Fuel Cell Truck System Cost Analysis

Brian D. James

Jennie M. Huya-Kouadio

Cassidy Houchins

Strategic Analysis Inc.

July 30th-31st, 2018

Overview

- Strategic Analysis Inc. (SA) is a 200 person consulting company in Arlington VA.
- We specialize in Techno-economic analysis (TEA) of emerging energy systems
- Under contract to DOE to conduct TEA of:
  - Onboard H_2 storage systems
  - H_2 Production and Delivery systems
  - PEM fuel cell systems for transportation
    - 80kW light-duty vehicles (mid-size sedan)
    - 160kW 40’ Transit bus
    - 160kW Medium Duty Truck (Class 6) ← Today’s Focus
- Employ the DFMA™ cost analysis methodology

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 cost targets
- Benchmark against production vehicle power systems
- Identify fuel cell system cost drivers to facilitate Fuel Cell Technology Office programmatic decisions.

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

What is DFMA®?

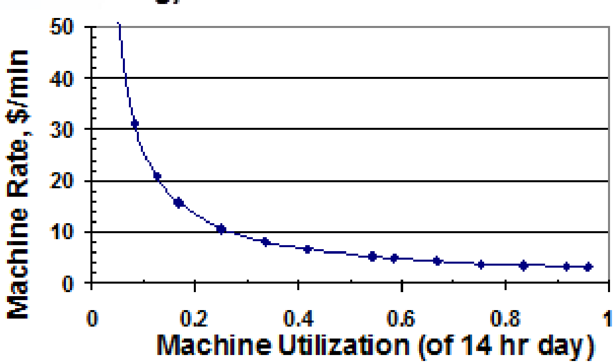
- DFMA® = Design for Manufacture & Assembly = Process based cost estimation methodology
  - Registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Company (Ford) design/costing method for the past 20+ years
- SA practices are a blend of: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

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

Cost Estimate Caveats

- Theses are fuel cell system **cost** projections (not price)
  - They include materials and manufacturing costs
  - They **do not include** final integrator markup for:
    - Profit
    - R&D
    - Non-recurring engineering (NRE)
    - Overhead
    - Advertising
    - Warranty
- Per DOE analysis guidance, designs and manufacturing are based on State-of-the-Art technology in the designated year (2018, 2020, or 2025) projected at higher manufacturing rates
  - Thus the 2018 cost is not the current cost (nor price) of a fuel cell system available in 2018. (But is representative of today's technology manufactured at scale.)
- Cost estimation is iterative process
  - This is first public pass at Truck FCV costing
  - We desire candid feedback and assumption correction
- Cost analysis consists of two main parts
  - Design and manufacturing assumptions ← **Highly Subjective**
  - Cost projections ← **(Mostly) Objective**

