long-Haul Truck System**
  - Preliminary results: ~\$182/kW$_{net}$ (current 2022), ~\$145/kW$_{net}$ (2025), ~\$107/kW$_{net}$ (2030) at 100k sys/year
- **HDV Humidifiers**
  - The addition of a humidifier improves the FC performance and reduces the overall cost. Based on OEM feedback, humidifiers were added to the HDV systems to enable the required stack operating range needed for HDV drive cycles and durability.
- **Manufacturing Automation**
  - Conversations with automation equipment manufacturers with proven FC manufacturing lines contributed to updated capital cost and cycle time assumptions for the baseline models, improving the cost model
- **Cell RTA Catalyst**
  - Addition of RTA catalyst can delay cell reversal damage and thus is a strategy to protect the stack and possibly eliminate the CVM. RTA catalyst without a CVM may only be cost optimal at partial active area coverage (e.g, <=30% coverage at 0.04 mg Ir/cm^2)
- **Phase Change Material for Stack Heat Rejection**
  - A hybrid PCM/radiator fan coolant system would reduce the parasitic power of the system but would add undesirable volume and weight to the system, depending on the PCM material.

Project Summary

- **Overview**
  - Exploring subsystem alternative configurations and benchmark cost where possible for LDV, MDV, and HDV FC Systems
  - In first year of project
- **Relevance**
  - Cost analysis used to assess practicality of proposed power system, determine key cost drivers, determine the cost impact of durability, and provide insight for direction of R&D priorities
  - Provides non-proprietary benchmark for discussions/comparison
- **Approach**
  - Process-based cost analysis methodologies (e.g. DFMA®)
  - Full transparency, open discussion of assumptions and results, extensive briefing to industry/researchers for validation
- **Accomplishments**
  - Analyses:
    - Preliminary system design and cost results for LDV, MDV, and HDV FC systems for 2022, 2025, and 2030 technology years
    - Investigation of HDV humidifier designs and possible future design improvements
    - Automated MEA manufacturing, cell stacking, and conditioning assumption clarifications from companies
    - (Side Study) Cost trade-off of CVM replacement with RTA catalyst at various percentages of active area coverage
    - (Side Study) Phase Change Material/radiator coolant fan hybrid system comparison
- **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 2022 final report.

Technical Back-up Slides

Technology Transfer Activities

Not applicable for SA's Cost Analysis

Special Recognitions and Awards

- Team members on this project from Strategic Analysis and Argonne National Lab received the 2021 Annual Merit Review Award in Fuel Cells for cost analysis of fuel cell technologies adjusted to account for durability, and cost analysis of fuel cells for long-haul fuel cell trucks.
  - Team members: James, B.D., Huya-Kouadio, J.M., Houchins, C., Ahluwalia, R., and Wang, X.,

2021/2022 Publications and Presentations

- James, B.D., Huya-Kouadio, J.M., Houchins, C., “Fuel Cell Systems Analysis”, Presentation to the USDRIVE Fuel Cell Technical Team and 21st Century Truck, March 10th, 2022.
- James, B.D., “Bipolar Plate Overview and Opportunities”, Presentation at the Fraunhofer and JTEKT workshop, Greenville, South Carolina, April 12th, 2022.
- Houchins, C., “Gas Diffusion Layer Challenges and Opportunities”, Presentation at the DOE Workshop on Gas Diffusion Layer (GDL) Manufacturing Needs for Clean Hydrogen Technologies, April 19, 2022.

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

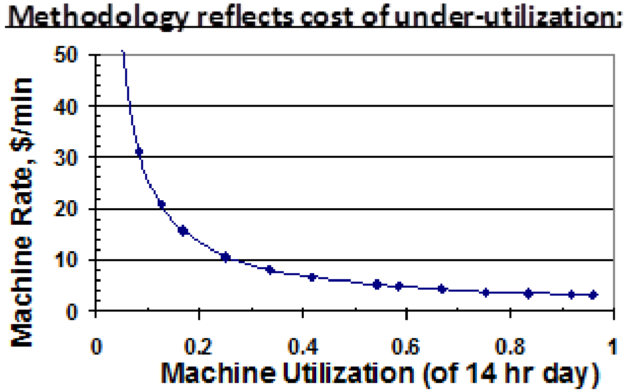
What is DFMA®?

