2017 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: 15% of five year project (in Year 1 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
  - $145k (through March 2017, including Labs)
- Total DOE Project Value
  - $1.5M (over 5 years, including Labs)

Partners

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

Relevance: Contract 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

- **New contract incorporates new analyses:**
  - **Future Tech 2020 & 2025 Analysis**
    - 2020 Auto System: based on projected 2020 laboratory demonstrated technologies.
    - 2025 (High Innovation) Auto System: based on projected 2025 technology advances that are expected to be achievable from a well-funded, focused, and successful program.
  - **Medium & Heavy Duty Fuel Cell Truck Analysis**
  - **Validation Study (Mirai fuel cell system)**
- **Bus updates in Year 3 and 5 (not annually)**

Relevance

Overall Project Objectives:

- Project current (2017) 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 2020 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 2016 AMR:

- Overall cost reduction from \$53 to \$45/kW$_{net}$ for 80 kW LDV System
- 2020 future system projection: \$42/kW$_{net}$
- 2025 future system projection: \$36/kW$_{net}$

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

What is DFMA®?

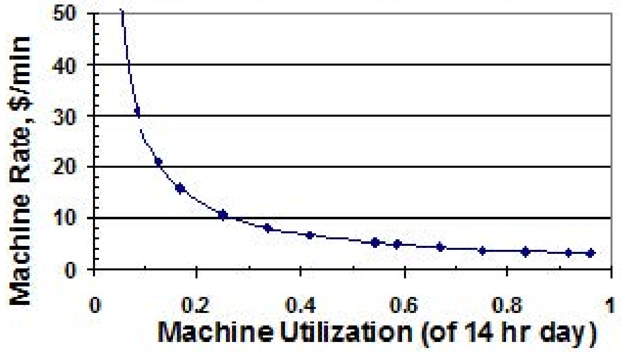
- DFMA® = Design for Manufacture & Assembly = Process based cost estimation methodology
  - Registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Company (Ford) design/costing method for the past 20+ years
- SA practices are a blend of: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

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

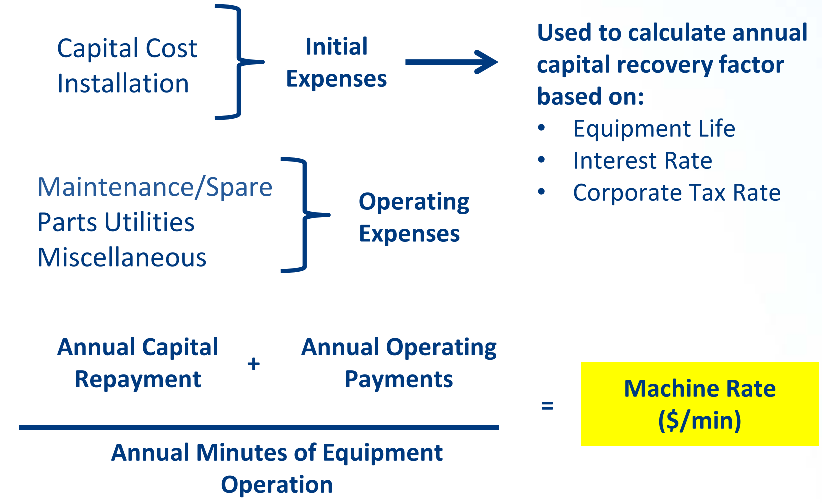
Manufacturing Cost Factors:

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

Methodology reflects cost of under-utilization:



Methodology Reflects Cost of Under-utilization:



Used to calculate annual capital recovery factor based on:

- Equipment Life
- Interest Rate
- Corporate Tax Rate

Approach:

Topics Examined Since 2016 AMR

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

Changes since 2016 AMR that Affect Baseline 2017/2020/2025 Automotive System

- **Catalyst Performance:** Switch from d-PtNi/C to PtCo/HSC-e (based on GM performance)
- **Membrane Fabrication Process:** Gore Direct-Coat process for applying ionomer/ePTFE
- **Bipolar Plate Forming:** Updated prog. stamping parameters based on 2017 industry input
- **Bipolar Plate Coating:** TreadStone DOTS-R and TreadStone TIOX lower cost coating
- **H_2 and Air Exhaust Mixer:** Added component to FC stack exhaust lines

2016/2017 Side Studies for Automotive System (not affecting baseline)

- **MEA Fabrication:** Re-Evaluated Gore Direct-Coat (3-layer) MEA (previously done in 2013)
- **Bipolar Plate Forming:** Cell Impact AB high-velocity adiabatic forming process
- **Bipolar Plate Coating:** Amorphous carbon on Ti and SS
- **Hydrogen Recirculation System Configurations:** Four different configurations analyzed for cost, weight, and volume (includes DFMA® of Mirai Roots H_2 recirculation blower)

