2018 DOE Hydrogen and Fuel Cells Program Review

Fuel Cell Systems Analysis

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Project ID# FC163

Overview

Timeline

- Project Start Date: 9/30/16
- Project End Date: 9/30/21
- % complete: 30% of five year project (in Year 2 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
  - ~$430,000 (through March 2018, including Labs)
- Total DOE Project Value
  - $1.5M (over 5 years, including Labs)
  - 0% Cost share

Partners

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

Relevance

Overall Project Objectives:

- Project current (2018) and future cost (2020/2025) 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 2025 goal of $\$40/kW_{net}$ (automotive) at 500,000 systems per year
- Benchmark against production vehicle power systems
- Identify fuel cell system cost drivers to facilitate Fuel Cell Technology Office programmatic decisions.

Impact since 2017 analysis final results:

- Overall cost increases $\$1.73/kW_{net}$ for 80 kW LDV System
- 2020 future system cost increases $\$0.75/kW_{net}$
- 2025 future system cost increases $\$3.03/kW_{net}$

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	LDV	Current (2018), 2020, 2025
		MD/HD Truck #1	Current (2018), 2020, 2025
2019	3	LDV	Current (2019), 2020, 2025
		Buses	Current (2019), 2020, 2025
2020	4	LDV	Current (2020), 2025
		MD/HD Truck System #2 or update of #1	Current (2020), 2025
2021	5	LDV	Current (2021), 2025
		Update to Buses & Trucks as needed	Current (2021), 2025

- **Project Analyses:**
  - **Auto and Medium & Heavy Duty Fuel Cell Truck Analysis**
  - **Current and Future Tech 2020 & 2025 Analysis**
    - 2020 Systems: based on projected 2020 laboratory demonstrated technologies.
    - 2025 (High Innovation) Systems: based on projected 2025 technology advances that are expected to be achievable from a well-funded, focused, and successful program.
- **Bus updates in Year 3 and 5 (not annually)**

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

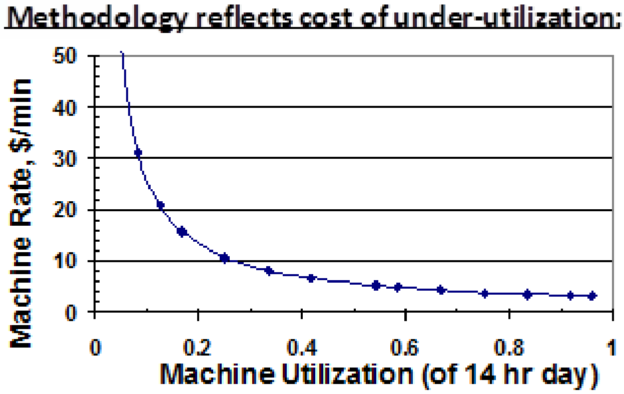
What is DFMA®?

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

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

Manufacturing Cost Factors:

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


Methodology reflects cost of under-utilization:

Methodology Reflects Cost of Under-utilization:

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

- Equipment Life
- Interest Rate
- Corporate Tax Rate

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

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

Approach:
Topics Examined Since 2017 AMR

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

Changes since 2017 AMR that Affect Baseline 2018/2020/2025 Automotive System

- **Catalyst Synthesis Cost:** Switch from d-PtNi/C to PtCo/HSC-e (to align cost and performance)
- **Bipolar Plate Joining:** Update to laser welding capital cost and station design
- **Compressor/Expander/Motor:** Update to Honeywell CEM cost model
- **BOP Components:** Switch from dual ejector to pulsed ejector for H_2 recirculation (2018), Pressure sensor, cathode stack bypass valve, stack isolation valve
- **Bipolar Plate Forming:** Switch from prog. stamping to hydroforming (2020/2025 only)
- **Membrane Material:** Switch from ePTFE to electrospun PPSU supported membrane (2020/2025 only)

2017/2018 Side Studies for Automotive System (not affecting baseline)

- **Catalyst Fabrication:** PVD coating of PtNbO on carbon catalyst synthesis
- **Electrospun Materials:** Membrane support, co-spun dual-fiber membrane, and electrodes

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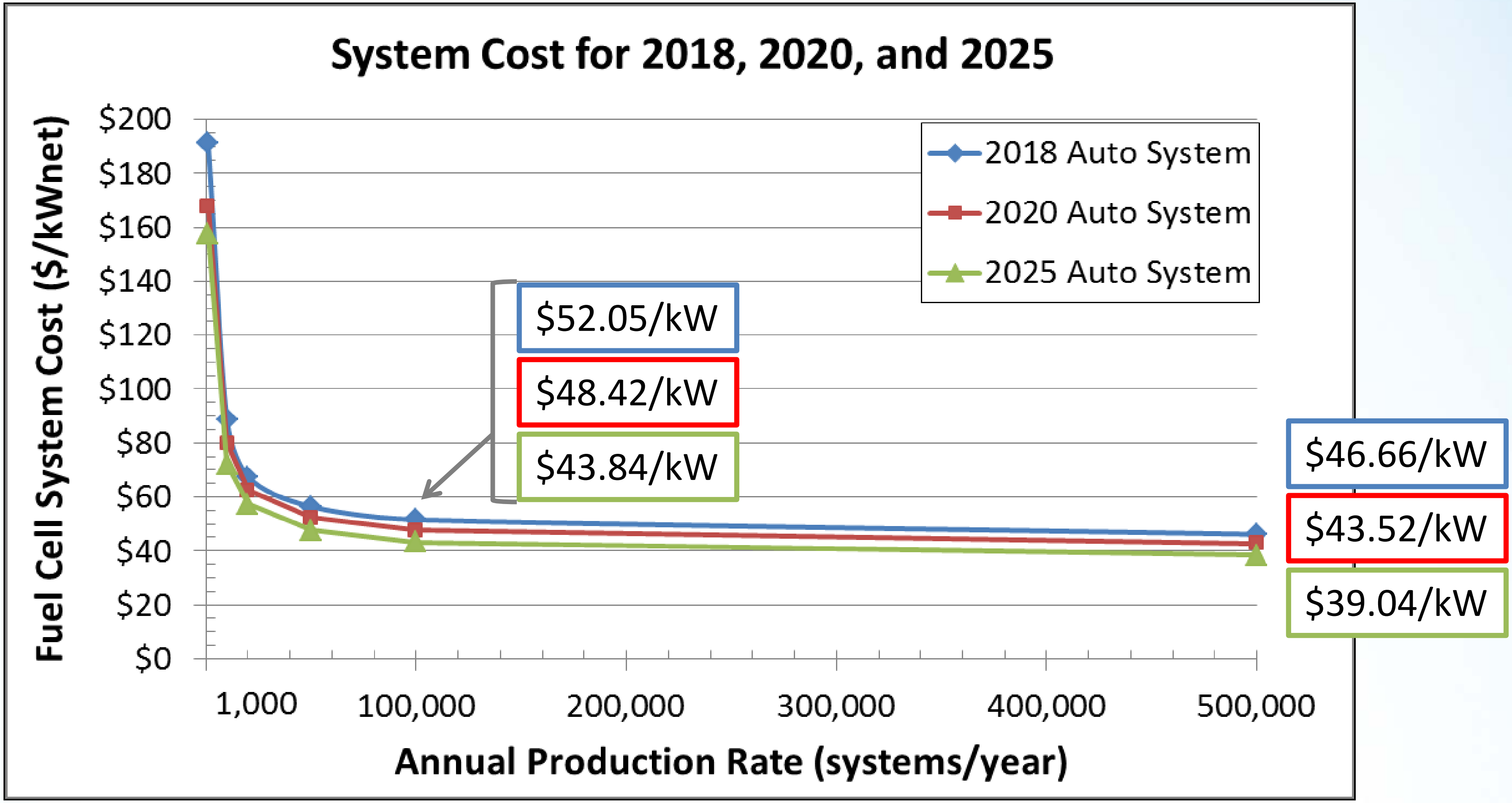
***Milestone 1: Validation Study* – Completed in 2017**

***Milestone 2: System Definition* – Completed for 2018/2020/2025 Auto and MD Systems**

***Milestone 3: DFMA® Cost Analysis* – Completed for 2018/2020/2025 Auto and MD Systems**

***Milestone 4: Reporting of Cost Results* – (due Sept 2018) => Go/No-Go Decision**

Cost Results for 80kW$_e$ Auto Systems



$52.05/kW

$48.42/kW

$43.84/kW

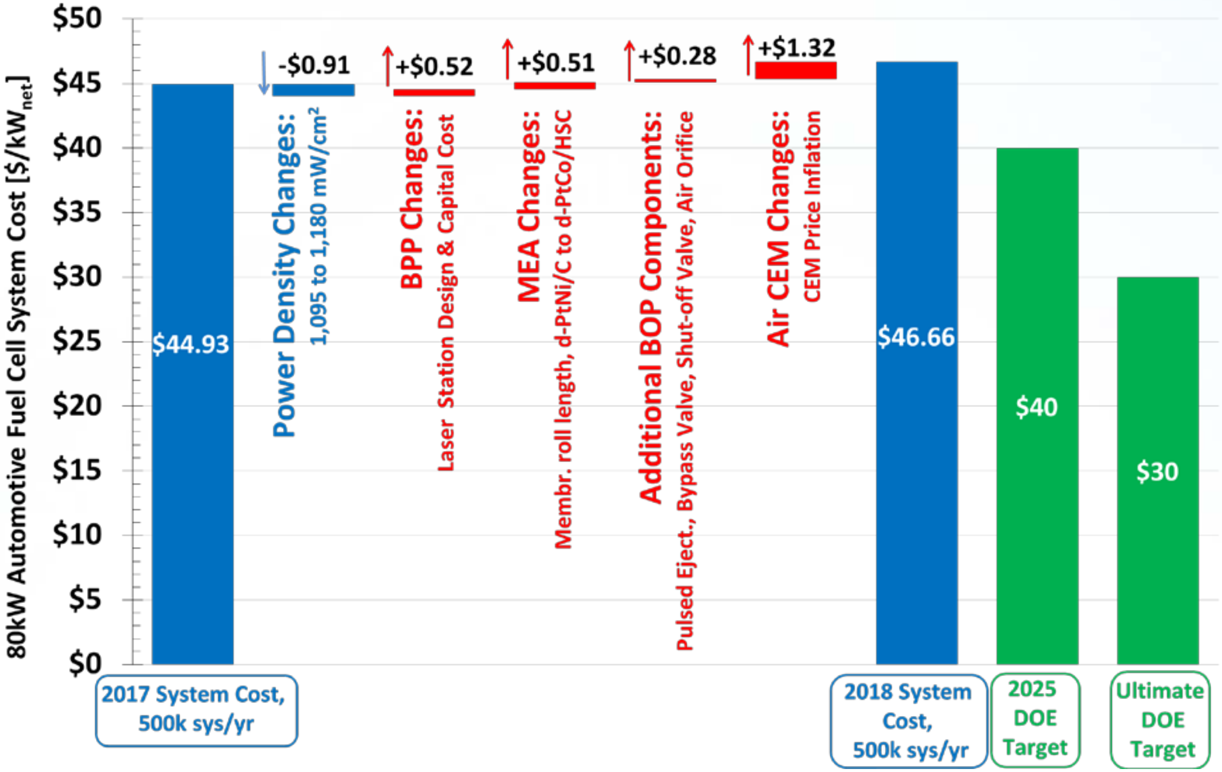
$46.66/kW

$43.52/kW

$39.04/kW

Approach: Annual Updates of Automotive System Cost Preliminary 2018 Projection Compared to DOE Targets