Fuel Cell Truck Analysis

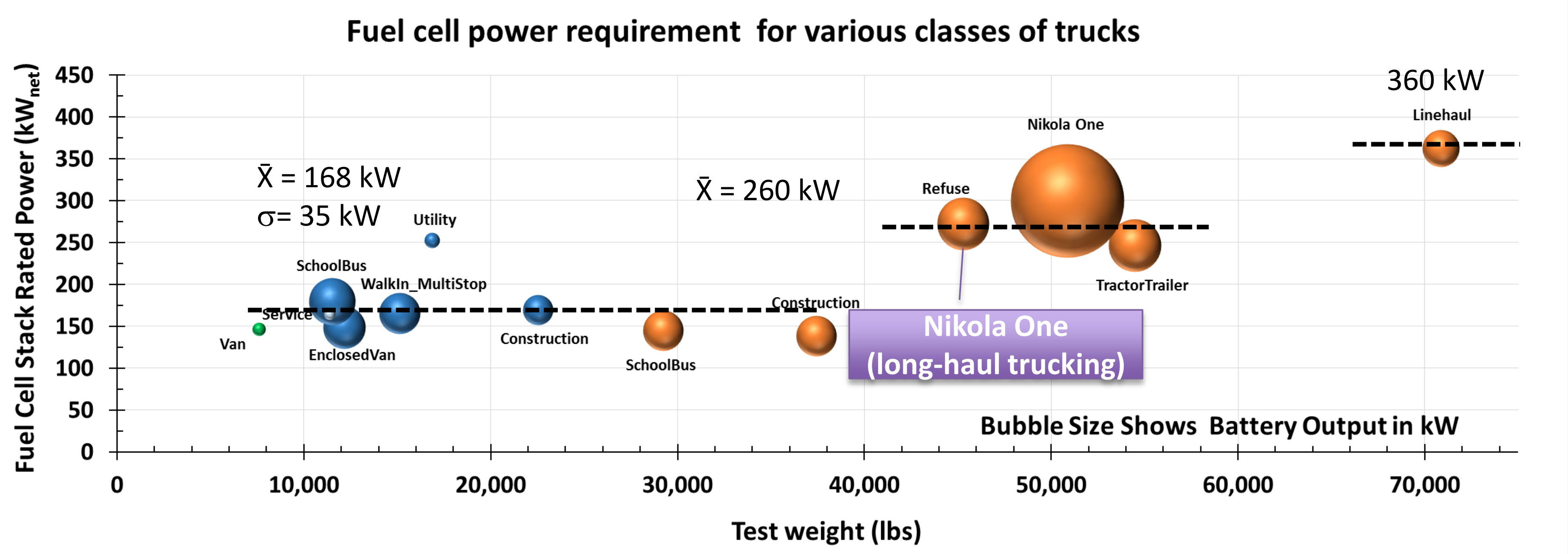
- DFMA analysis of FC Medium Duty Vehicle (MDV) or Heavy Duty Vehicle (HDV)
- Leverage past work:
  - ANL studies (Ram Vijayagopal et al): 12 truck applications studied
  - 21st Century Truck:

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	21st Century Truck
	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	← MDV Baseline (approximation)
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	← HDV Baseline

MDV/HDV Fit into 3 Power-Level Bins



ANL Study Findings:
- Two power levels capture most MDV/HDV applications
- Stacks can be built-up from ~80 kW modules