Milestone 1: Validation Study – Continued Work (due in month 9)

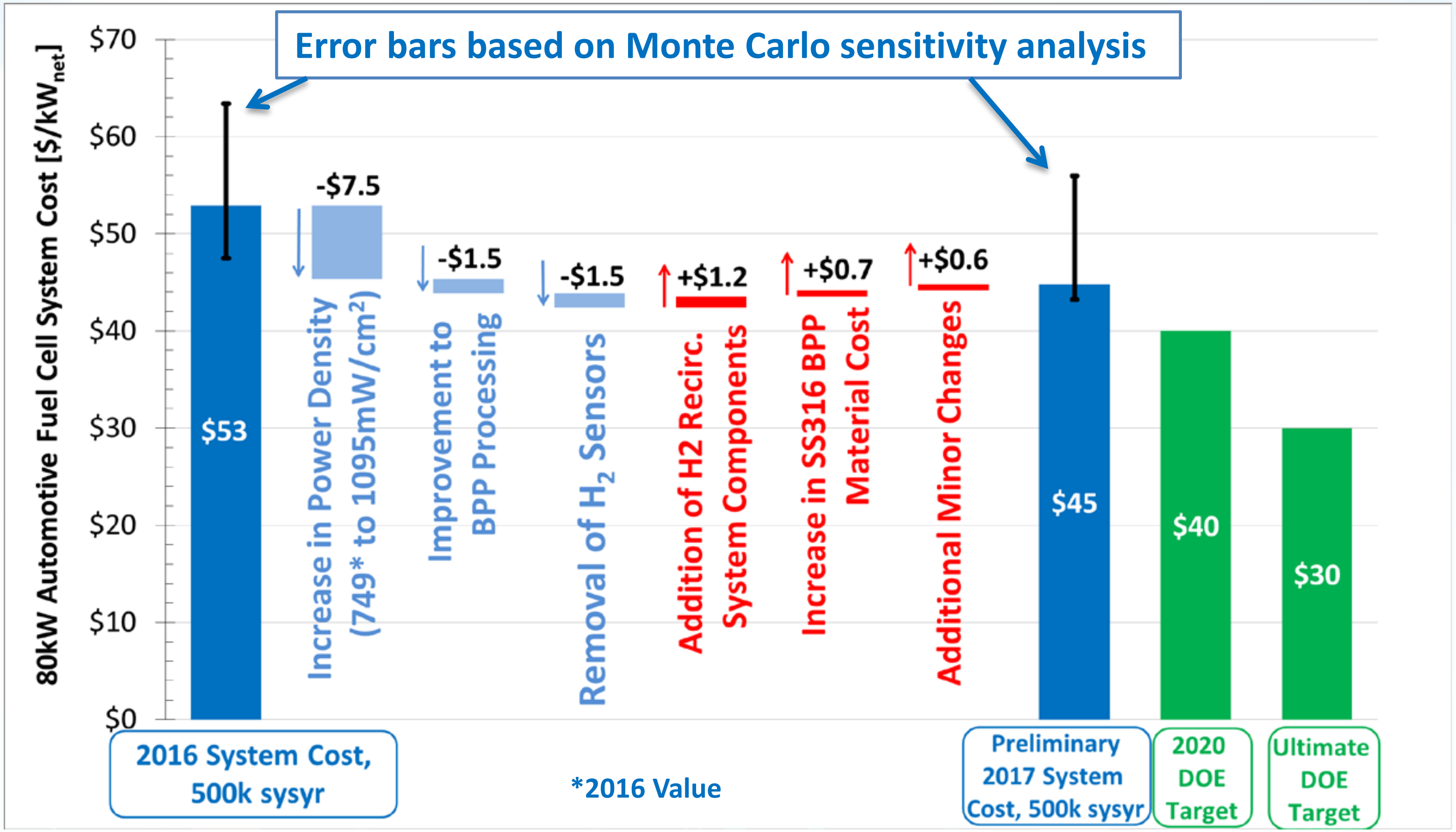
Milestone 2: System Definition – Completed for 2017, 2020, and 2025 Auto Systems

Milestone 3: DFMA® Cost Analysis – Completed for Auto Baseline System for 2017, 2020, and 2025