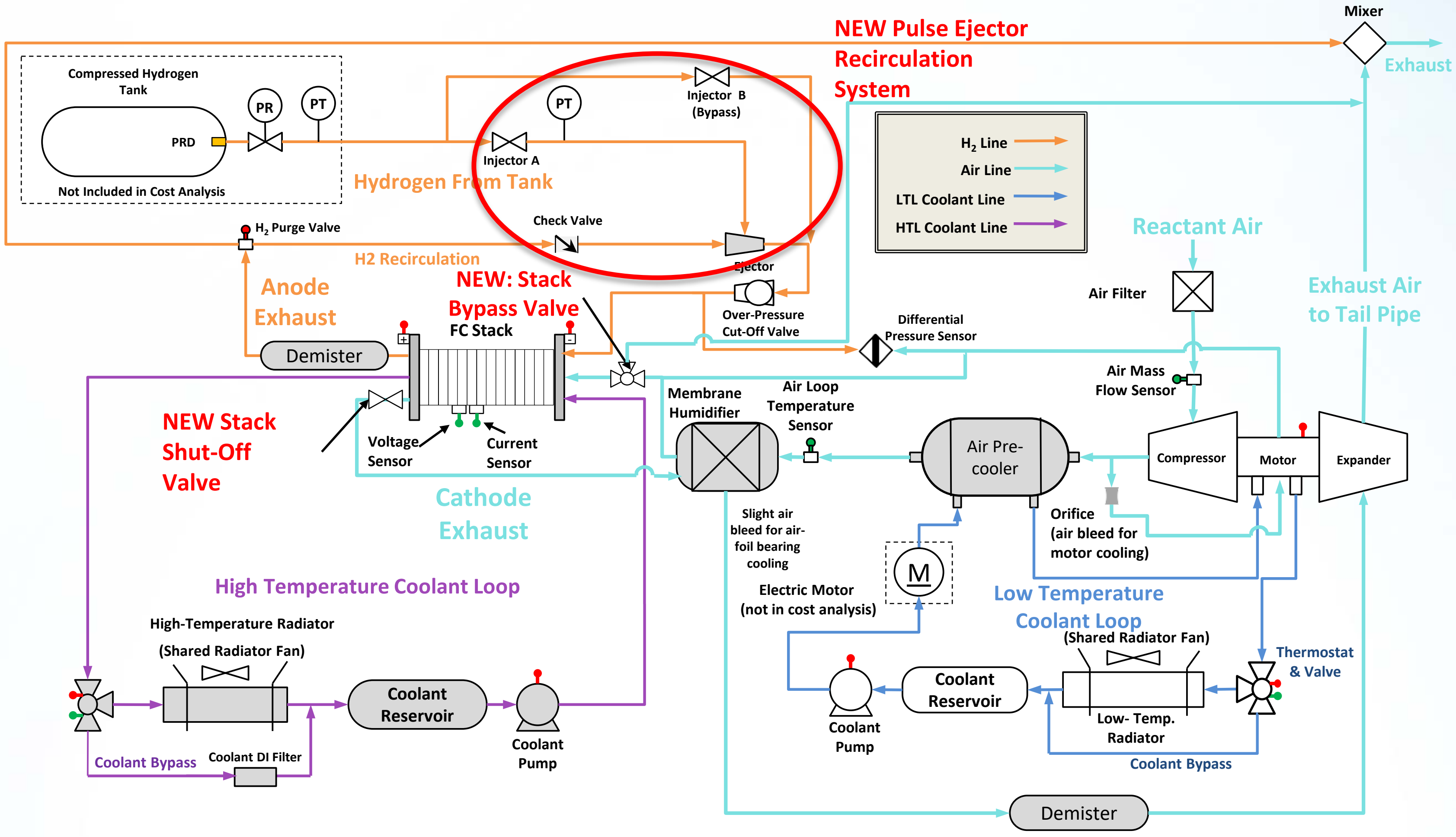
(2018 Baseline System at 500k systems/year)



- ~$0.91/kW$_{net}$ cost reduction from new optimized operating conditions of PtCo/HSC catalyst (major improvement of $7.5/kW observed last year in switch to PtCo/HSC)
- Pulsed Ejector implement to allow adequate recirculation at low power
- Multiple analysis improvements/refinements
- Preliminary 2018 system cost: ~$47/kW$_{net}$

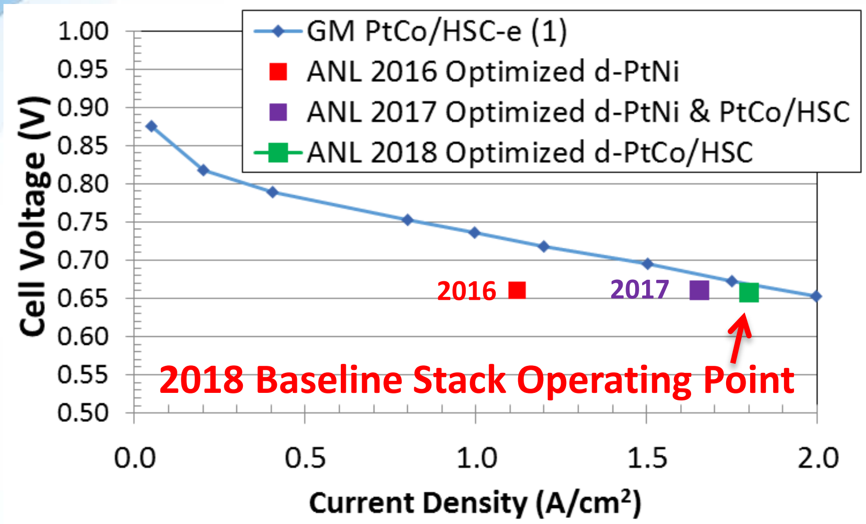
2018, 2020, & 2025 System Configuration Summary
80kW$_{net}$ Light Duty Vehicle (Auto)

No change in system configuration between technology years



Accomplishments and Progress:

Power Density Increase due to Improved High Surface Carbon (HSC) Supports: ANL Optimized Performance Model with d-PtCo



2018 Baseline Stack Operating Point

- **2017 Catalyst Assumptions**
  - d-PtNi/C catalyst fabrication cost combined with derating of GM performance data for d-PtCo/HSC
- **2018 Baseline: d-PtCo/HSC**
  - Data from GM for d-PtCo/HSC catalyst used in ANL optimized performance model
  - SA modeled d-PtCo/HSC fabrication cost

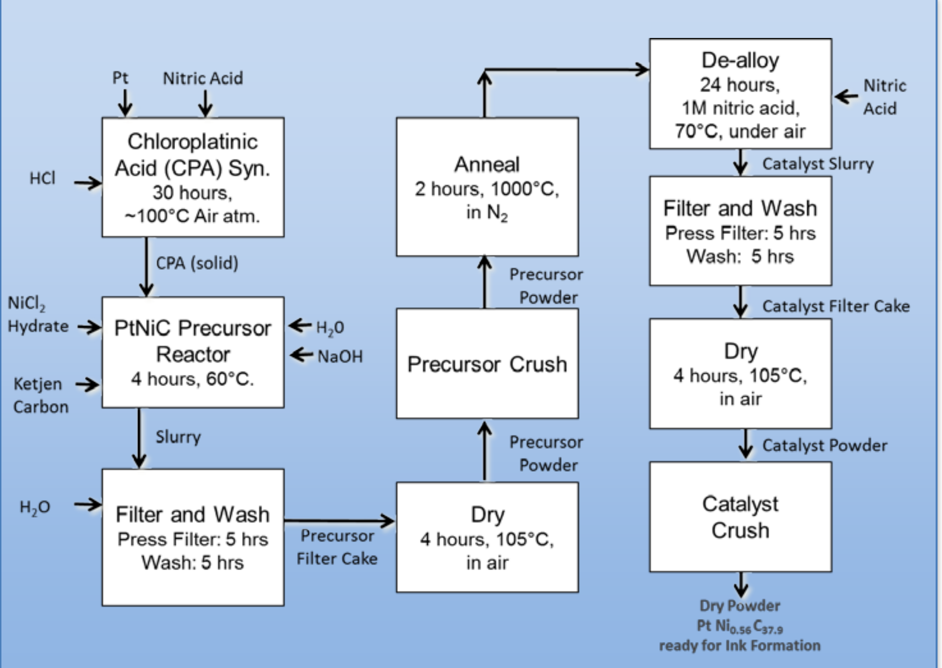
8% power density increase from 2017 to 2018