Domestic MDV/HDV Market Large and Growing

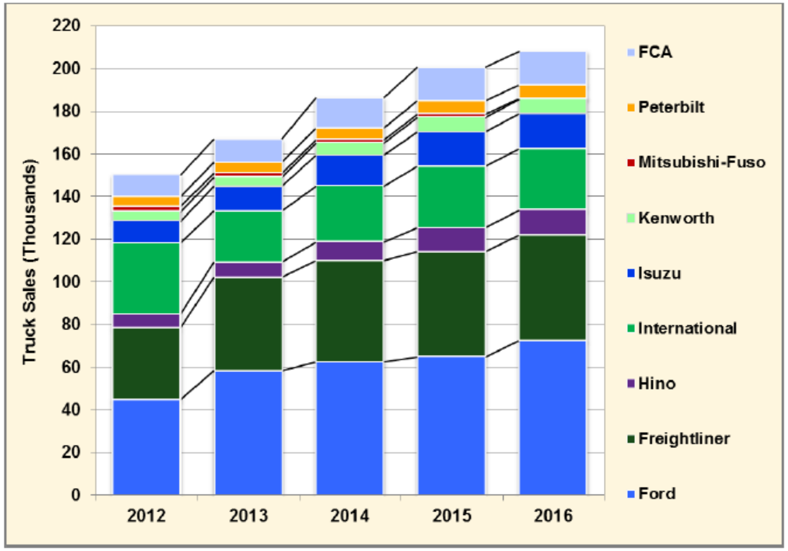


FIGURE 97. Class 4-7 Truck Sales by Manufacturer, 2012-2016

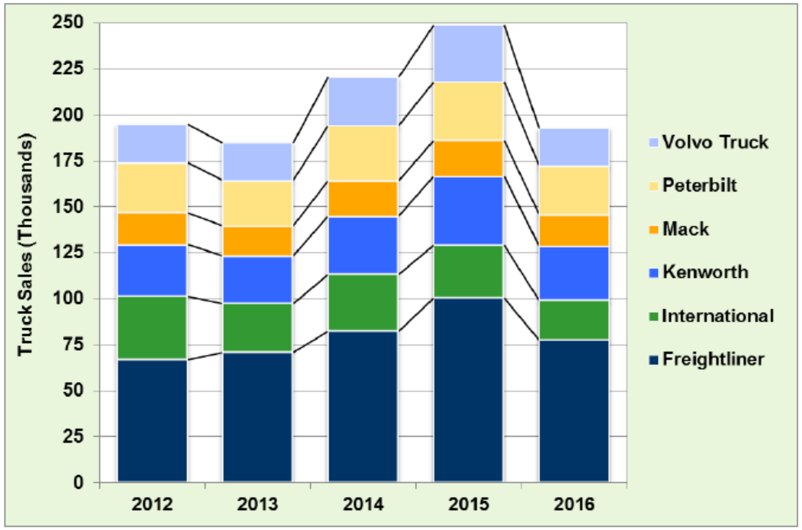


FIGURE 98. Class 8 Truck Sales by Manufacturer, 2012-2016

Only ~3% of MDV/HDV are imported into US