- 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:**

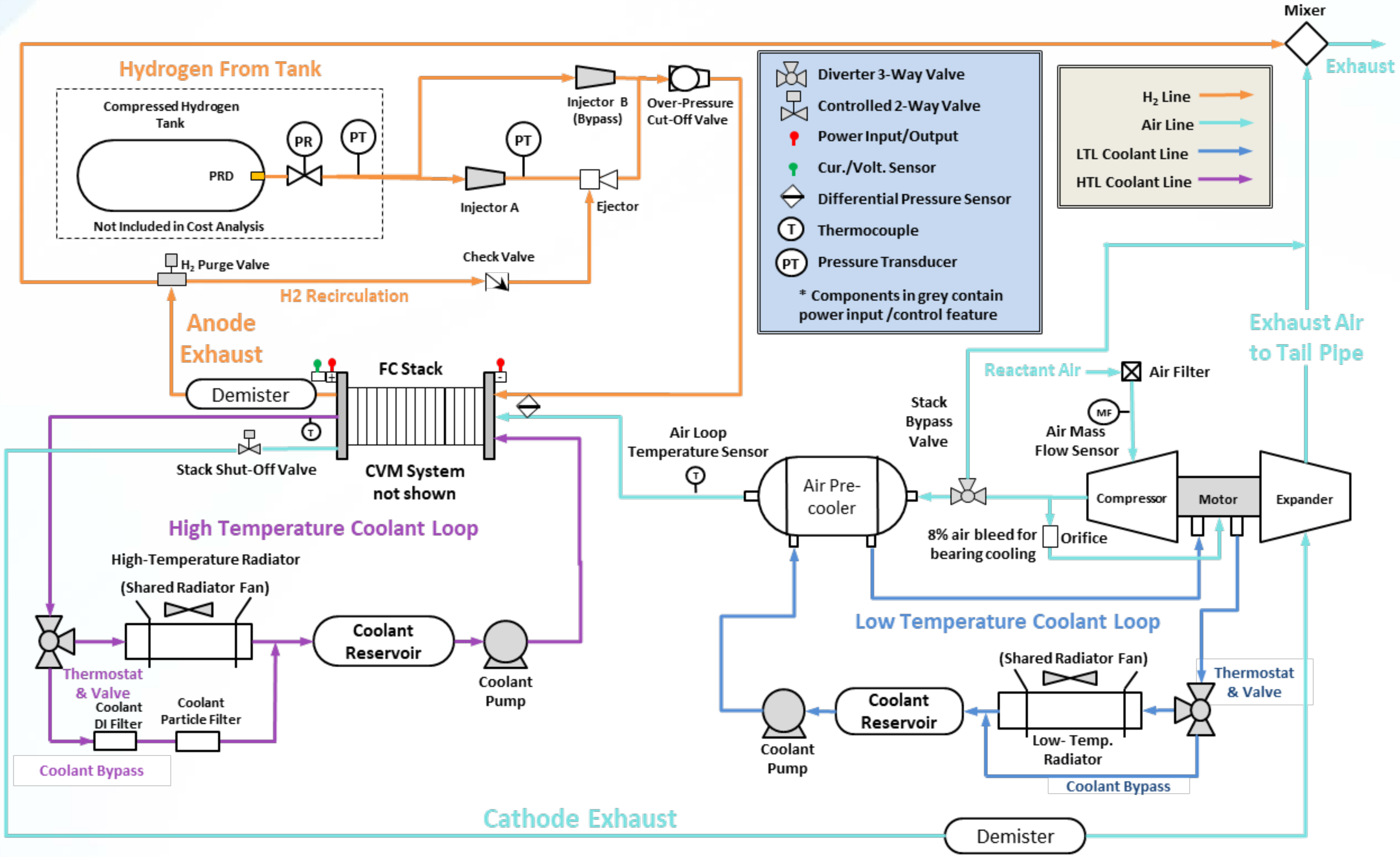
- Equipment Life
- Interest Rate
- Corporate Tax Rate

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 2022 System Diagram



No change in system configuration between technology years.

No changes were made to the LDV system diagrams since 2021.

LDV System Definition

Values in green are a change from the previous year

	2020/2021 Auto System	2022 Auto System	2025 Auto System	2030 Auto System (High Innovation)	Notes
Net Rated Power (kWnet)	89(sized)/80(operation) (BOL), 72 (EOL)	89(sized)/80(operation) (BOL), 72 (EOL)	91(sized)/80(operation) (BOL), 72 (EOL)	83(sized)/80(operation) (BOL), 72 (EOL)	
Gross Power (kW_{gross})	89 (BOL), 81 (EOL)	89 (BOL), 81 (EOL)	89 (BOL), 81 (EOL)	87 (BOL), 79 (EOL)	**Assume more efficient CEM for 2030**
Cell Voltage (V)	0.705 (BOL), 0.65 (EOL)	0.705 (BOL), 0.65 (EOL)	0.676 (BOL), 0.65 (EOL)	0.684 (BOL), 0.656 (EOL)	
Stack Power Density @ Rated Power (mW/cm^2 active area)	1107 (BOL), 911 (EOL)	1107 (BOL), 911 (EOL)	1195 (BOL), 964 (EOL)	1325 (BOL), 1151(EOL)	
Total Pt loading ($mgPt/cm^2_{\text{total area}}$)	0.175 (0.15 cath,0.025 anode)	0.175 (0.15 cath,0.025 anode)	0.125 (0.1 cath,0.025 anode)	0.125 (0.1 cath,0.025 anode)	
Pt Group Metal (PGM) Total Content (g/kW_{gross})	0.192	0.192	0.13	0.109	
Catalyst Durability: ECSA loss after 8k hrs operation	69% (based on ANL durability modeling)	69% (based on ANL durability modeling)	69% (based on ANL durability modeling)	53% (based on ANL durability modeling)	
Operating Pressure (atm)	2.5	2.5	2.5	2.5	
Stack Temp. (Coolant Exit Temp) (°C)	~92	~92	~92	~92	
Air Stoichiometry	1.5	1.5	1.5	1.5	
H2 Stoichiometry	2	2	2	2	
$Q/\Delta T$ ($kW_{th}/°C$)	1.45	1.45	1.45	1.45	
Active Cells per system	307	307	307	304	
Cell Active Area (cm^2)	291	291	275	225	
Active to Total Area Ratio	0.625	0.625	0.65	0.65	
Stacks per System	1	1	1	1	
Total System Voltage	200	200	200	200	
Stack Oversizing	23%	23%	21%	21%	**Values may change with further investigation of membrane degradation.**
Total Active Area per System (m^2)	8.92	8.92	8.43	6.84	
BOP Replacement Cost Over Vehicle Life (% of Total BOP Cost)	30%	NA	NA	NA	**Removed BOP Replacement Cost**