Parameter/Conditions	🟥 d-PtNi /C (2016)	🟪 d-PtCo/HSC (2017)	🟩 d-PtCo/HSC (Update for 2018)
Power Density (mW/cm^2)	739	1,095	1,180
Cell Voltage	0.66	0.66	0.66
Stack Pressure (atm)	2.5 (inlet)	2.5 (inlet)	2.5 (inlet)
Temperature (coolant exit)	94°C	94°C	95°C
Total Pt Loading (mg/cm^2)*	0.134	0.125	0.125
Air Stoichiometry	1.4	1.5	1.5
System Cost ($/kWnet)	$52.89	$44.93	$46.66

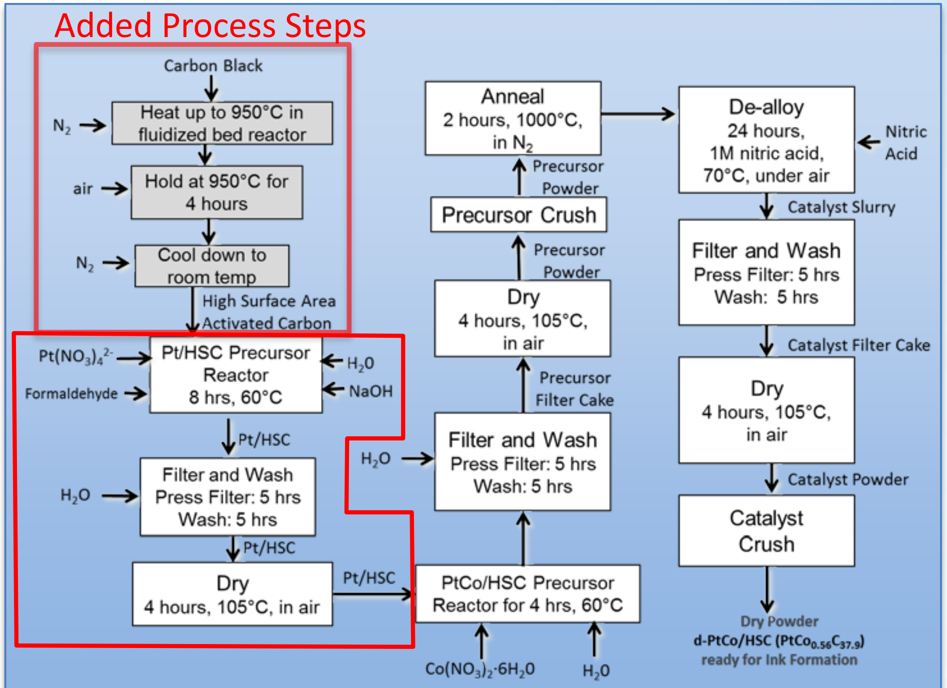
(1) Kongkanand, A., Mathias, M., “The Priority and Challenge of High-Power Performance of Low-Platinum Proton-Exchange Membrane Fuel Cells”, Journal of Physical Chemistry Letters, 2016, 7, 1127-1137.

*Anode catalyst is 0.025mgPt/cm^2 Pt/C for all systems.

Accomplishments and Progress:
D-PtCo/HSC (High Surface Area Carbon) Similar Catalyst Synthesis to d-PtNi/C Process Leads to Low Cost Impact



$PtNi_{0.56}C_{37.9}$ Process Diagram



$PtCo_{0.56}C_{37.9}$ Process Diagram

- Added HSC process[1]: increased carbon cost from \$9/kg to ~\$116/kg at high volume
- Added Pt/HSC synthesis process[1]: use of $Pt(NO_3)_4$ rather than chloroplatinic acid
- PtCo/HSC synthesis[2] uses $Co(NO_3)_2 \cdot 6(H_2O)$ (between \$11 and \$72/kg)
- Cost results: Overall ~\$0.13/kW$_{net}$ cost decrease in switch from d-PtNi/C to d-PtCo/HSC
  - Includes increased catalyst processing cost and cost reduction from higher power density

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[1] JM Patent Application US2014/0295316 A1 (referenced in [2])

[2] GM/JM Patent Application US 2016/0104898 A1 (patent from DOE funded project: “High-Activity Dealloyed Catalysts”, Final Technical Report, General Motors LLC, DE-EE0000458, 30 Sept 2014)

Accomplishments and Progress:

Electrospun Materials for Fuel Cell Components

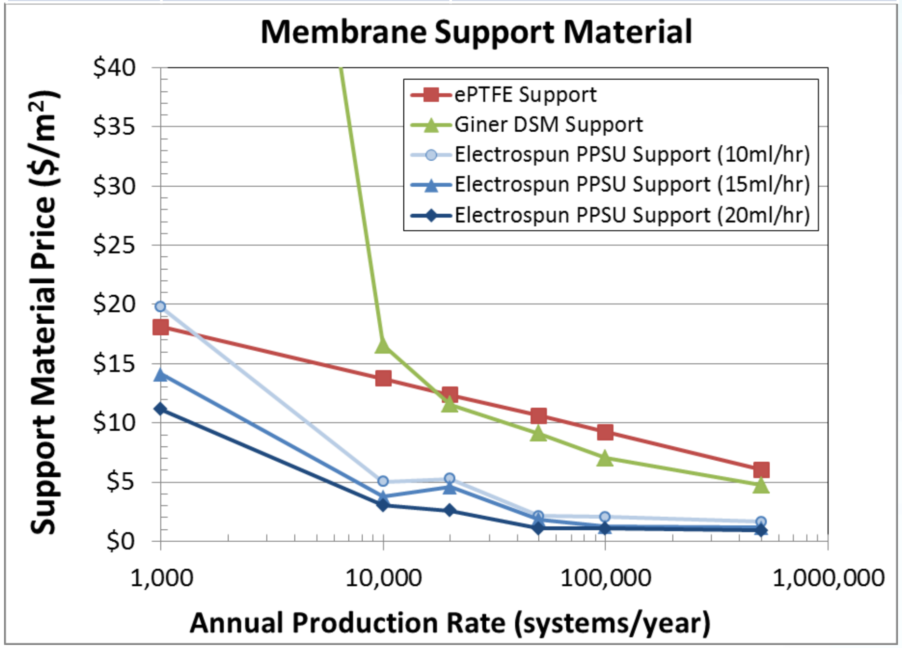
Three Materials Investigated:

1. Membrane Support Material (direct substitute for ePTFE)
2. Complete Membrane Dual-Fiber (co-spun) Membrane Support and Ionomer Material
3. Electrode Application to Membrane (Anode and Cathode)

Membrane Support Material

- Modeled as a substitute for ePTFE in $\$/\text{m}^2$
- 22 vol% of 10μm thick membrane
- Inovenso Nanospinner 416
- Assumed output capacity:
  - 2.7 g/hr per nozzle x 154 nozzles = 416 g/hr
  - 10ml/hr (could be higher for tested material)
  - 3.6 g/m^2
- Line Rate: 1.8m/min
- Web width: 1m
- Price: $<\$2/\text{m}^2$ compared to $\$6/\text{m}^2$ for ePTFE
- ~$\$0.60/\text{kW}_{\text{net}}$ reduction (at same performance)
- Used for 2020 and 2025 system analysis

	Polymer	Solvent
Support Slurry	PVDF or PPSU (25wt% of slurry)	N-methyl-2pyrrolidone (80wt%) Acetone (20wt%)



Material composition based on US Patent 9,350,036 B2, 2016 “Composite Membranes, Methods of Making Same, and Applications of Same”, P. Pintauro, A. Park, J. Ballengee.

Electrospun support cost projected to be significantly less than ePTFE.

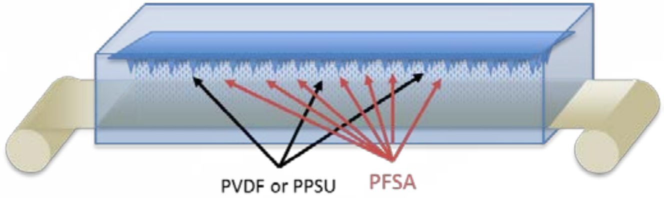
Accomplishments and Progress:

Electrospun Materials for Fuel Cell Components

Dual-Fiber (co-spun) Membrane Support and Ionomer Material

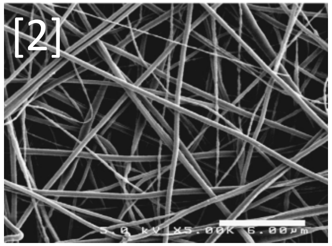
Electrospinning Machine: Inovenso (14 rows of 11 nozzles)

-3 rows of PVDF or PPSU nozzles (10ml/hr nozzles)
-11 rows of PFSA nozzles (10ml/hr nozzles)
-PVDF or PPSU and Nafion nozzles interspersed

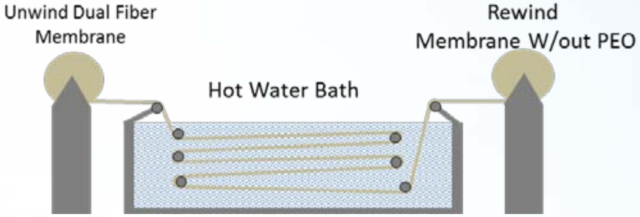


Component	Polymer(s) [1]	Solvent [1]
Support Slurry	**PVDF or PPSU**	**N-methyl-2pyrrolidone (80wt%) Acetone (20wt%)**
Ionomer Slurry	**Nafion (99wt%) PEO (1wt%)**	**N-propanol (66.6wt%) Water (33.3wt%)**

Nafion/PPSU Dual-Fiber Mat before compaction

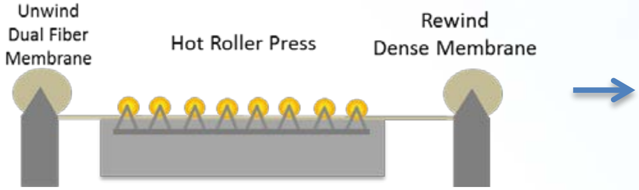


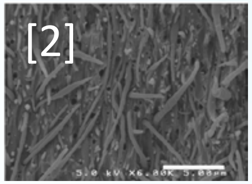
Removal of PEO in Hot Water Bath

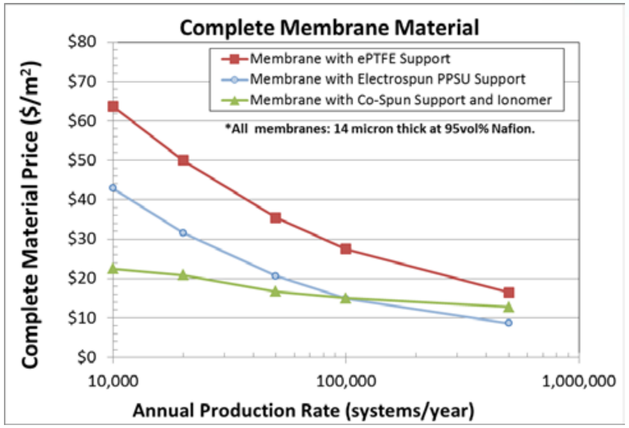


Hot Roller Compression/Compaction

- Final Material: Dense Nafion layer reinforced with PPSU nanofibers (Nafion melted around PPSU fiber)







[1] US Patent 9,350,036 B2, 2016 “Composite Membranes, Methods of Making Same, and Applications of Same”, P. Pintauro, A. Park, J. Ballengee.
[2] J.B. Ballengee, P.N. Pintauro, "Preparation of nanofiber composite proton exchange membranes from dual fiber electrospun mats“, Journal of Membrane Science 442 (2013) 187-195. (Fig. 8)

Electrospun membrane projected to be less than ePTFE-supported membrane.