Milestone 4: Reporting of Cost Results – (due in month 12) => Go/No-Go Decision

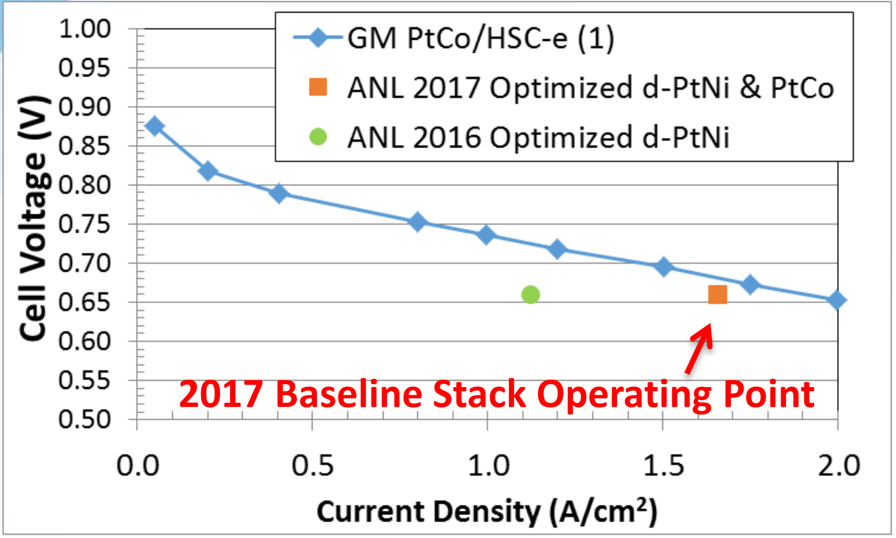
Approach: Annual Updates of Automotive System Cost

Preliminary 2017 Projection Compared to DOE Targets



- ~$7.50/kW$_{net}$ cost reduction from new optimized operating conditions of PtCo/HSC catalyst (majority of improvement from increased power density due to PtCo catalyst high surface area carbon (HSC-e) pore structure)
- Refined H_2 recirculation system to account for purge events
- Preliminary 2017 system cost: ~$45/kW$_{net}$

Accomplishments and Progress:
Comparison of d-PtNi and PtCo Cathode Catalyst



2017 Baseline Stack Operating Point

- **2017 d-PtNi Catalyst**
  - ANL provided optimized conditions for SA
  - FC Tech Team suggestion: No performance loss between single cell & stack (Removal of 10mΩ·cm²)
- **2017 Baseline: PtCo/HSC-e**
  - Data from GM for high surface area carbon PtCo
  - ANL aligned operating conditions, derating power density (pressure & air stoichiometry)

48% power density increase from 2016 to 2017

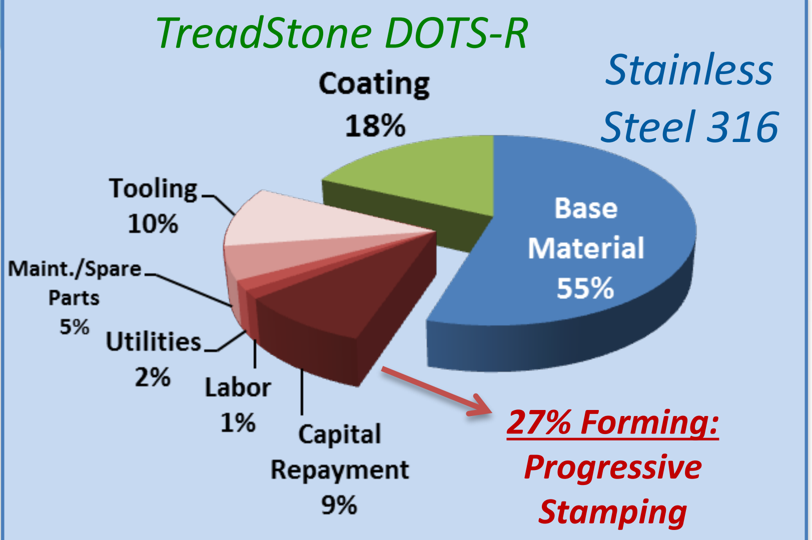
Parameter/Conditions	● d-PtNi (2016)	■ d-PtNi (2017)	◇ PtCo/HSC-e (from GM)	■ PtCo/HSC-e (ANL derating of GM data)
Power Density (mW/cm²)	739	1,095	1,250 →	1,095
Cell Voltage	0.66	0.66	0.66	0.66
Stack Pressure (atm)	2.5 (inlet)	2.5 (inlet)	2.5 (outlet) →	2.5 (inlet)
Temperature (coolant exit)	94°C	94°C	94°C	94°C
Total Pt Loading (mg/cm²)*	0.134	0.125	0.125	0.125
Air Stoichiometry	1.4	1.5	2 →	1.5
System Cost ($/kWnet)	$52.89	$44.80	NA	$44.80