LDV System Definitions: Stack Components

	2020/2021 Auto System	2022 Auto System	2025 Auto System	2030 Auto System (High Innovation)
Membrane Material	14 μm Nafion (850EW) supported	14 μm Nafion (850EW) supported	**High performance membrane (cost based on 10 μm Nafion)**	High performance membrane (cost based on 10 μm Nafion)
Membrane Support	ePTFE	ePTFE	**Electrospun PVDF**	Electrospun PVDF
Gas Diffusion Layers	150 microns (105 μm GDL, 45 μm MPL, uncompressed) hot-pressed to CCM	150 microns (105 μm GDL, 45 μm MPL, uncompressed) hot-pressed to CCM	150 microns (105 μm GDL, 45 μm MPL, uncompressed) hot-pressed to CCM	150 microns (105 μm GDL, 45 μm MPL, uncompressed) hot-pressed to CCM
Catalyst & Application	Slot Die Coating of: Cath.: Dispersed 0.15 mgPt/cm^2 d-PtCo on HSC Anode: Dispersed 0.025mgPt/cm^2 Pt on C	Slot Die Coating of: Cath.: Dispersed 0.15 mgPt/cm^2 d-PtCo on HSC Anode: Dispersed 0.025mgPt/cm^2 Pt on C	**Slot Die Coating of advanced performance catalyst. Cost modeled as: Cath.: Dispersed 0.1 mgPt/cm^2 d-PtCo on HSC Anode: Dispersed 0.025mgPt/cm^2 Pt on C (Assume catalyst cost still dominated by Pt price and no major improvements in application)**	Slot Die Coating of advanced performance catalyst. Cost modeled as: Cath.: Dispersed 0.1 mgPt/cm^2 d-PtCo on HSC Anode: Dispersed 0.025mgPt/cm^2 Pt on 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	Gore Direct-Coated Membrane with dual-side slot-die coated electrodes, acid washing
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	R2R PET sub-gaskets, hot-pressed to CCM
Bipolar Plates and Coating	SS 316L with TreadStone LIteCell™ Coating (Dots-R)	SS 316L with TreadStone LIteCell™ Coating (Dots-R)	**SS 304L with Vacuum Coating (modeled as TreadStone TIOX)**	**Alloy that requires no coating (based on input from industry experts on current R&D programs) Modeled as SS 304L cost**
BPP Forming	Progressive stamping	Progressive stamping	**Hydroforming or HVIF**	**Hydroforming or HVIF**
BPP Joining	Welding	Welding	Welding	Welding
BPP-to-MEA Gaskets	Screenprinted polyolefin elastomer on BPP	Screenprinted polyolefin elastomer on BPP	Screenprinted polyolefin elastomer seal on BPP	Screenprinted polyolefin elastomer seal on BPP
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)	Laser Welded(Cooling)/ Screen-Printed Polyolefin Elastomer (End)
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	Composite Molded End Plates with Compression Bands
Cell Assembly	Robotic assembly of: welded BPP assembly, sub-gasketed MEA	Robotic assembly of: welded BPP assembly, sub-gasketed MEA	Robotic assembly of: welded BPP assembly, sub-gasketed MEA	Robotic assembly of: welded BPP assembly, sub-gasketed MEA
Cell Voltage Monitoring	Sensor every 2 cells (low volume)	Sensor every 2 cells (low volume)	**Sensor every 4 cells (low volume)**	Sensor every 4 cells (low volume)
Stack Conditioning (hrs)	2	2	**1**	1

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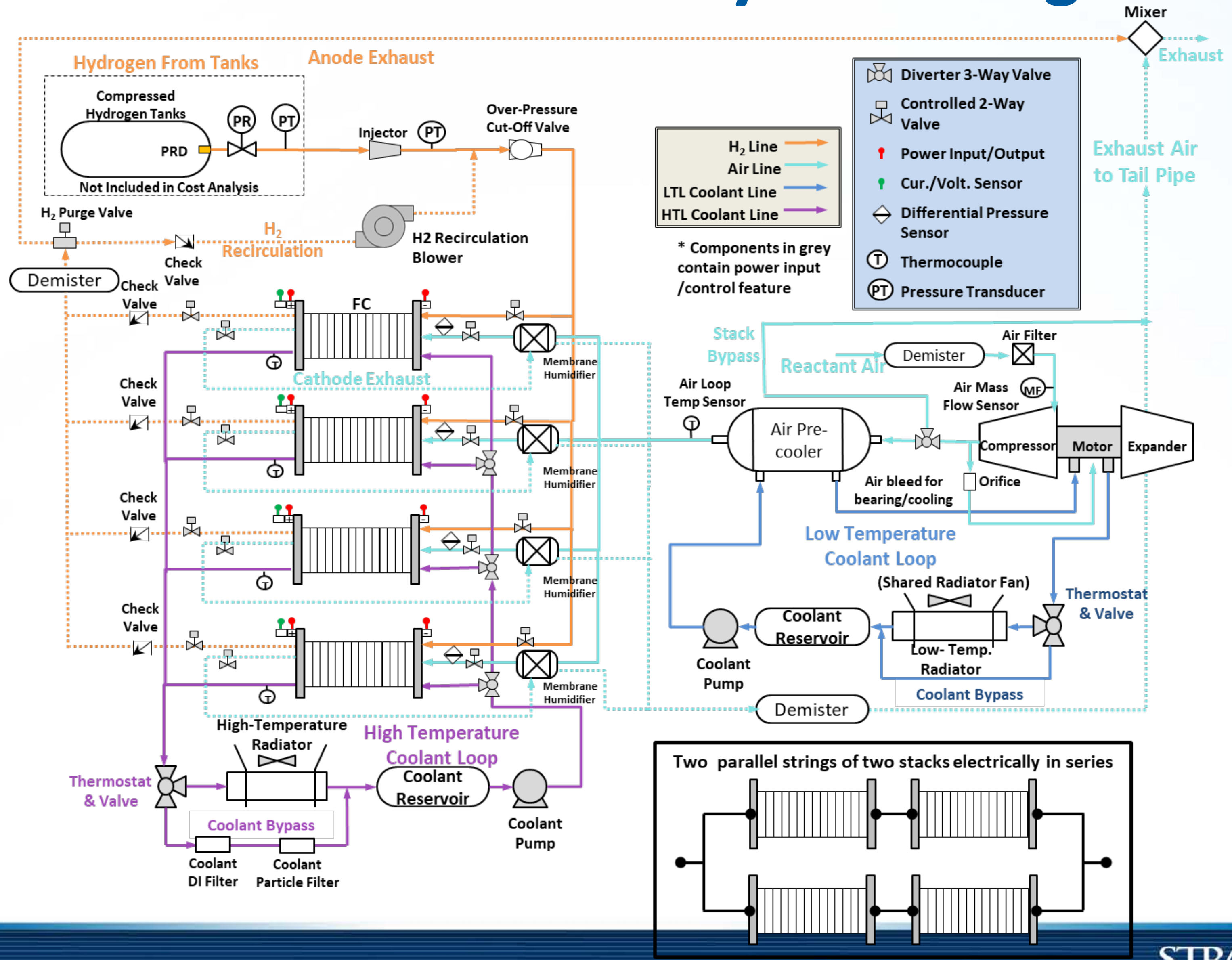
LDV System Definitions: BOP Components