Accomplishments and Progress:

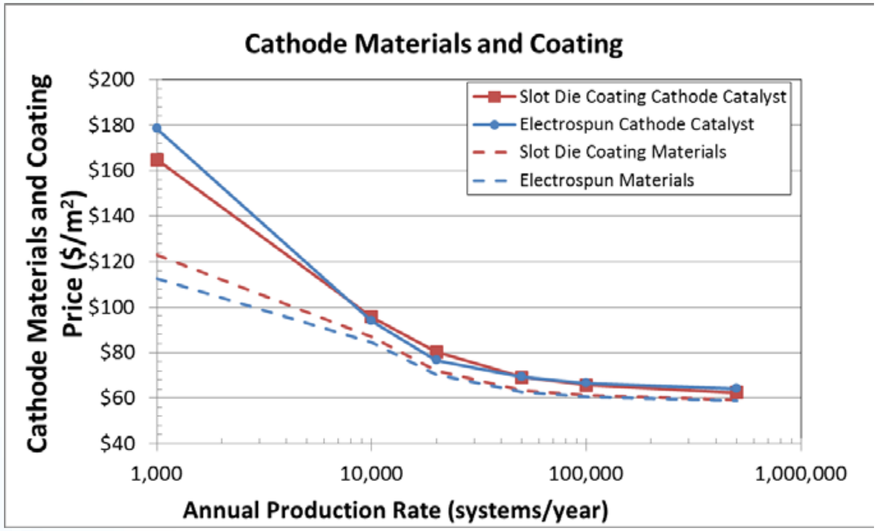
Electrospun Materials for Fuel Cell Components

Cathode Catalyst Application to Membrane

	Polymer [1]	Solvent [1]
Cathode Slurry	PtNi/C:Nafion:Polyacrylic Acid 55:30:15 (13.4wt% of slurry)	Isopropanol: water 2:1 (86.6wt% of slurry)

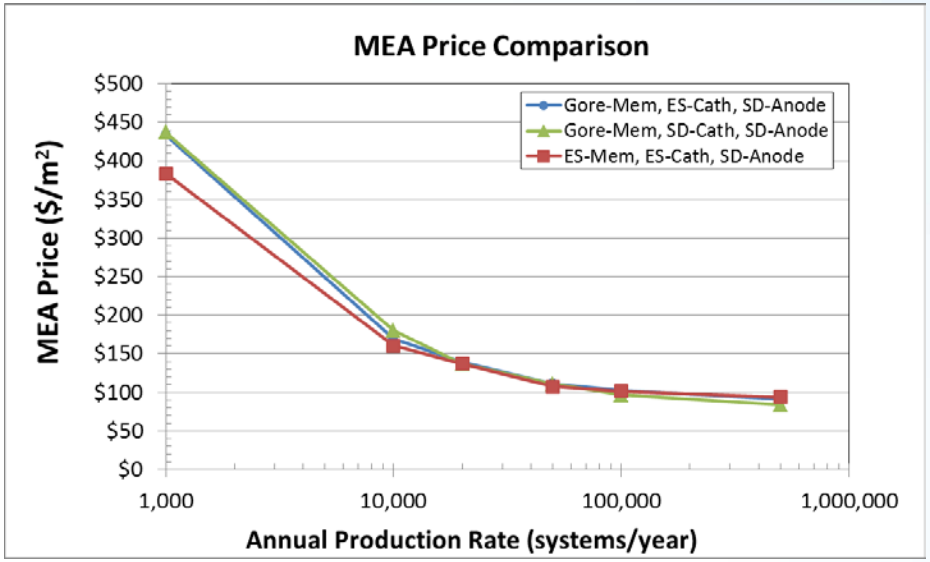
Electrospinning Machine: Inovenso Nanospinner

- 5.12 g/hr per nozzle x 154 nozzles = 788 g/hr
- 25 g/m2 (combined catalyst powder, ionomer, and PAA)
- Line Rate: 0.53m/min (3-25m/min for slot die coating)
- Web width: 1m



Comparison of Different MEAs

- ES: electrospun material
- SD: slot die coating (dual sided-coating when using SD on anode and cathode)
- Prices are nearly identical at high volume for $\$/m^2$. Performance & durability will be the deciding factor



- **Next Step:** Incorporate performance of catalyst to obtain MEA price of stack for $80kW_{net}$ vehicle.

[1] US Patent Application 2017/0250431 A1 “Polymer Solution, Fiber Mat, and Nanofiber Membrane-Electrode-Assembly Therewith, and Method of Fabricating Same”.

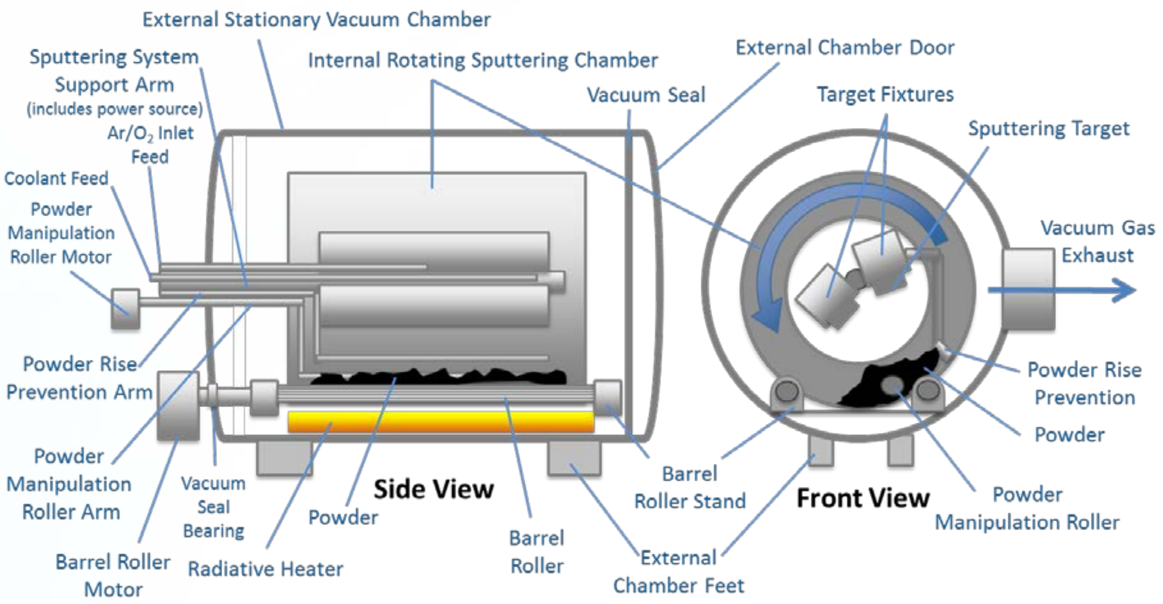
Membrane prices similar: performance & durability will decide.

Accomplishments and Progress:

Catalyst Powder Coating with Physical Vapor Deposition (PVD)

- Under DOE’s award DE-EE0007675,
  - Ford Motor Co., Oakridge National Laboratory (ORNL), and Exothermics
  - Development of new catalyst powder synthesized by PVD coating: Pt and Nb onto carbon powder to form Pt/NbOx/C

Dual Barrel System Preliminary Design



Not shown:

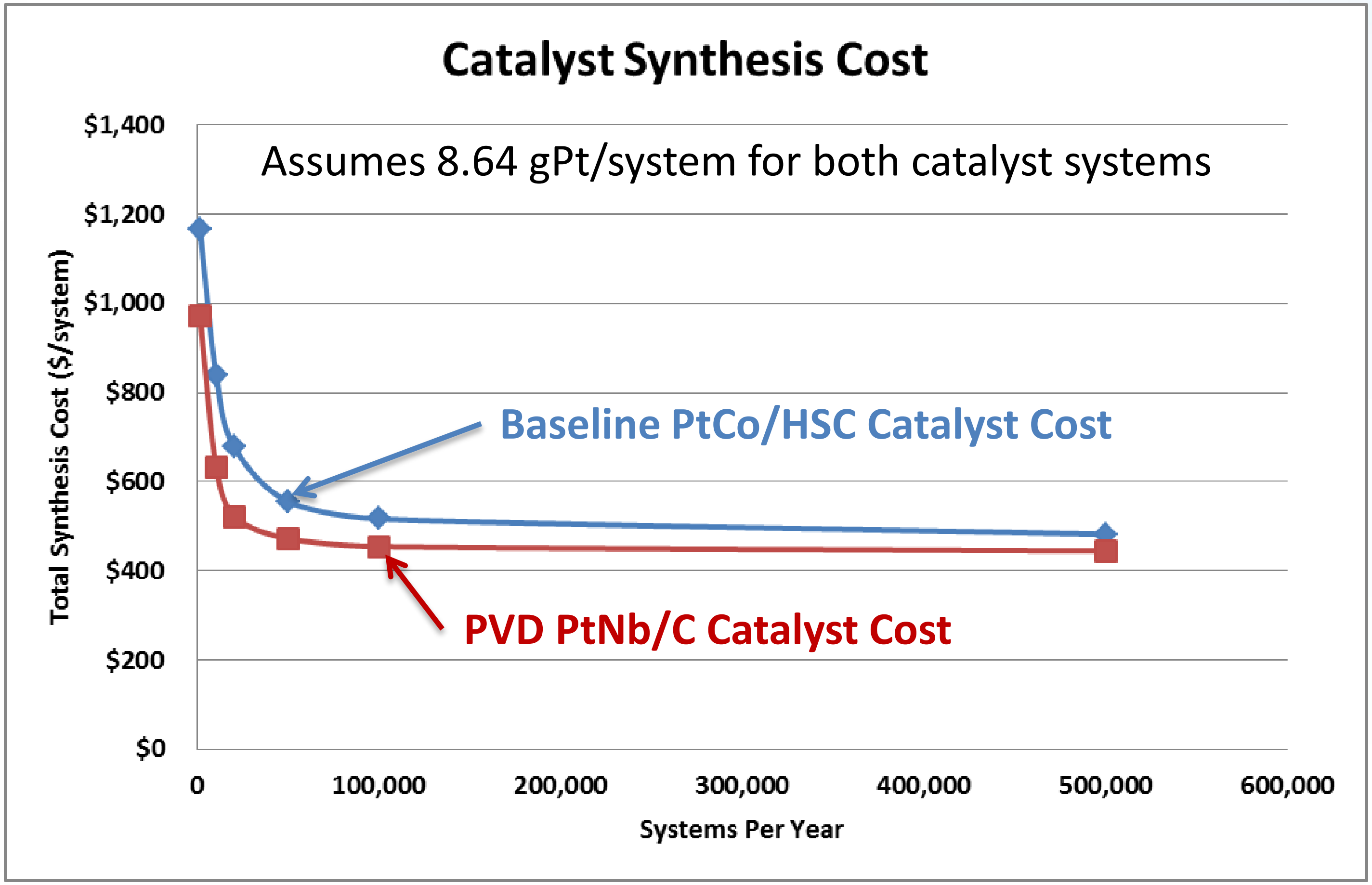
- position of magnet and cathode
- insulation inside/outside stationary chamber
- Support Structure
- Balance of System: Power Electronics/Control/Coolant System

Dual Barrel Design Properties

- External barrel fixed while internal concentric barrel rotates
- Motor external to vacuum
- Rotation wheels inside vacuum chamber
- Avoid vacuum seal bearings for the centerline components
- Possibly quicker change-out times (replacing one barrel for the next)

[1] Design loosely based on Milman Barrel Sputter Machine: http://www.milmanthinfilms.com/barrel-sputtering-equipment/barrel-sputtering-equipment

Preliminary comparison of Baseline Catalyst Cost vs. PVD Catalyst Cost



In the past, traditional synthesis methods have been predicted for catalyst operation. Particle Vapor Deposition may provide lower cost option for generating platinum based catalyst.

Accomplishments and Progress:

Updates to Compressor-Motor-Expander (CEM) Unit

- **SA design is based on 2008 Honeywell concept**
  - ~3atm, 165krpm, centrifugal compressor, radial inflow expender, central motor, single (common shaft), air bearings
  - Size and cost scaling with pressure ratio, flow rate, and motor power
- **2018 re-evaluation of assumptions (with ANL and Honeywell input)**
  - Basic CEM design appropriate: No significant design changes needed
  - Updated air flow rate for air-bearing/motor-cooling
  - CEM re-sized for 2018 mass flows & motor power
  - Inflation adjustment: Previously in 2008\$: + Δ\$1.32/kW$_{net}$ in 2018\$

	2017/2018 Model Value
Compressor Efficiency	71%
Expander Efficiency	73%
Motor & Motor Controller Efficiency	80% combined

Fuel Cell Truck Analysis

- DFMA analysis of FC Medium Duty Vehicle (MDV) or Heavy Duty Vehicle (HDV)
- Leverage past work:
  - ANL studies (Ram Vijayagopal et al): 12 truck applications studied
  - 21st Century Truck:

Two powertrain architecture options can be considered:

1. Battery powered electric vehicle with fuel cell range extender
2. Fuel cell dominant system with battery for peak acceleration events

← Selected for analysis

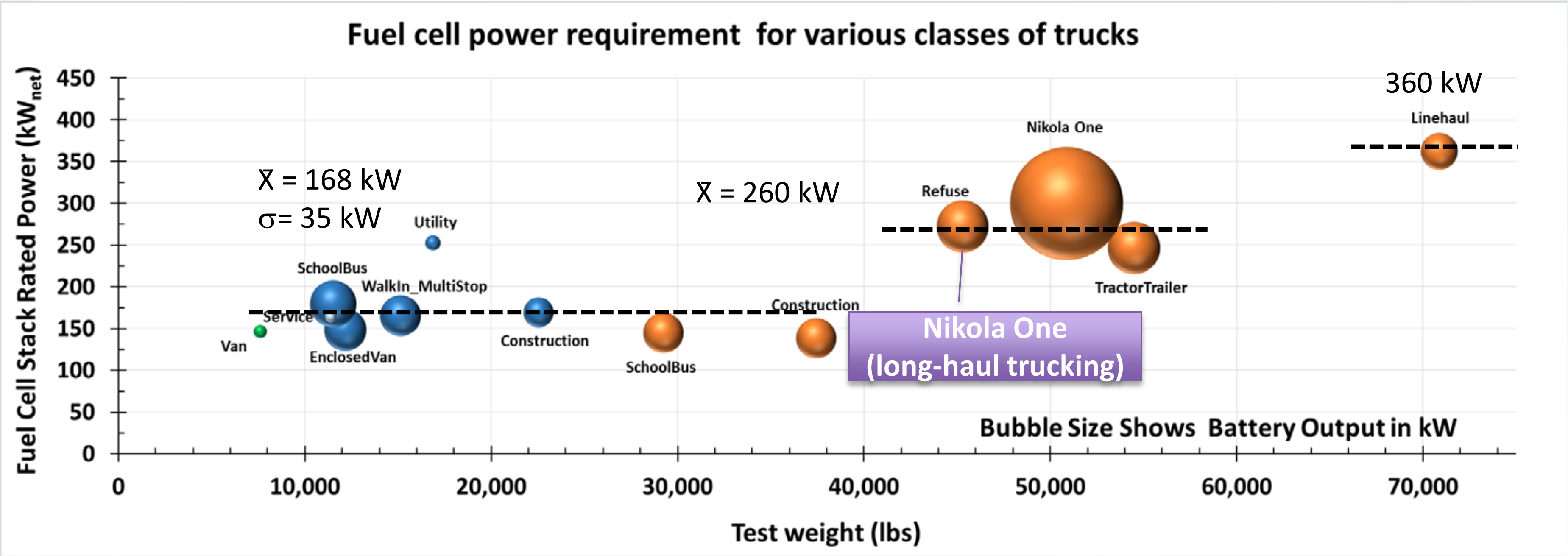
	Class and Vocation	FHA Vehicle Class Definition	ANL Analysis Assumption/Results		
			TestWeight (lbs)	Fuelcell (kW)	Battery (kW)
Light Duty	Class 1	Class 1: < 6,000 lbs	Not eval.	Not eval.	Not eval.
	Class 2 Van	Class 2: 6,001 - 10,000 lbs	7,588	147	6
Medium Duty	Class 3 Service	Class 3: 10,001 - 14,000 lbs	11,356	165	4
	Class 3 SchoolBus	Class 3: 10,001 - 14,000 lbs	11,512	180	76
	Class 3 EnclosedVan	Class 3: 10,001 - 14,000 lbs	12,166	149	62
	Class 4 Walk-In, Multi-Stop	Class 4: 14,001 - 16,000 lbs	15,126	166	59
	Class 5 Utility	Class 5: 16,001 - 19,500 lbs	16,860	253	8
	Class 6 Construction	Class 6: 19,501 - 26,000 lbs	22,532	170	30
Heavy Duty	Class 7 SchoolBus	Class 7: 26,001 - 33,000 lbs	29,230	145	56
	Class 8 Construction	Class 8: >33,001 lbs	37,429	139	57
	Class 8 Refuse		45,291	273	94
	Class 8 Nikola One		50,870	300	446
	Class 8 TractorTrailer		54,489	247	95
	Class 8 Linehaul		70,869	363	47

21st Century Truck

← MDV Baseline (approximation)

← HDV Baseline

MDV/HDV Fit into 3 Power-Level Bins


Fuel cell power requirement for various classes of trucks

$\bar{X}$ = 168 kW
σ= 35 kW

$\bar{X}$ = 260 kW

360 kW

Nikola One
(long-haul trucking)