(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/cm² Pt/C for all systems

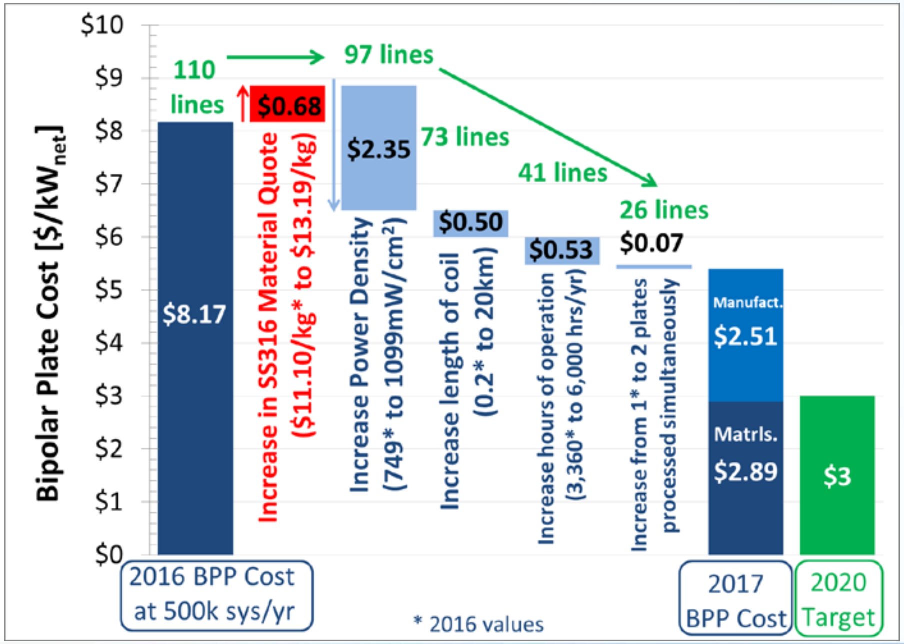
Accomplishments and Progress:

Reconsideration of Bipolar Plate Forming



2017 Total BPP Cost: $5.40/kW
(excluding welding)

- **Presented at DOE BPP Workshop in Feb 2017**
- **Scoped a variety of forming methods:**
  - Progressive stamping (eg. Dana)
  - Hydroforming (eg. Borit, Graebener)
  - High velocity impact forming (eg. Cell Impact)
- **Progressive stamping used in baseline system**
  - 100+ processing lines at 2016 assumptions
  - Reduce to <30 simultaneous lines for 2017**



- **316SS base material costs are higher than the 2020 DOE target $3/kW**
- **Switch to SS304 is only $0.23/kW reduction**
- **3,000 mW/cm² power density is required to meet $3/kW target (assuming current system)****

**See Technical Backup slides for additional information

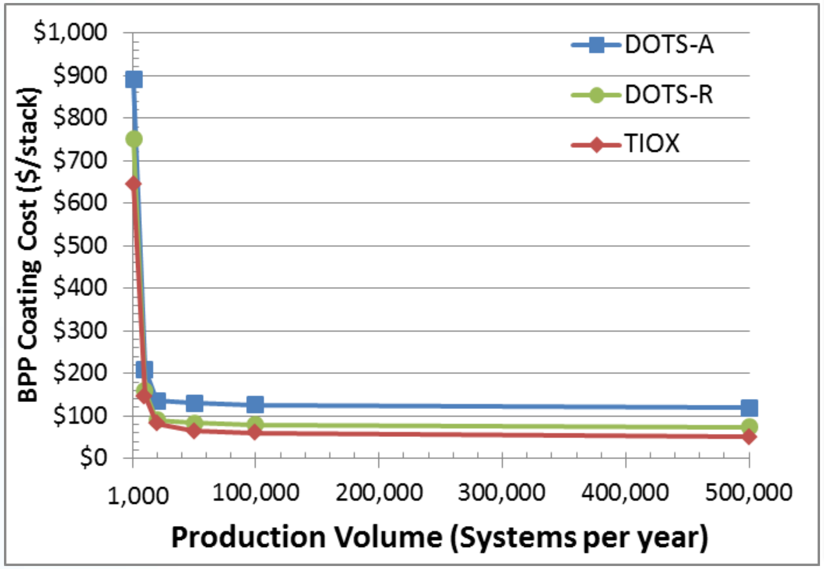
Accomplishments and Progress:

Reconsideration of Bipolar Coating

Four types of coatings investigated since 2016 AMR

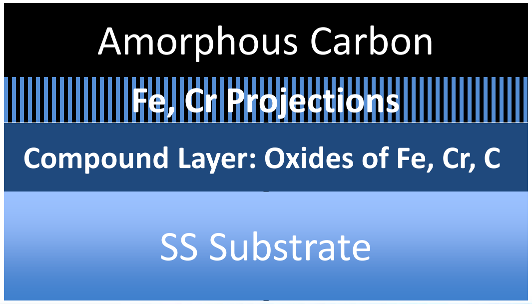
TreadStone Technologies LLC

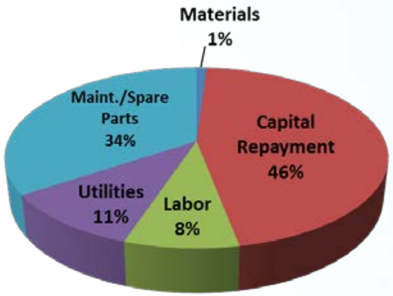
- DOTS-A (Gen 1): 2015 Baseline
- DOTS-R (Gen 2): 2016 & 2017 Baseline, alternative materials, fewer processing steps, and lower cost than DOTS-A
- TIOX: 2020 Future analysis, precious metal-free coating using PVD, lowest cost of all TreadStone coatings
- Coating details proprietary



Amorphous Carbon Coating on Ti and SS316

- Coating used on Toyota Mirai Ti BPPs
- Modeled at low volume as plasma enhanced chemical vapor deposition (PECVD)
  - Pyridine and nitrogen precursor with argon carrier gas
  - $1.2M Tribo 960 Mustang Vacuum Deposition System
  - Coating layer thickness: 0.5-2 µm
  - Batch Cycle Time: ~1.5 hrs for ~200 part batch
  - Effective Cycle time: ~25 sec/plate
- Coating on Ti: $1.60/plate (at 1k sys/yr) =>$1,150/stack
- Coating onto stainless steel requires compound layer and projections into amorphous carbon
- No significant difference in coating cost for Ti or SS



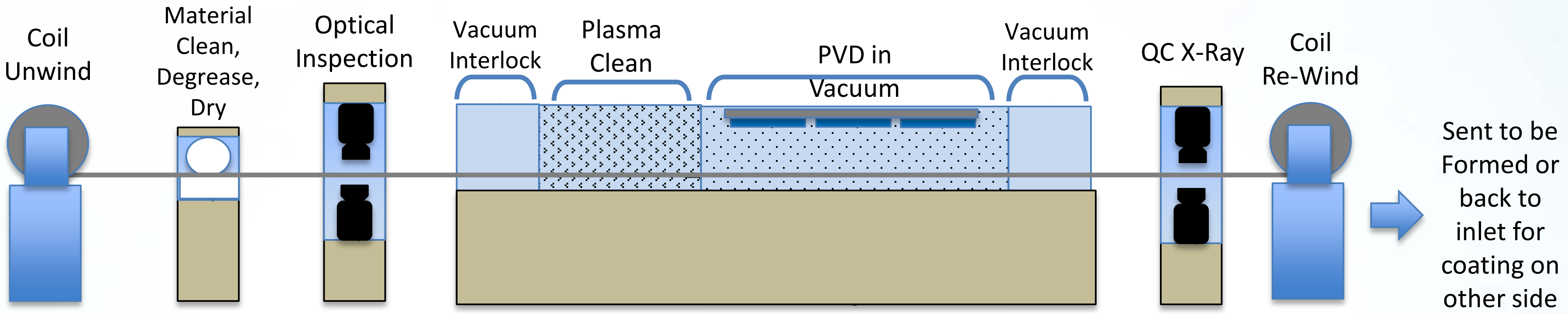


Accomplishments and Progress:

Reconsideration of Bipolar Coating (continued)

Pre-Forming Coating (Coat before Forming)

- Modeled after Sandvik process (open-source, patent info)
- Inline PVD coating process on flat metal coil (coats one side at a time)
- "Graphite-Like Carbon (GLC)": metal interlayer and graphite-like top coat
- Simpler than coating after forming: **less handling of plates**
- Preliminary costs very similar to baseline (TreadStone) coating system