	2020/2021 Auto System	2022 Auto System	2025 Auto System	2030 Auto System (High Innovation)
Air Compression	Centrifugal Compressor, Radial-Inflow Expander)	Centrifugal Compressor, Radial-Inflow Expander)	Centrifugal Compressor, R adial-Inflow Expander (with adv. mech. design)	Centrifugal Compressor, Radial-Inflow Expander (with adv. mech. design)
Air Compressor/Expander/ Motor Efficiency	Compressor: 71% Expander: 73% Motor/Controller: 85%	Compressor: 71% Expander: 73% Motor/Controller: 85%	Compressor: 71% Expander: 73% Motor/Controller: 85%	**Compressor: 75%** Expander: 73% **Motor/Controller: 92%**
Air Filtration	Activated Carbon Air Filter, Entaron FC7.5	Activated Carbon Air Filter, Entaron FC7.5	Activated Carbon Air Filter, Entaron FC7.5	Activated Carbon Air Filter, Entaron FC7.5
Air Humidification	None	None	None	None
Hydrogen Humidification	None	None	None	None
Anode Recirculation	Pulse Ejector with bypass	Pulse Ejector with bypass	Pulse Ejector with bypass	Pulse Ejector with bypass
Exhaust Water Recovery	None	None	None	None
Freeze Protection	Drain Water at Shutdown	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	0 for FC System
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	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air-Precooler
BOP Replacement Cost (% of Total BOP Cost)	30%	**NA**	NA	NA

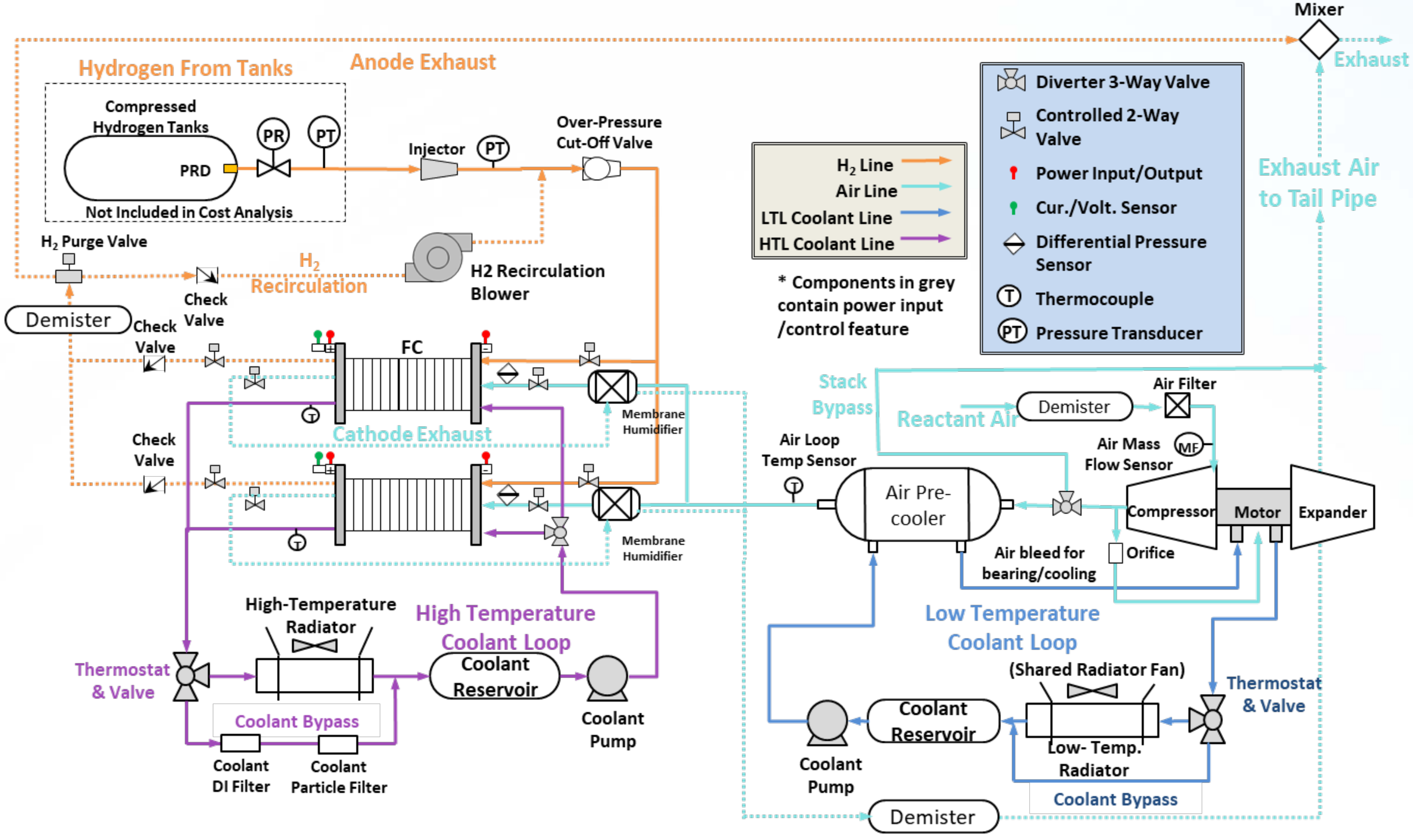
Accomplishments and Progress:

2022 and 2025 HDV System Diagram

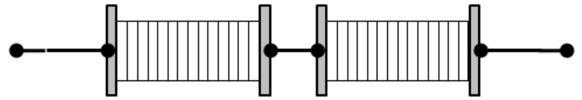


Accomplishments and Progress:

2030 HDV System Diagram



Two stacks electrically in series



HDV Stack Component Assumptions

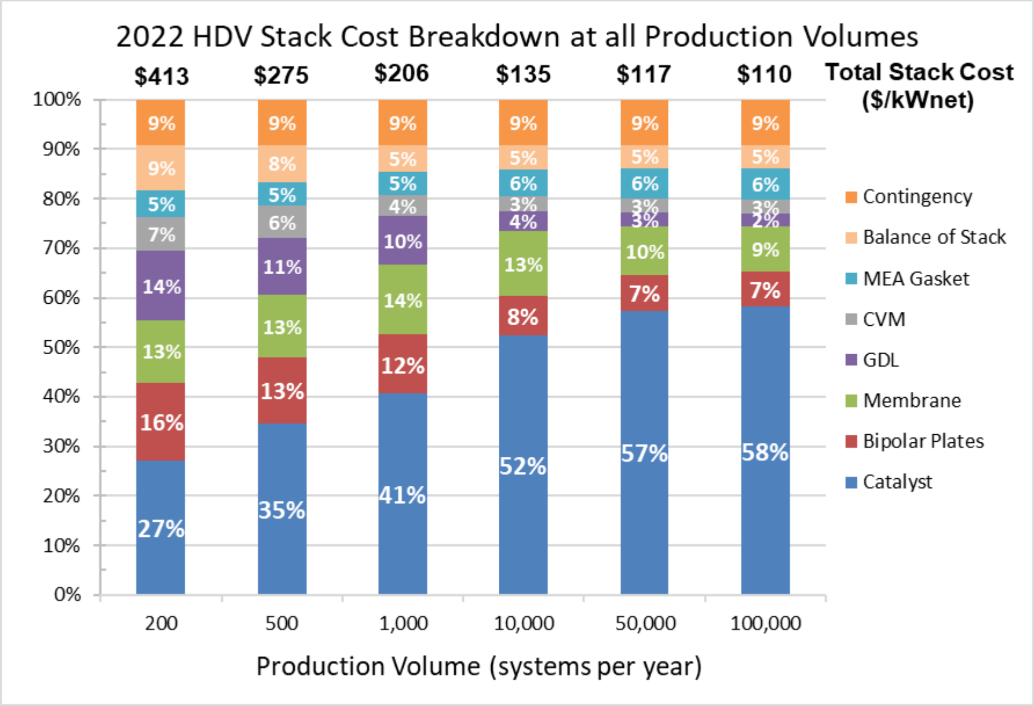
	2021 HDV Technology System	2022 HDV Technology System	2025 HDV Technology System	2030 HDV Technology System
Membrane Material	20-micron Nafion® (850EW)	20-micron Nafion® (850EW)	**15-micron Nafion® (850EW)**	15-micron Nafion® (850EW)
Membrane Support	ePTFE	ePTFE	Electrospun PPSU	Electrospun PPSU
Gas Diffusion Layers	150 microns (105 mm GDL, 45 mm MPL, uncompressed) hot-pressed to CCM	150 microns (105 mm GDL, 45 mm MPL, uncompressed) hot-pressed to CCM	150 microns (105 mm GDL, 45 mm MPL, uncompressed) hot-pressed to CCM	150 microns (105 mm GDL, 45 mm MPL, uncompressed) hot-pressed to CCM
Catalyst & Application	Slot Die Coating of: Cath.: Dispersed 0.35 mgPt/cm2 a-Pt/HSC Anode: Dispersed 0.05mgPt/cm2 Pt/HSC	Slot Die Coating of: **Cath.: Dispersed 04 mgPt/cm2 a-Pt/HSC** Anode: Dispersed 0.05mgPt/cm2 Pt/HSC	**Slot Die Coating of advanced perf. Catalyst cost modeled as:** **Cath.: Dispersed 0.3 mgPt/cm^2 a-Pt/HSC** Anode: Dispersed 0.05mgPt/cm2 Pt/HSC	**Slot Die Coating of advanced perf. Catalyst cost modeled as:** **Cath.: Dispersed 0.25 mgPt/cm^2 a-Pt/HSC** Anode: Dispersed 0.05mgPt/cm2 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	Gore Direct-Coated Membrane with dual-side slot-die coated electrodes
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	R2R PET sub-gaskets, hot-pressed to CCM
Bipolar Plates and Coating	Flexible graphite with resin impregnation	Flexible graphite with resin impregnation	Flexible graphite with resin impregnation	Flexible graphite with resin impregnation
BPP Forming	Embossed	Embossed	Embossed	Embossed
BPP Joining	Adhesive	Adhesive	Adhesive	Adhesive
BPP-to-MEA Gaskets	Screenprinted polyolefin elastomer seal on BPP	Screenprinted polyolefin elastomer seal on BPP	Screenprinted polyolefin elastomer seal on BPP	Screenprinted polyolefin elastomer seal on BPP
Coolant & End Gaskets	Adhesive(Cooling)/ Screen-Printed Polyolefin Elastomer (End)	Adhesive(Cooling)/ Screen-Printed Polyolefin Elastomer (End)	Adhesive(Cooling)/ Screen-Printed Polyolefin Elastomer (End)	Adhesive(Cooling)/ Screen-Printed Polyolefin Elastomer (End)
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	Composite Molded End Plates with Compression Bands
Cell Assembly	Robotic assembly of: graphite BPP assembly, sub-gasketed MEA	Robotic assembly of: graphite BPP assembly, sub-gasketed MEA	Robotic assembly of: graphite BPP assembly, sub-gasketed MEA	Robotic assembly of: graphite BPP assembly, sub-gasketed MEA
Cell Voltage Monitoring	Sensor every 2 cells (low volume) Sensor every 4 cells (high volume)	Sensor every 2 cells (low volume) Sensor every 4 cells (high volume)	**Sensor every 4 cells (low volume)** **Sensor every 10 cells (high volume)**	Sensor every 4 cells (low volume) Sensor every 10 cells (high volume)
Stack Conditioning (hrs)	2	2	**1**	1