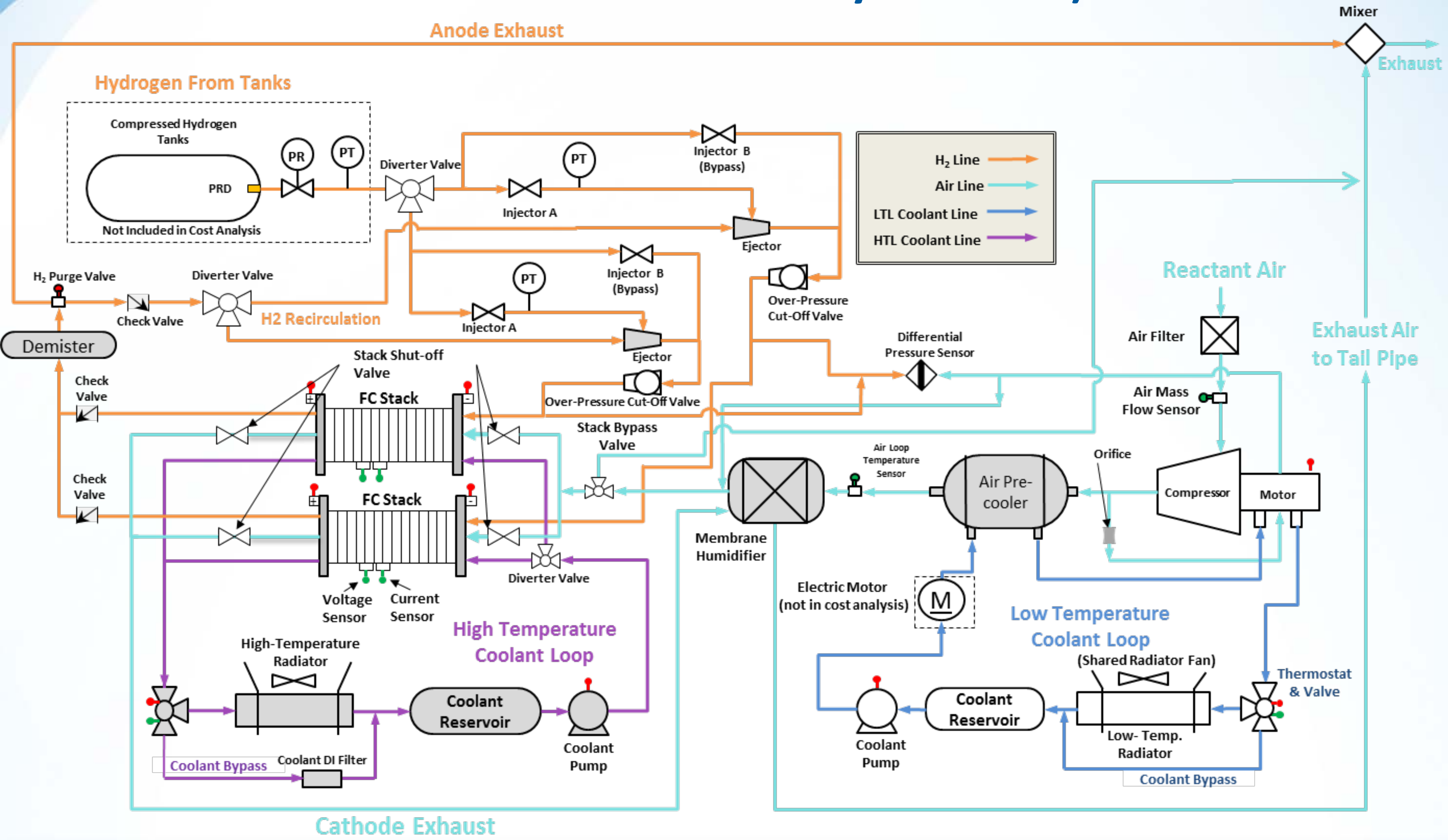
Bubble Size Shows Battery Output in kW

ANL Study Findings: - Two power levels capture most MDV/HDV applications

- Stacks can be built-up from ~80 kW modules

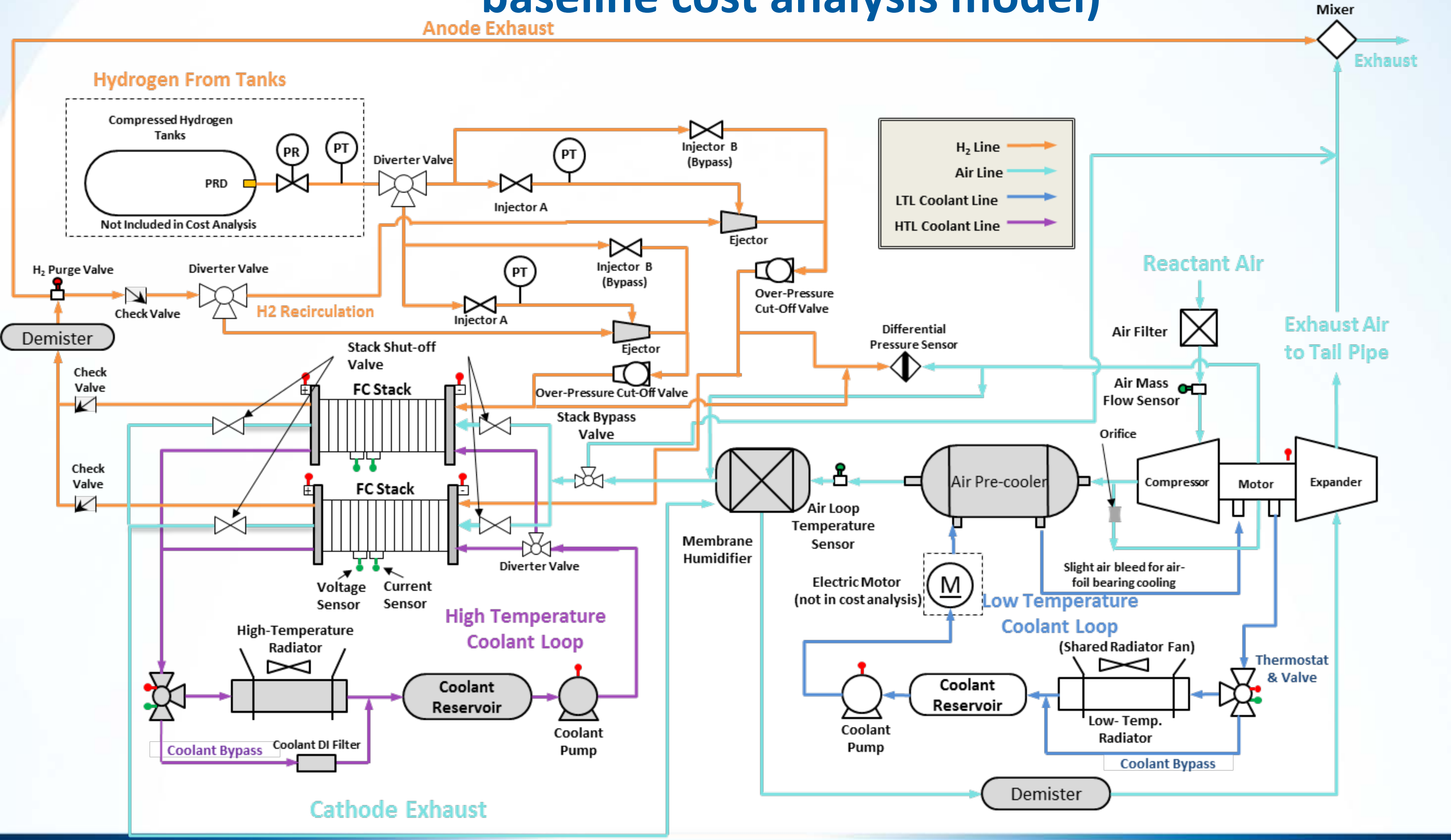
2018 MDV System

(Diagram shows system components included in baseline cost analysis model)



2020/2025 MDV System

(Diagram shows system components included in baseline cost analysis model)



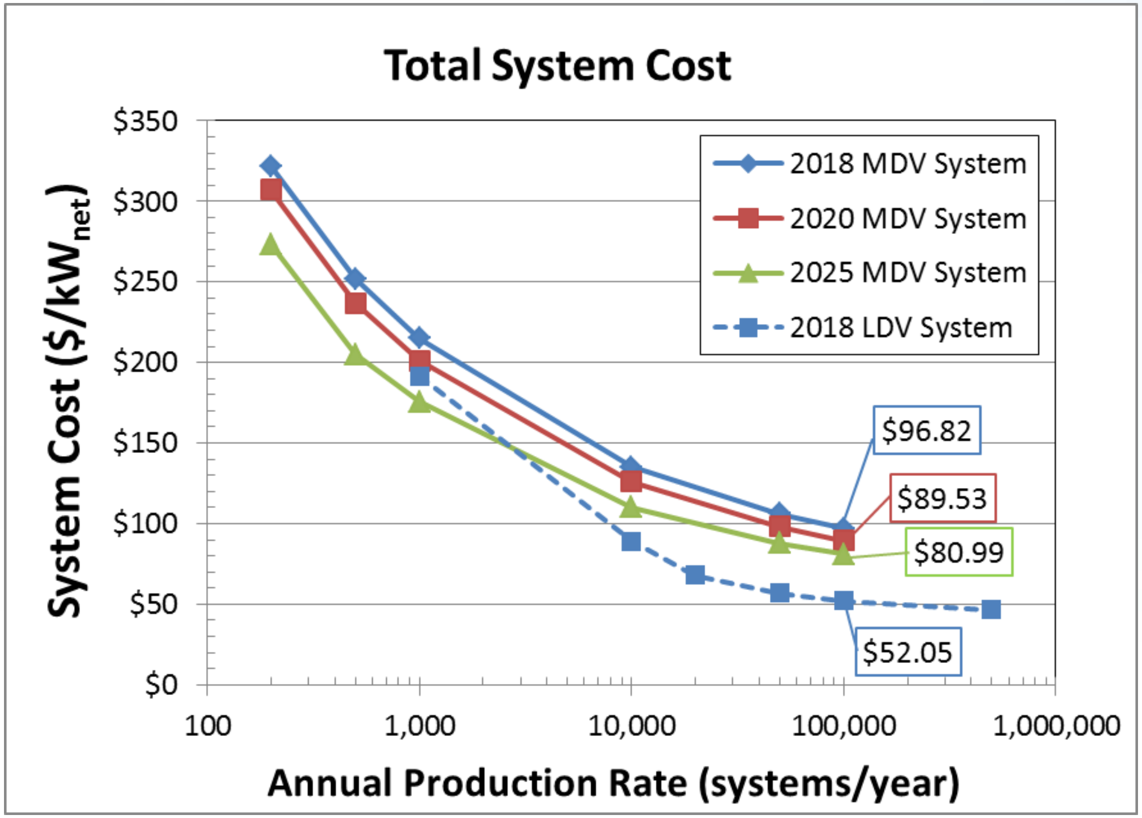
Accomplishments and Progress:
MDV Operating Parameters