- **Class 4-7 truck sales up 38% since 2012**
- **~200k truck sales in 2016**

Compared to:

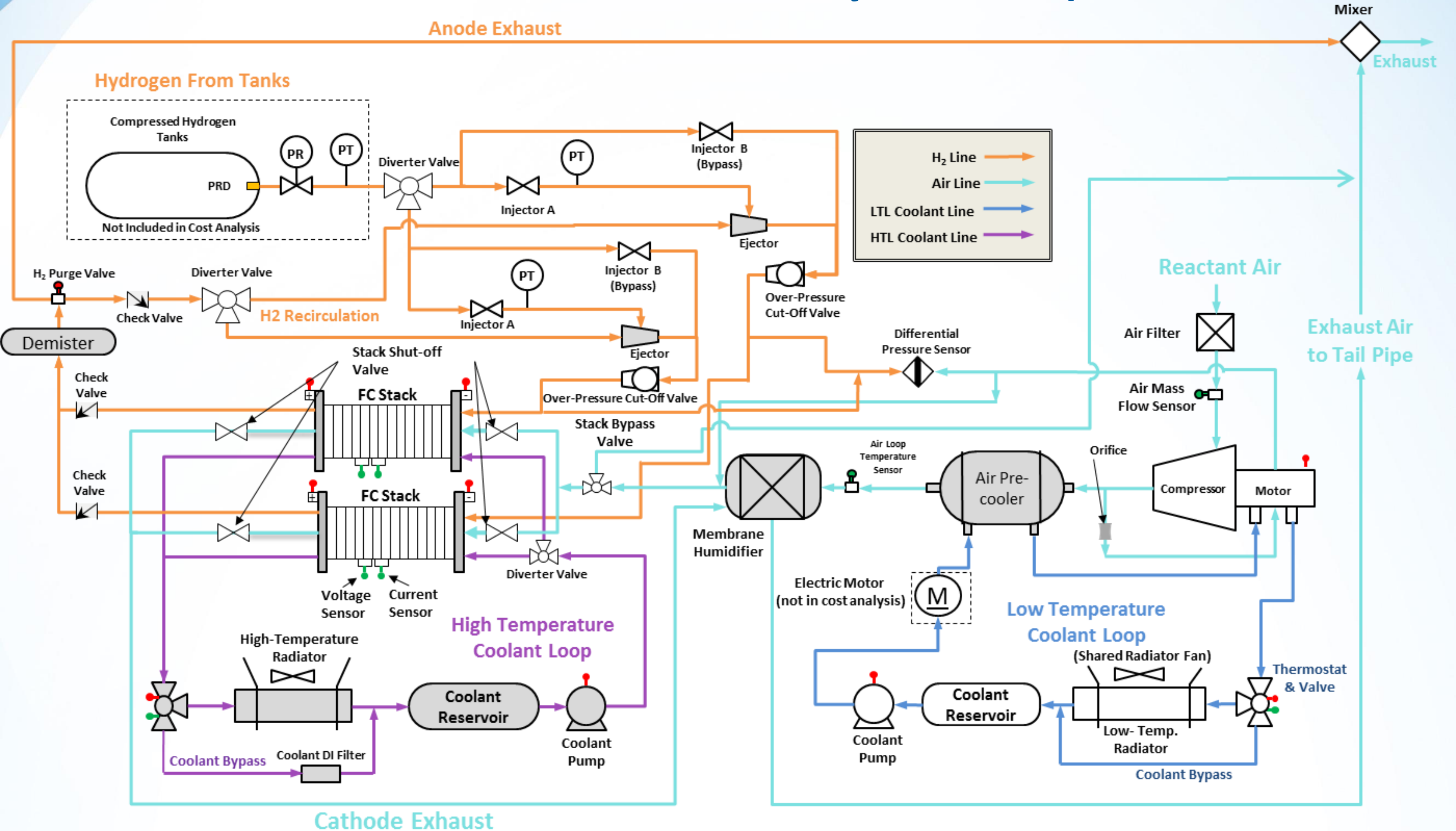
- **~12M Light-Duty Vehicle made in US in 2015**
  - (~90M LDV produced worldwide)
- **~4k Transit buses made in US in 2015**
  - (~75k Transit Buses produced worldwide)