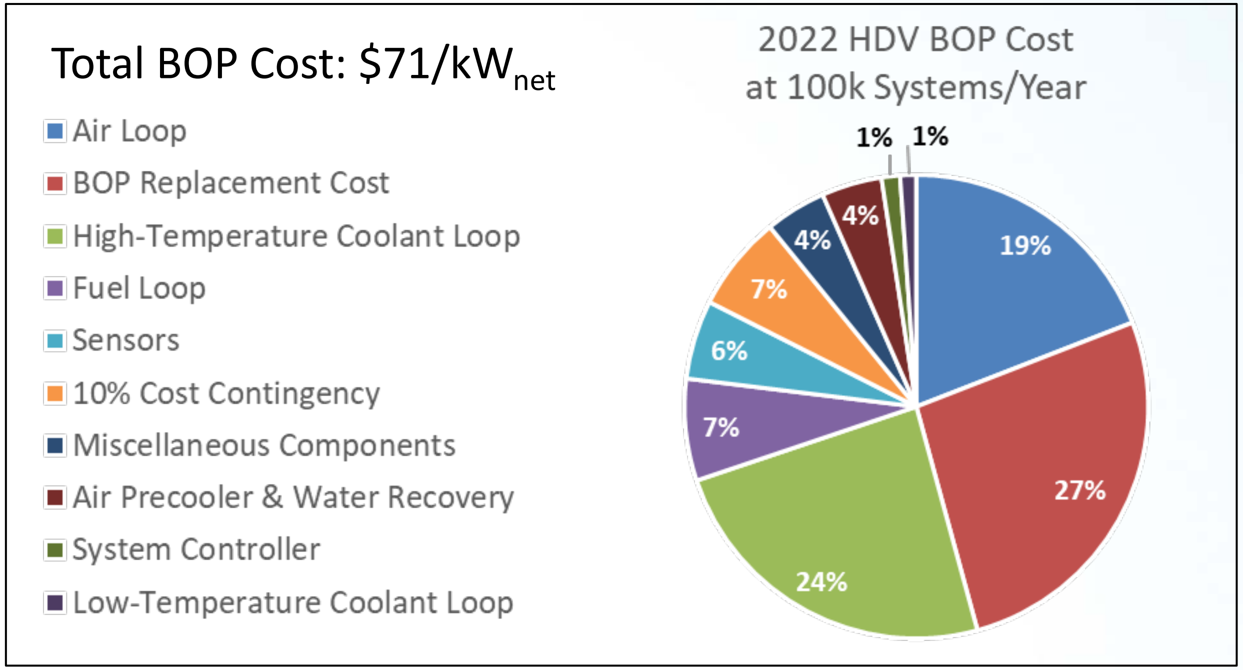
HDV BOP Component Assumptions

	2021 HDV Technology System	2022 HDV Technology System	2025 HDV Technology System	2030 HDV Technology System
Air Compression	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, Radial-Inflow Expander
Air Compressor/Expander/ Motor Efficiency	Compressor: 73% (centrifugal) Expander: 72% Motor/Controller: 85%	**Compressor: 72% (centrifugal)** **Expander: 75%** **Motor/Controller: 84%**	Compressor: 72% (centrifugal) Expander: 75% Motor/Controller: 84%	**Compressor: 75% (centrifugal)** **Expander: 80%** **Motor/Controller: 92%**
Air Filtration	Activated Carbon,2 x Entaron FC7.5	**Activated Carbon,4 x Entaron FC7.5**	Activated Carbon,4 x Entaron FC7.5	**Activated Carbon,2 x Entaron FC7.5**
Air Humidification	None	**4x plate frame membrane humidifier stacks**	4x plate frame membrane humidifier stacks	**2x plate frame membrane humidifier stacks**
Hydrogen Humidification	None	None	None	None
Anode Recirculation	H_2 Recirculation Pump	H_2 Recirculation Pump	H_2 Recirculation Pump	H_2 Recirculation Pump
Exhaust Water Recovery	None	None	None	None
Freeze Protection	Drain Water at Shutdown	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	1 for FC System
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	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air-Precooler
BOP Replacement Cost (% of Total BOP Cost)	30%	**40%**	40%	**30%**

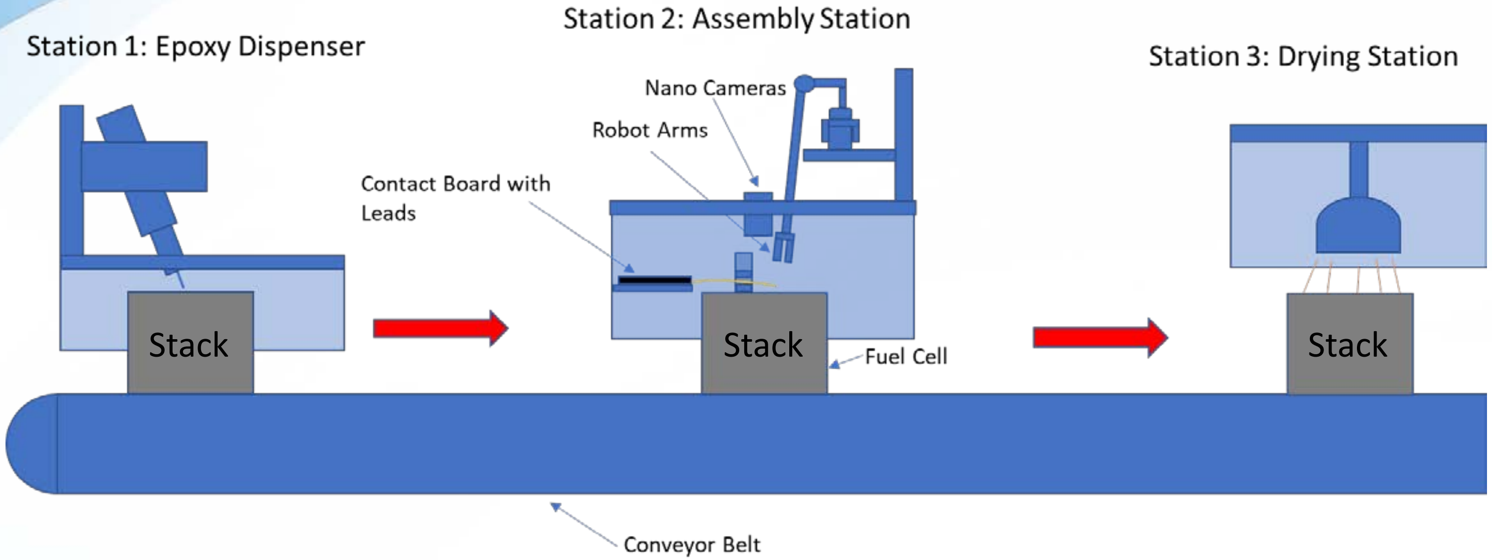
Accomplishments and Progress:
Preliminary 2022 HDV System Cost Breakdown