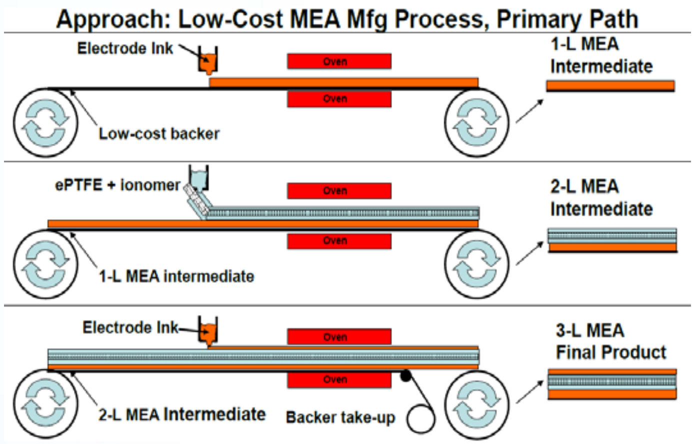
PVD Sputtering Target Material Investigation

- For low-cost target materials (such as Ti), raw materials are only small portion of target cost (3-12%): target preparation cost dominates
- Low target material utilization is typical (**40-60%**)
  - Unused material typically not recycled (only precious metals are recycled)

Accomplishments and Progress:

Re-Evaluation of Gore Direct-Coat MEA

- Updated SA 2013 analysis
- Additional steps revealed in Gore's 2016 Patent Application: US 233532 A1
  - Membrane application to anode in two coating/drying steps: 1st protective ionomer layer, 2nd ionomer layer with ePTFE
- Minimization of processing cost by optimal sizing of oven length and operating line speed (limitation of 20m/min due to membrane total drying time ~5min)
- Adjustment of PFSA ionomer cost to account for lower equivalent weight
- Bottom line cost did not change significantly between 2013 & 2016 estimate
  - $91/m^2 in 2013 compared to $92/m^2 in 2016



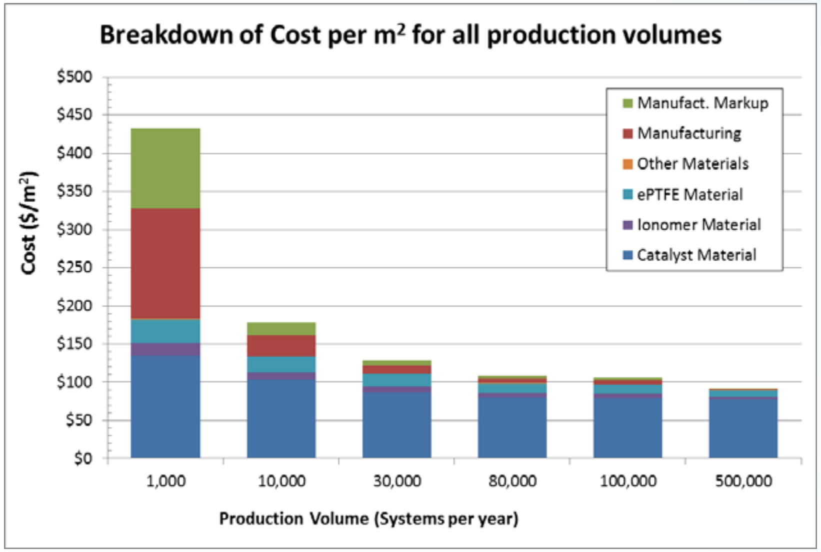
Station 1: Anode Application

Station 2: Membrane Applied to Anode (two separately dried ionomer layers)

Station 3: Cathode Application

Source: 2012 Gore AMR Presentation "Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies Engineered for Rapid Conditioning", F.C. Busby, W.L. Gore & Assoc., 16 May 2012.