- **Class 8 truck sales stagnant/declining**
  - Reflects shift away from long-haul toward regional-haul
  - Will driver-less trucks reverse this trend?
- **~185k truck sales in 2016**

Source: 2016 Vehicle Technologies Market Report, Oak Ridge National Laboratory, http://cta.ornl.gov/vtmarketreport/index.shtml

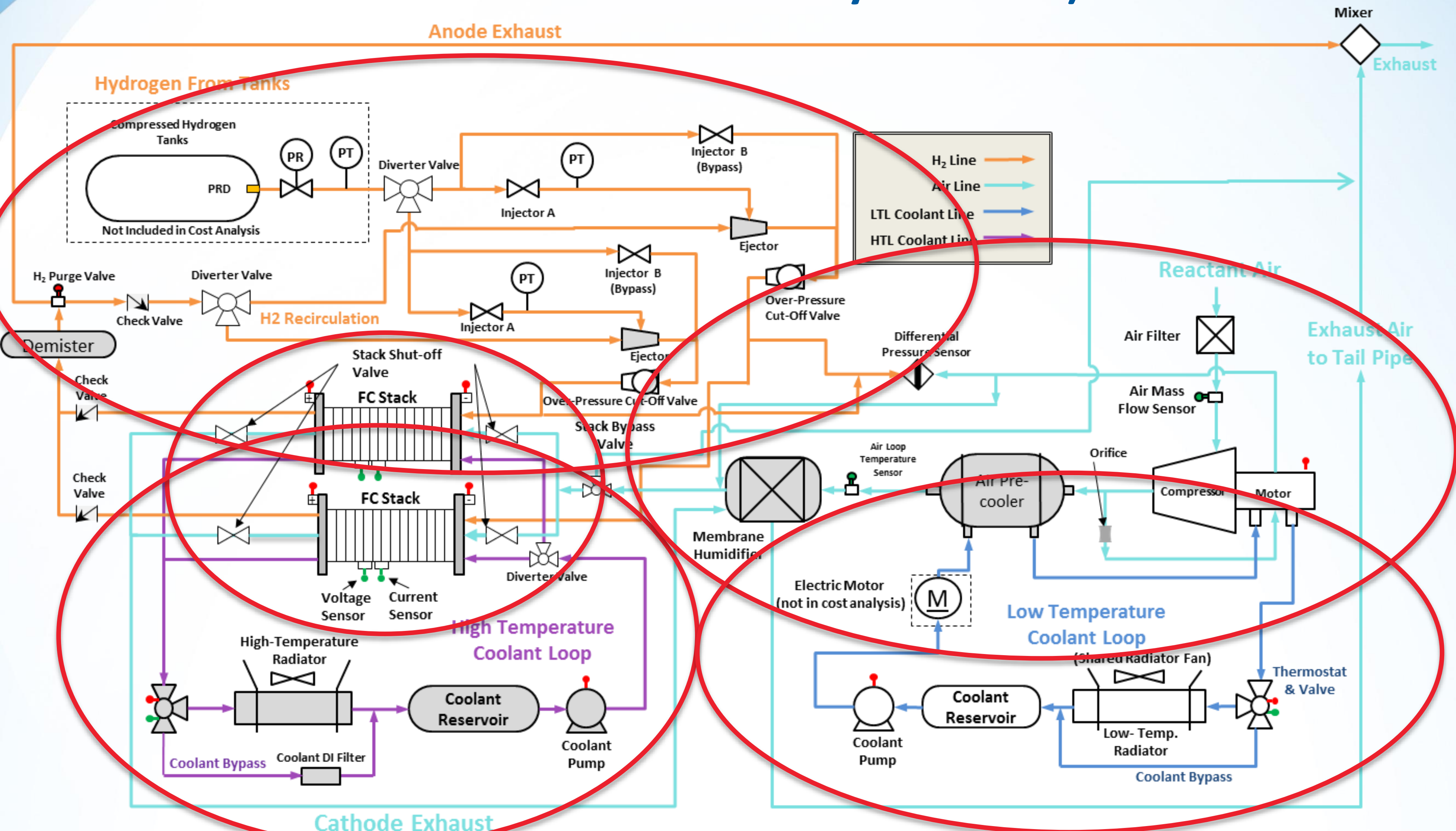
2018 MDV System

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



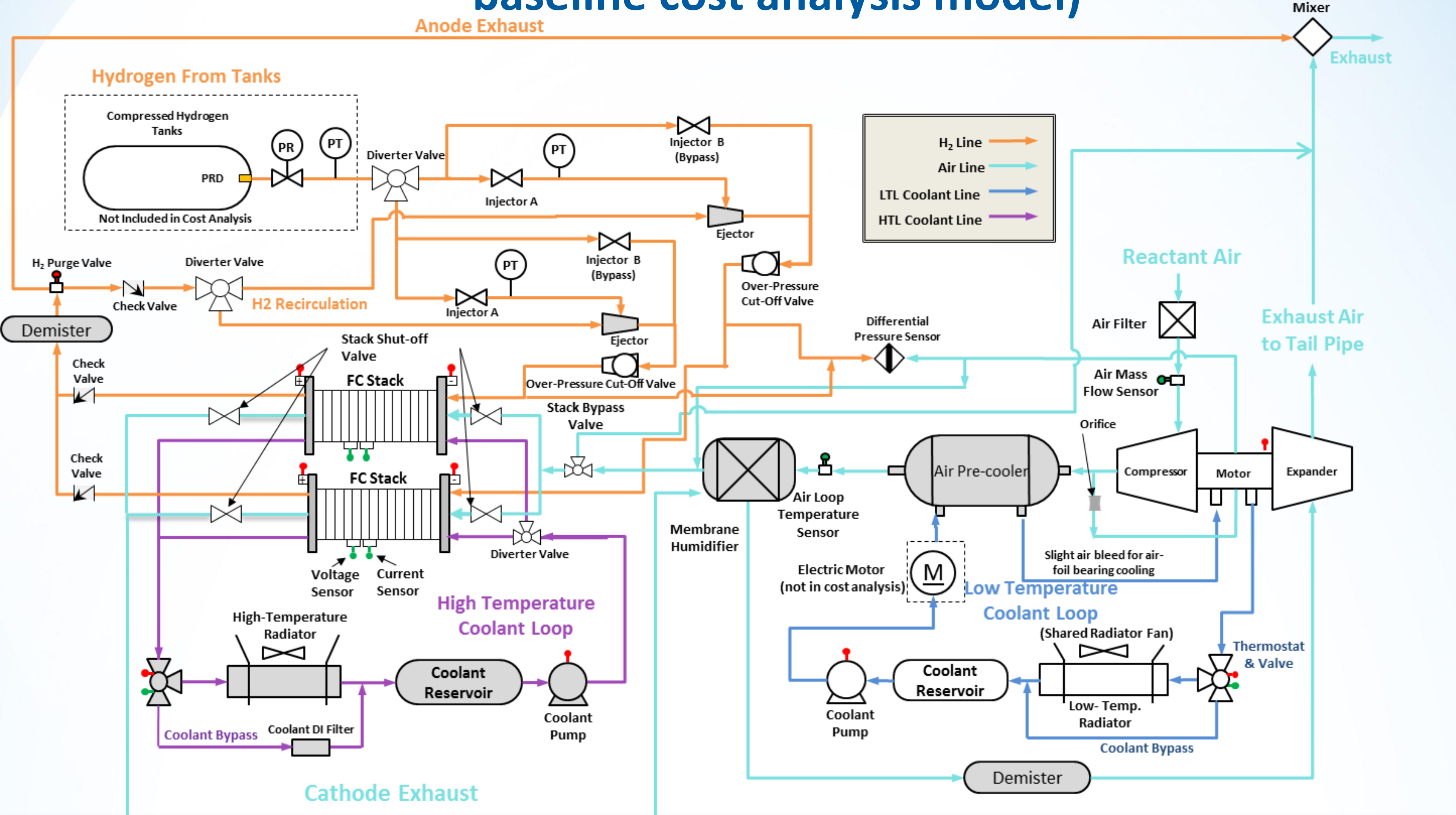
2018 MDV System

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



2020/2025 MDV System

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



Expected FC Power System Trends

	LDV (Mid-size auto)	MDV/HDV (Class 6/7)	Comments
Lifetime (durability)	↓ 5,000hr	↑ Higher/25,000hr	MDV/HDV must be ≥ diesel
Catalyst Loading	↓ ~0.1mgPt/cm^2	↑ ~0.3mgPt/cm^2	Higher loading for durability
Temperature	↑ ~90°C	↓ ~60°C	Lower temp. for durability
FC Net Power	↓ ~80-100kW	↑ 160-360kW (FC dominant)	Higher vehicle weight
Membrane thickness	↓ ~10-15 microns	↑ ~15 microns	Thicker for durability
Stack Design & Other Materials	Similar	Similar	SS bipolar plates, carbon GDL, Pt-alloy catalyst
Operating Pressure and Compression	~2-3 atm, Compr./Expander	Similar	Expect similar compression concepts
Power Density	↑ ~1.1-1.5W/cm^2	↓ Slightly lower	Expect slightly lower as result of above and desire to optimize TCO.

Expected Trends, cont.

	LDV (Mid-size auto)	MDV/HDV (Class 6/7)	Comments
Production Volume	↑ Up to 500k/yr (by single prod. facility)	↓ Up to 100k/yr (by single prod. facility)	Market segmentation & power plant commonality will be important
Vertical Integration	↑ High degree	↓ Lower degree	Similar to today's industry
Onboard Hydrogen Storage	(Mostly) 700 bar compressed	(Probably) 350 bar compressed	Central refueling, fixed routes make alternate storage/refueling options possible

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

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™ 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)

Green font indicates a change from the column to the left.

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

Green font indicates a change from the column to the left.

MDV System Definition- Part 3

(Configuration, Operating, and Manufacturing Parameters)