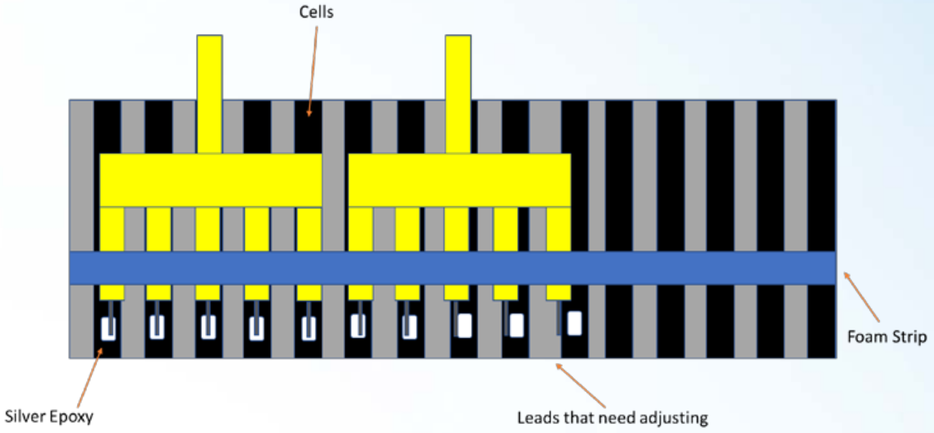
- HDV system cost dominated by stack cost
  - Catalyst accounts for > 50% of stack at mid to high-volume
  - Operating conditions and a more durable catalyst contribute to lower power density than LDV application
- High-Temperature Coolant Loop cost driven by radiator fan motor assembly



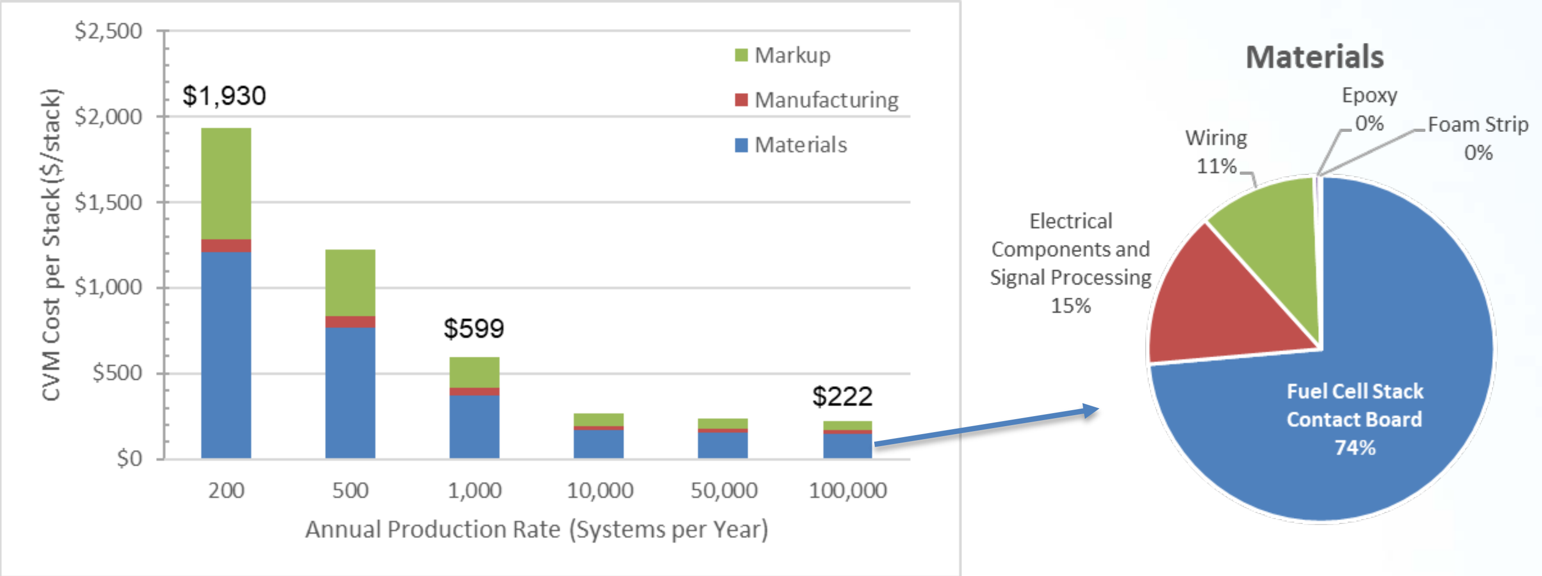


Cell Voltage Monitoring System Assembly



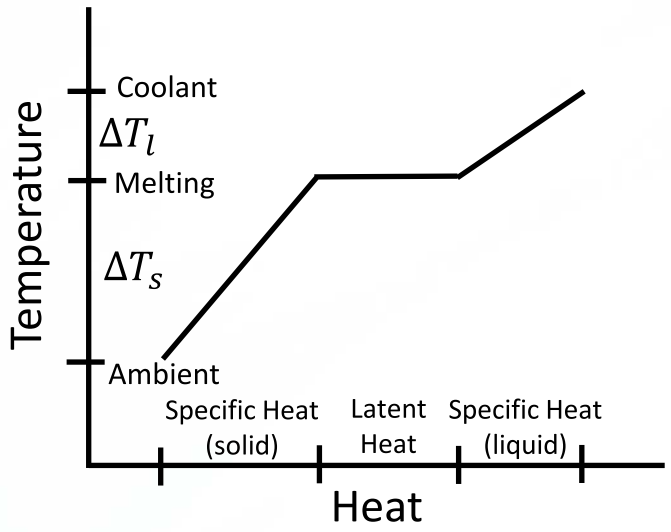


- In 2021, SA estimated the assembly cost for CVM
  - 3-step automated process applies epoxy, inserts and adjusts contact arms, and dries the epoxy
  - Single line ($0.5M) fully utilized by 10k sys/yr



Accomplishments and Progress:
Side Study: Phase Change Material (PCM) for Heat Rejection in HDV system
(Analyzed for 20-minute Hill Climb)

Heat Rejection Calculation



$$\textit{Heat Rejected by PCM}\ (kJ) = \textit{Heat Rejected by PCM}\ (kW) * \textit{Time}$$

$$\Delta T_s = \textit{Melting Point} - \textit{Ambient Temperature}$$

$$\Delta T_l = \textit{Coolant Temperature} - \textit{Melting Point}$$

$$\textit{PCM Mass Required} = \frac{\textit{Heat Rejected By PCM}\ (kJ)}{(\textit{Specific Heat of Solid Phase} * \Delta T_s) + (\textit{Latent Heat}) + (\textit{Specific Heat of Liquid Phase} * \Delta T_l)}$$

$$\textit{PCM Volume Required} = \frac{\textit{PCM Mass Required}}{\textit{Density of Liquid Phase}}$$