	2018 LDV System	2016 Bus System	2018 MDV System	2020 MDV System	2025 MDV System
Annual Production (fuel cell systems/year)	1,000-500,000	200-1,000	200-100k[1]	200-100k[1]	200-100k[1]
Configuration	Centrifugal Compressor, Radial-Inflow Expander	Multi-Lobe Compressor	Multi-Lobe Compressor	Multi-Lobe Compressor and Expander	Centrifugal Compressor, Radial-Inflow Expander
Target Stack Durability (hours)	5,000	25,000[2]	25,000[2]/5,000[3]	25,000[2]/5,000[3]	25,000[2]/5,000[3]
Power Density	1,095	739	1,178	1,200	1,350
Total Pt loading ($mgPt/cm^2_{total\ area}$)	0.125	0.5	0.35	0.35	0.3
Pt Group Metal (PGM) Total Content (g/kW_{gross})	0.114	0.719	0.321	0.316	0.242
Cell Voltage (V/cell)	0.663	0.659	0.68	0.68	0.68
Net Power (kW_{net})	80	160	160	160	160
Gross Power (kW_{gross})	88	194.7	196.5	189.3	185.2
Operating Pressure (atm)	2.5	1.9	2.35	2.35	2.35
Stack Temp. (Coolant Exit Temp) (°C)	94	72	63[4]	63[4]	63[4]
Air Stoichiometry	1.5	1.8	1.5	1.5	1.5
$Q/\Delta T$ ($kW_{th}/°C$)	1.45	5.4	7.2	6.9	6.7

1. VTO Market Report Chapter 3: Heavy Trucks (http://cta.ornl.gov/vtmarketreport/pdf/2015_vtmarketreport_full_doc.pdf)
2. DOE Ultimate Bus Target (https://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf)
3. CAFCP Action Plan (http://cafcp.org/sites/default/files/MDHD-action-plan-2016.pdf)
4. Lower temperature selected for durability

Accomplishments and Progress:

Preliminary Cost Results for MDV Systems



- MDV cost curves more shallow due to low-volume manufacturing assumptions/criteria representative of the bus system.
- Large cost difference between LDV and MDV at 100k sys/yr due to:
  - Pt loading (0.125 Vs 0.35mgPt/cm^2)
  - CEM/gross power
  - Non-vertical integration (application of extra markup and job shop for truck)

Accomplishments and Progress:

Responses to Previous Year’s Reviewers’ Comments

2017 Reviewer’s Comments	Response to Reviewer’s Comment
“The project sometimes limits itself to what is known through DOE-funded projects. The investigator should more aggressively seek out technology alternatives that are not already related to the Fuel Cells sub-program.”	1) Although focusing on DOE-funded projects can facilitate communication and information, SA continues to seek out new demonstrations of technologies through patent literature and networking at conferences such as Fuel Cell Seminar. 2) Two areas of study (not DOE-funded projects) for 2018 will include evaluation of 2D cell assembly (Nissan-inspired idea) and Precors BPP pre-coating.
“Some attention should be given to the costs of recycling PGMs during catalyst synthesis. This could be an unusually large factor in the costs of alternative synthesis techniques, such as physical vapor deposition and atomic-layer deposition. ”	Allowance for Pt recycling are in the analysis. 1) Recycling of Pt during catalyst synthesis process for Pt Nitrate used in Pt/HSC. Industry has commented on Pt % recovery being ~95% during these types of processes. 2) End of life value of system as part of Lifecycle Cost Analysis (LCA). 3) SA has also looked into the capture and recycle of Pt in PVD coating of catalyst.

Collaborations

*Additional Collaborations
Listed in Reviewer Slides

Partner/Collaborator/Vendor	Project Role
National Renewable Energy Laboratory (NREL) (sub on contract)	• Provides knowledge and expertise on QC systems for FC manufacturing lines. • Reviews and provides feedback on SA's assumptions for MEA processing and techniques (electrospinning for 2018). • Provided feedback on 2020 and 2025 analysis systems and manufacturing processes. • Participates in researching the affect of durability on cost.
Argonne National Laboratory (ANL) (sub on contract)	• Supplies detailed modeling results for optimized fuel cell operating conditions (based on experimental cell data). • Provides SA with model results for system pressure, mass flows, CEM η, and membrane area requirements for optimized system. • Provided feedback and small modeling efforts on 2020 and 2025 analysis systems. • Provided input/modeling data on FC Med Duty Truck Analysis
2017/2018 DOE Sponsored Collaborators	• Peter Pintauro (Vanderbilt University) and Mike Yandrasits (3M) provided detailed reviews of electrospinning analysis. • Jim Waldecker (Ford) – provided information to facility cost analysis for PVD coating of catalyst powders. • Anusorn Kongkanand (GM) – gave feedback on PtCo/HSC synthesis
Vendors/Suppliers	See back-up material for list of ~30 other companies with which we have consulted.

Remaining Barriers and Challenges

Automotive System

- PFSA ionomer cost uncertainty: Some suggest that ionomer may be ~$500/kg even at high volumes. May require alternative formulation or fabrication process.
- BPP material cost: Base material 316SS contributes ~$3/kW$_{net}$ making it difficult to reach DOE's 2025 cost target of $3/kW total BPP (material/forming/coating).
- Ammonia contamination: Presence of ammonia in air feed of FC vehicles presents difficulty in maintaining membrane air humidifier performance.
- $40/kW DOE target difficult to achieve: Advancements projected for 2025 fuel cell system cost aligns with DOE's 2025 $40/kW target cost.
- $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 (75% of stack cost).
- Massively parallel BPP forming lines: Even with ~2sec/plate forming speed, many parallel BPP production lines are needed for 500k systems/year. This presents part uniformity problems.

MDV Study

- Better understanding of FCV truck preferred operation mode (how much hybridization).

Proposed Future Work

Automotive Systems

- Investigate ways to incorporate durability into cost modeling
- Model cost of PFSA/PFIA ionomers
- Review end-of-life disposal costs for auto system
- Conduct DFMA analysis of 2D manufacturing of cells
- Investigate Precors BPP non-vacuum pre-coating process
- Conduct cost sensitivity studies on 2018/2020/2025 systems

Medium/Heavy Duty Truck

- Incorporating feedback from DOE planned MDV/HDV truck workshop
- Conduct cost sensitivity studies on 2018/2020/2025 systems

Document in 2018 Final Report

- Report due September 2018

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

Technology Transfer Activities

Not applicable for SA’s Cost Analysis

Summary of Findings

- Auto cost results show small adjustments from 2017 analysis:
    - ~\$47/kW$_{net}$ (2018, +Δ\$1.73), \$44/kW$_{net}$ (2020, +Δ\$.75), \$39/kW$_{net}$ (2025, +Δ\$3.03)
- Moderate improvement (6%) in performance using latest PtCo/HSC-e cathode catalyst
- Cost analysis of d-PtCo/HSC cathode catalyst shows only slight cost difference with previous d-PtNi/HSC catalyst.
- Laser welding re-examined with cost increasing due to weld fixture & CapEx reappraisal.
- BOP components were added to isolate the fuel cell stack during shut-down and to throttle air flow to stack during part-power operation. This raised cost (~\$0.67/kW) but is consistent with OEM practice.
- Electrospinning can be used to fabricate multiple components: membrane support, membrane, electrodes. Cost analysis shows electrospinning is cost competitive and process selection will largely depend on demonstrated performance levels.
- Catalyst synthesis via PVD onto a carbon substrate is cost competitive when conducted in large batches. Process selection will largely depend on performance levels.
- Projected cost for 2025 does meet DOE Target of \$40/kW (but is close).
- 160kW Medium Duty Vehicle (MDV truck) selected for analysis.
    - Stacks very similar to auto except higher Pt loading & run cooler for longer life.
    - Projected costs are \$97/kW$_{net}$, \$90/kW$_{net}$, and \$81/kW$_{net}$ for 2018/2020/2025
    - Potentially high production rates (up to 100k's/year) but with higher markup due to business structure

Project Summary

- **Overview**
  - Annually updated cost analysis of automobile and truck fuel cell systems
  - Exploring subsystem alternative configurations and benchmark cost where possible
  - In year 2 of 5 year project
- **Relevance**
  - Cost analysis used to assess practicality of proposed power system, determine key cost drivers, and provide insight for direction of R&D priorities
  - Provides non-proprietary benchmark for discussions/comparison
- **Approach**
  - Process-based cost analysis methodologies (e.g. DFMA®)
  - Full transparency and open discussion of assumptions and results
- **Accomplishments**
  - 2017 Automobile analysis documented (report available)
  - LDV and MDV 2018, 2020, 2025 fuel cell systems analysis results
  - Components newly analyzed or revisited:
    - D-PtCo/HSC catalyst synthesis
    - Electrospun membrane support, dual-fiber (co-spun) membrane, and electrodes
    - PVD-coated catalyst powders
- **Collaborations**
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
  - Extensive discussions, interviews, feedback with 30+ industry vendors/suppliers
- **Future Work**
  - Complete studies and final report.

Thank you!

Questions?

Technical Backup Slides

LDV System Definition- Part 1

(Configuration, Operating, and Manufacturing Parameters)

	2018 Auto System (2017 Yr Value if different)	2020 Auto System (2017 Yr Value)	2025 Auto System "High Innovation" (2017 Yr Value)
Stack Power Density @ Rated Power (mW/cm^2 $_{\text{active area}}$)	1,183 **(1,095)** PtCo/HSC	**1,250 (1,165)** PtCo/HSC	1,500 Consistent with DOE 2025 target of 1,000 at 150kPa$_{\text{abs}}$
Total Pt loading (mgPt/cm^2 $_{\text{total area}}$)	0.125	0.125 DOE 2025 target	0.088 Reasonable improvement over 2025 target
Pt Group Metal (PGM) Total Content (g/kW$_{\text{gross}}$)[1]	**0.117 (0.114)**	**0.108 (0.107)**	0.064 **(0.065)**
Net Power (kW$_{\text{net}}$)	80	80	80
Gross Power (kW$_{\text{gross}}$)	**88 (87.9)**	**88 (87.9)**	**88 (87.9)**
Cell Voltage (V)	**0.657 (0.66)**	**0.657 (0.66)**	**0.657 (0.66)**
Operating Pressure (atm)	2.5	2.5	2.5
Stack Temp. (Coolant Exit Temp) °C)	**95 (94)**	**95 (94)**	**95 (94)**
Air Stoichiometry	1.5	1.5	1.5
Q/ΔT (kW$_{\text{th}}$/°C)	1.45	1.45	1.45
Active Cells	380	380	380
Active-to-Total-Area Ratio	0.625	0.625	0.65
Membrane Material & Support	14 µm Nafion, 850EW, supported on ePTFE	10 µm Nafion, 850EW supported on **Electrospun PPSU (ePTFE)**	High performance membrane, cost based on 10 µm Nafion, **720EW on Electrospun PPSU (Low-Cost Support [DSM, electrospun, other])**

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[1] PGM Total Content here refers to only the active area. Approximately 7% would be added to the mass of Pt when accounting for the catalyst coated onto the non-active border.