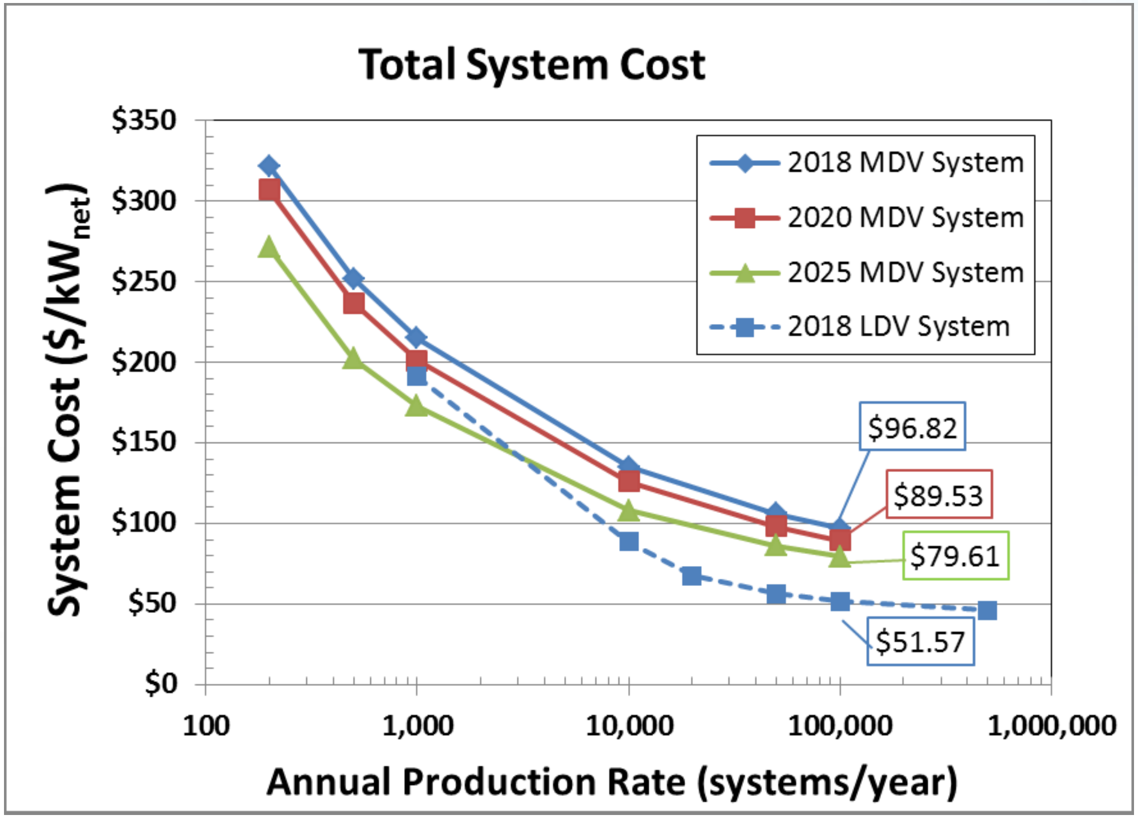
	2016 Bus System	2018 MD Truck System	2020 MD Truck System	2025 MD Truck System
Air Compressor/Expander/ Motor Efficiency	Compr.: 58% (multi-lobe) Expander: NA Motor/Controller: 95%	Compr.: 58% (multi-lobe) Motor/Controller: 95%	**Compr.: 58% (multi-lobe) Exp.: 59% (multi-lobe) Motor/Controller: 95%**	**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).

Green font indicates a change from the column to the left.

Accomplishments and Progress:

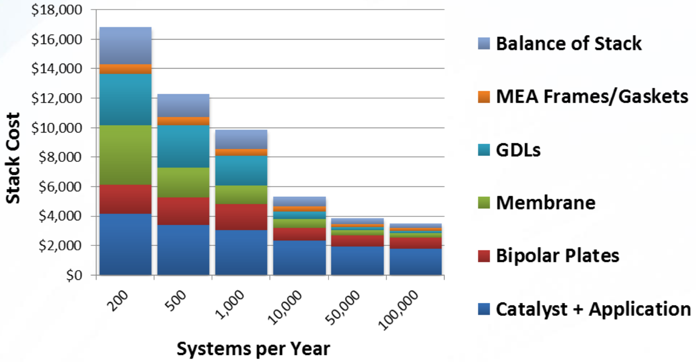
Cost Results for MDV Systems



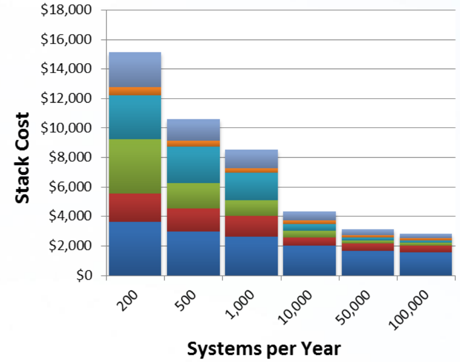
- MDV cost curves more shallow due to low-volume manufacturing assumptions/criteria representative of the bus system.
- Large cost difference between LDV and MDV at 100k sys/yr due to:
  - Pt loading (0.125 Vs 0.35mgPt/cm^2)
  - CEM/gross power
  - Non-vertical integration (application of extra markup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

MDV Cost Comparisons

2018 MDV Stack Cost

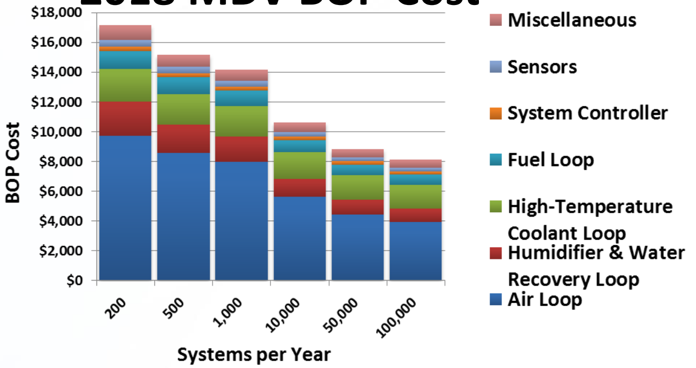


2025 MDV Stack Cost

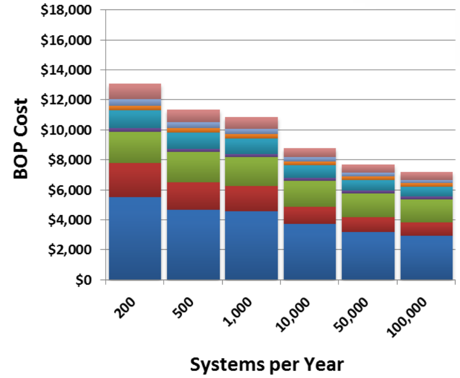


- Catalyst dominates stack cost at high volume
- Steep cost decline with prod. volume

2018 MDV BOP Cost

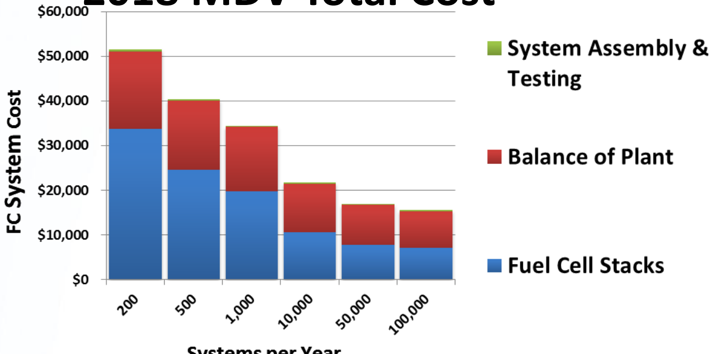


2025 MDV BOP Cost

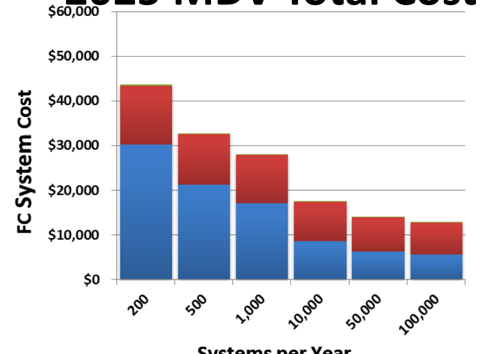


- Air loop is large cost item
- BOP has (more) modest cost declines with vol.

2018 MDV Total Cost



2025 MDV Total Cost



- Stack and BOP are (roughly) equally split

Thank you!

Questions?