PCM Candidates

TABLE 2

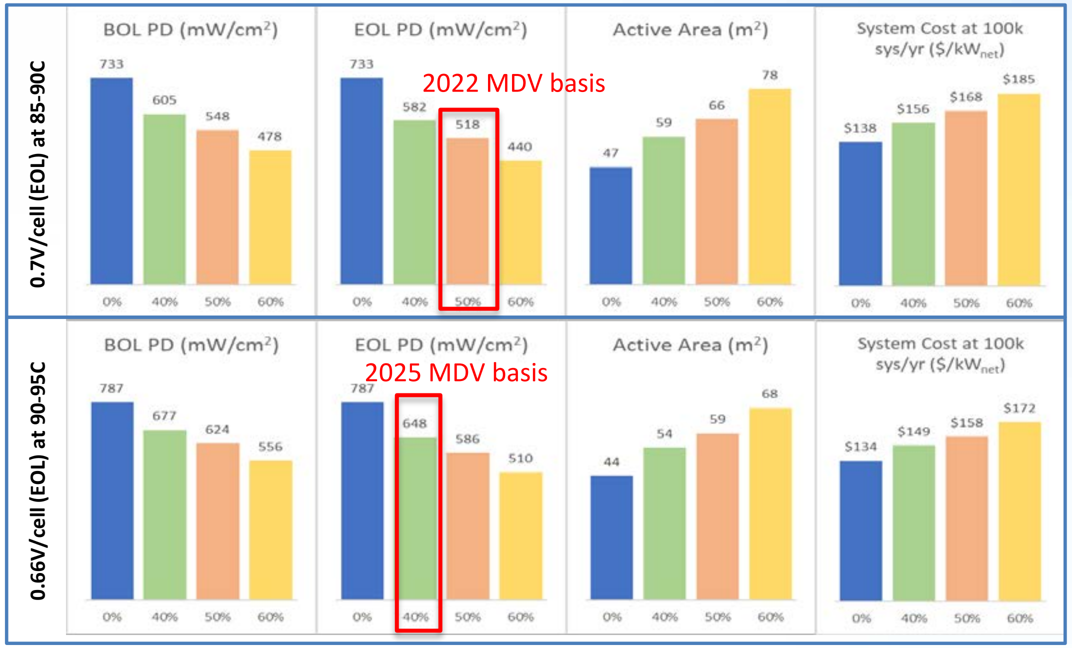
Name	Melting point (° C.)	Latent heat (KJ/Kg)	Density of liquid phase (Kg/m^3)	Specific heat of liquid phase (KJ/Kg° C.)	Specific heat of solid phase (KJ/Kg° C.)
Sorbitan fatty acid ester	64~68	38.5	1003.4	4.548	6.163
Stearic acid	70	327.1	794.2	3.92	3.19
Cetearyl alcohol	65	217.8	861.94	7.163	6.997
Butyl paraben	67~70	576.9	1059.14	7.235	3.414
Butyl-methoxydi-benzoyl-methane	81~84	140	1101.44	7.426	1.74
Carnauba wax	81~86	566.8	819.34	10.842	2.421

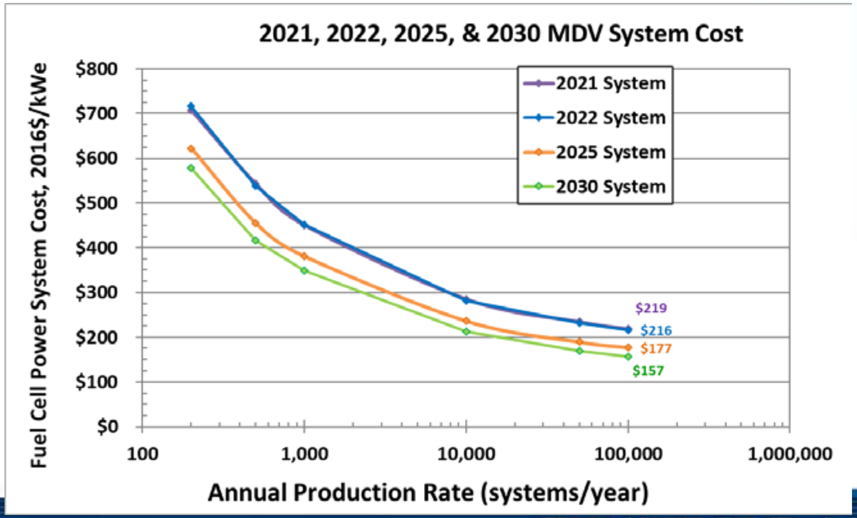
Kwon et al. Hyundai Motor Company (Seoul, KR). *Thermal Management System For Fuel Cell Vehicle And Control Method Thereof.* Oct. 5, 2021. U.S. Patent 11,139,491.

Accomplishments and Progress:
2022 MDV System Design and Preliminary Cost Results

- **<u>Present results are based on ANL 2021 modeling</u>**
- MDV Operating Conditions to be re-evaluated using ANL's 2022 HDV performance and durability modeling
- **2022 MDV System:**
  - Assume 50% ECSA loss at 0.66V EOL: 518mW/cm ^{2} for base
  - Assume additional 10% on PD for humidifier: 866mW/cm^2
- **2025 MDV System:**
  - Assume 40% ECSA loss at 0.66V EOL: 648mW/cm^2 for base
  - Assume additional 20% on PD (10% for humidifier and 10% for one design iteration): 777mW/cm^2
  - Assume lower Pt loading (0.35 vs 0.4mgPt/cm^2)
- **2030 MDV System:**
  - Assume 30% ECSA loss at 0.66V EOL: 666mW/cm ^{2} for base
  - Assume additional 30% on PD (10% for humidifier and 20% for two design iterations): 866mW/cm^2
  - Assume at lower Pt loading (0.3 vs 0.35mgPt/cm^2), reduced BOP replace. cost from 20% to 10%, and no air loss due to motor cooling

ANL 2021 HDV Perf./Durability Study





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