Changes from 2017 analysis highlighted in green.

LDV System Definition- Part 2

(Configuration, Operating, and Manufacturing Parameters)

	2018 Auto System (2017 Yr Value)	**2020 Auto System (2017 Yr Value)**	**2025 Auto System “High Innovation” (2017 Yr Value)**
Catalyst & Application	Slot Die Coating of: Cath.: Dispersed 0.1 mgPt/cm^2 d-PtCo on HSC Anode: Dispersed 0.025mgPt/cm^2 Pt/C	Slot Die Coating of: Cath.: Dispersed 0.107 mgPt/cm^2 d-PtCo on HSC Anode: Dispersed 0.018mgPt/cm^2 Pt/C	Slot Die Coating of advanced performance catalyst. Cath.: Dispersed 0.07 mgPt/cm^2 d-PtCo on HSC Anode: Dispersed 0.018mgPt/cm^2 Pt/C (Assume catalyst cost still dominated by Pt price and no major improvements in application)
CCM Preparation	R2R dip-coated ePTFE/Ionomer membrane, 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
Gas Diffusion Layers	150 microns Based on 105 μm GDL, 45 μm MPL, uncompressed	150 microns Based on 105 μm GDL, 45 μm MPL, uncompressed	150 microns Based on 105 μm GDL, 45 μm MPL, uncompressed
Catalyst Durability: ECSA loss after 30k cycles (per 2016 MYPP Table P.1 protocol)	50% Based on catalyst only, does not capture membrane degradation	40% Based on achievement of DOE 2025 target	<40% Exceeds DOE 2025 target
MEA Containment	R2R sub-gaskets, hot-pressed to CCM	R2R sub-gaskets, hot-pressed to CCM	R2R sub-gaskets, hot-pressed to CCM
Bipolar Plates and Coating	316SS with PVD Coating modeled as Treadstone Dots Gen2	304SS with PVD Coating, modeled as Treadstone TIOX	**304SS with PVD Coating, modeled as Treadstone TIOX (Alloy requiring no coating Modeled as SS 304L cost)**
BPP Forming/Joining	Progressive Stamping/ Laser Welding	**Hydroforming (Prog. Stamping)**/ Laser Welding	**Hydroforming (Prog. Stamping)**/ Laser Welding
BPP-to-MEA Gaskets	Screen-printed polyolefin elastomer seal on BPP	Screen-printed polyolefin elastomer seal on BPP	Screen-printed polyolefin elastomer seal on BPP

Changes from 2017 analysis highlighted in green.

LDV System Definition- Part 3

(Configuration, Operating, and Manufacturing Parameters)

	2018 Auto System (2017 Yr Value)	2020 Auto System (2017 Yr Value)	2025 Auto System “High Innovation” (2017 Yr Value)
Air Compression/CEM Efficiencies	Centrifugal Compressor, Radial-Inflow Expander/ Comp: 71%, Expand: 73%, Motor/Control. 80%	Centrifugal Compressor, Radial-Inflow Expander/ Comp: 71%, Expand: 73%, Motor/Control. 80%	Centrifugal Compressor, Radial-Inflow Expander (with adv. mech. design)/ Comp: 71%, Expand: 73%, Motor/Control. 80%
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
Air Humidification	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)
Hydrogen Humidification	None	None	None
Anode Recirculation	**Pulse Ejector (2 fixed geometry ejectors)**	Pulse Ejector with bypass	Pulse Ejector with bypass
Exhaust Water Recovery	None	None	None
Coolant and 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)
Cell Assembly	Robotic assembly of welded BPP assembly and sub-gasketed MEA	Robotic assembly of welded BPP assembly and sub-gasketed MEA	Robotic assembly of welded BPP assembly and sub-gasketed MEA
Freeze Protection	Drain water at shutdown	Drain water at shutdown	Drain water at shutdown
Hydrogen Sensors	None	None	None
End-Plate/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 (hours)	2	2	1

Changes from 2017 analysis highlighted in green.

MDV System Definition- Part 1

(Configuration, Operating, and Manufacturing Parameters)

	2016 Bus System	2018 MD Truck System	2020 MD Truck System	2025 MD Truck System
Power Density (mW/cm^2)	739	1,178	1,200	1,350
Total Pt loading (mgPt/cm^2)	0.5	0.35	0.35	**0.3**
Pt Group Metal (PGM) Total Content (g/kW$_{gross}$)	0.719	**0.321**	**0.316**	**0.242**
Net Power (kW$_{net}$)	160	160	160	160
Gross Power (kW$_{gross}$)	194.7	**196.5**	**189.3**	**185.2**
Cell Voltage (V)	0.659	**0.68**	0.68	0.68
Operating Pressure (atm)	1.9	**2.35**	2.35	2.35
Stack Temp. (°C) (Coolant Exit Temp)	72	**63**	63	63
Air Stoichiometry	1.8	**1.5**	1.5	1.5
Q/ΔT (kW$_{th}$/°C)	5.4	**7.2**	**6.9**	**6.7**
Active Cells	758	**736**	736	736
Total System Voltage	500 - 720	500 **- 700**	500 - 700	500 – 700
Active to Total Area Ratio	0.625	0.625	0.625	0.65
Membrane Material	20-micron Nafion (1100EW) supported on ePTFE	**14-micron Nafion (850EW) supported on ePTFE**	14-micron Nafion (850EW) supported on ePTFE	**14-micron Nafion (850EW) supported on electrospun support**
Radiator/ Cooling System	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler
Bipolar Plates and Coating	SS 316L with TreadStone LIteCell^{TM} Coating (Dots-R)	**SS 316L with PVD Gold Coating**	**316SS with Vacuum Coating (modeled as TreadStone TIOX)**	316SS with Vacuum Coating (modeled as TreadStone TIOX)

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MDV System Definition- Part 2

(Configuration, Operating, and Manufacturing Parameters)

	2016 Bus System	2018 MD Truck System	2020 MD Truck System	2025 MD Truck System
BPP Forming/Joining	Progressive Stamping/Welding	Progressive Stamping/Welding	**Hydroforming or HVIF**	Hydroforming or HVIF
Air Compression	Eaton-Style Multi-Lobe Compressor, Without Expander	Eaton-style compressor (no expander)	**Eaton-style compressor, Eaton-style expander**	**Centrifugal Compressor, Radial-Inflow Expander**
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Microporous Layer (DFMA® cost of Avcarb GDL)	**150 microns (105 μm GDL, 45 μm MPL, uncompressed)**	150 microns (105 μm GDL, 45 μm MPL, uncompressed)	150 microns (105 μm GDL, 45 μm MPL, uncompressed)
Catalyst & Application	Slot Die Coating of: Cath.: Dispersed 0.4 mgPt/cm^2 Pt on C Anode: Dispersed 0.1mgPt/cm^2 Pt/C	**Slot Die Coating of: Cath.: Dispersed 0.3 mgPt/cm^2 d-PtCo/HSC-e Anode: Dispersed 0.05mgPt/cm^2 Pt/C**	Slot Die Coating of: Cath.: Dispersed 0.3 mgPt/cm^2 d-PtCo/HSC-f Anode: Dispersed 0.05mgPt/cm^2 Pt/C	**Slot Die Coating of advanced perf. Catalyst cost modeled as: Cath.: Dispersed 0.25mgPt/cm^2 d-PtCo/HSC Anode: Dispersed 0.05mgPt/cm^2 Pt/C**
CCM Preparation	No acid wash	**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

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MDV System Definition- Part 3

(Configuration, Operating, and Manufacturing Parameters)

	2016 Bus System	2018 MD Truck System	2020 MD Truck System	2025 MD Truck System
Air Compressor/Expander/ Motor Efficiency	Compr.: 58% (multi-lobe) Expander: NA Motor/Controller: 95%	Compr.: 58% (multi-lobe) Motor/Controller: 95%	**Compr.: 58% (multi-lobe)** **Exp.: 59% (multi-lobe)** **Motor/Controller: 95%**	**Compressor: 71% (centrifugal)** **Expander: 73% (radial in-flow)** **Motor/Controller: 80%**
Air Humidification	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)
Hydrogen Humidification	None	None	None	None
Anode Recirculation	2 fixed geometry ejectors	**Pulse ejector with bypass**	Pulse ejector with bypass	Pulse ejector with bypass
Exhaust Water Recovery	None	None	None	None
MEA Containment	Screen Printed Seal on MEA sub-gaskets, GDL hot pressed to CCM	R2R sub-gaskets, hot-pressed to CCM	R2R sub-gaskets, hot-pressed to CCM	R2R sub-gaskets, hot-pressed to CCM
Coolant & End Gaskets	Laser Welded(Cooling)/ Screen-Printed Adhesive Resin (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)
Freeze Protection	Drain Water at Shutdown	Drain Water at Shutdown	Drain Water at Shutdown	Drain Water at Shutdown
Hydrogen Sensors	3 for FC System	**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	Composite Molded End Plates with Compression Bands
Stack Conditioning (hrs)	2	2	2	**1**
Stack Lifetime (hrs) (before replacement)	Not specified	25,000	25,000	25,000

There are a total of 3 hydrogen sensors on-board the 2016 FC bus fuel cell cost estimate (1 more than in the 2016 auto system).

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

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