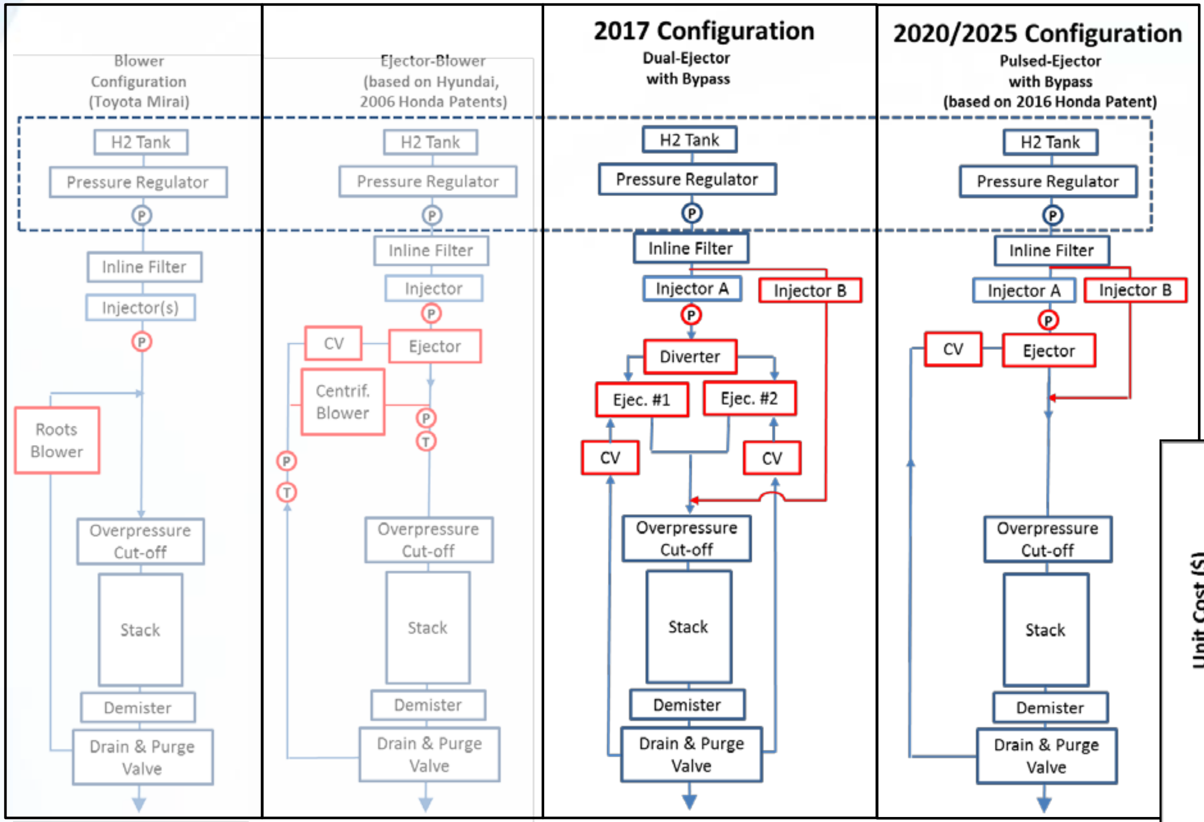
2016 Gore Direct-Coat MEA Cost Estimate



Accomplishments and Progress:

Hydrogen Recirculation Configuration Study

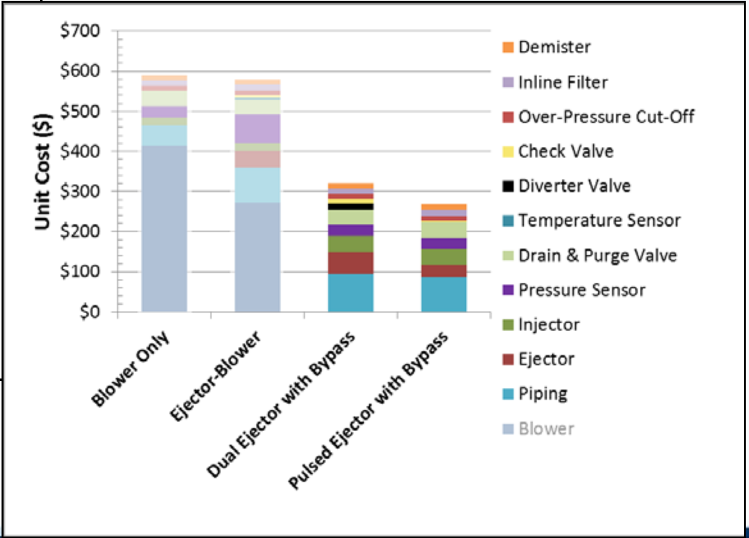
- Coordinated study with ANL to define configurations, cost, and performance
- 4 standard configurations reviewed: 2 selected for 2017/2020/2025 modeling
- Key performance metric is H_2 recirculation at part-power: ANL is modeling performance
- Pulsed-ejector system perf. is expected to meet requirements based on ANL CFD modeling



Components within dashed box are included in H2 Storage Subsystem

CV= Check Valve
P = Pressure Transducer
T = Temp Transducer

- Piping (~3m) and fitting (10+) costs can be significant
- Injector bypass added for required H_2 purge mass flow
- Pulsed Ejector is lowest cost, volume, & weight out of the 4 configurations studied



Accomplishments and Progress:

DFMA® Cost Analysis of Large H_2 Recirculation Blower

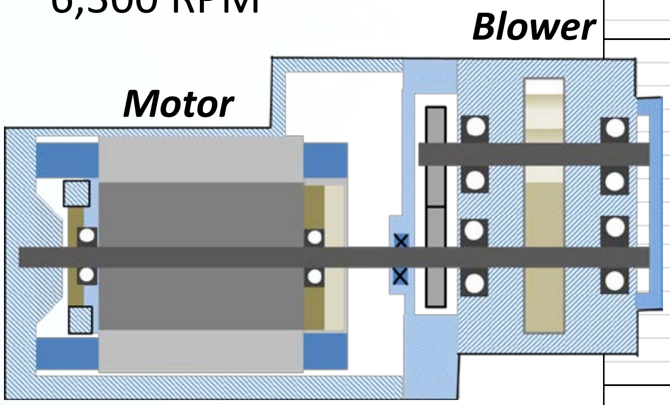
- SA cost-modeled the Toyota Mirai blower: Toyota Industries Corporation (Based on Patent: 2011 US 7,980,830 B2)
- Simplified cost equation provided to ANL for study on performance/cost tradeoff of various H_2 recirculation systems (not used in SA's 2017 baseline system)

Blower Cost (@ 500k units/yr) = $88.26 * P + 4.65 * V^{0.5} - 0.02 * V + 229.08$

P = electrical power into motor (kWe)
V = flow rate out of blower (L/min)

<u>Assumed Blower Sizing</u>

2-lobe Roots Blower
500-700 L/min (outlet)
430W (shaft power out)
6,300 RPM



Drawing of motor and blower assembly cross-sectional view (inspired by Toyota patent)

Blower Cost per System								
Annual Production Rate	units/yr		1,000	10,000	20,000	50,000	100,000	500,000
Component Costs per System								
Blower Rotor	$/sys	Laser Cut SS316 2-Lobe Straight Roots	$9	$6	$6	$6	$4	$6
Blower Housing	$/sys	SS316 Investment Casting	$65	$50	$49	$48	$48	$48
Blower End Plate	$/sys	SS316 Machined Plate	$9	$6	$6	$6	$6	$6
Gear Housing	$/sys	Aluminum Investment Casting	$33	$19	$18	$17	$17	$16
Gears	$/sys	Laser Cut SS316 Gears	$18	$18	$17	$9	$9	$8
Gear Plate	$/sys	SS316 Machined Plate	$5	$4	$3	$3	$3	$3
Driven Shaft	$/sys	High Carbon Steel Machined Rod	$17	$4	$3	$3	$3	$3
Large Bearings	$/sys	Steel Ball Bearings	$9	$9	$9	$9	$9	$9
Screws	$/sys	1/4-20 socket head	$5	$5	$5	$5	$5	$5
O-Ring Seals	$/sys	1x motor housing, 2x gear housing, and 1	$16	$16	$16	$16	$16	$8
Motor Housing	$/sys	Aluminum Investment Casting	$62	$31	$28	$28	$27	$25
Small Bearings	$/sys	Steel Ball Bearings	$6	$6	$6	$6	$6	$6
Motor Drive Shaft	$/sys	High Carbon Steel Machined Rod	$19	$7	$7	$6	$6	$5
Stator Lamination Stamping	$/sys	Electrical Steel (high silicon content)	$10	$4	$4	$4	$3	$3
Stator Lamination Stacking and Laser Weld	$/sys		$2	$2	$2	$2	$1	$1
Stator Coil Winding	$/sys	Copper coil	$3	$3	$3	$3	$3	$3
Motor Dip Coating	$/sys	Epoxy Polyester Resin Dip Coating	$3	$3	$3	$2	$2	$1
Motor Heat Treat	$/sys	Heat for 3hrs at 350F	$5	$3	$3	$3	$3	$3
Motor Rotor Core	$/sys	Electrical Steel (high silicon content)	$10	$4	$4	$3	$3	$3
Motor Rotor	$/sys	Copper Die Casting	$30	$12	$10	$10	$10	$9
Brass Weight	$/sys	Machined Brass Plate	$7	$7	$7	$7	$7	$4
Hammer	$/sys	Sandcast SS316 Plate	$6	$6	$6	$6	$6	$6
Collision Member	$/sys	Machined SS316 Plate	$4	$4	$3	$3	$3	$3
Motor and Pump Assembly	$/sys	~7min Assembly	$14	$11	$10	$10	$10	$10
Motor Testing	$/sys	~30 min Testing	$40	$25	$13	$6	$4	$2
Motor Controller Cover	$/sys	Aluminum Plate	$5	$5	$5	$5	$5	$5
Motor Controller	$/sys	Previous DFMA model for motor controller adjusted for rpm and power	$212	$178	$178	$173	$166	$160
Contingency (5% of total)	$/sys		$31	$22	$21	$20	$19	$18
Total Blower Manufacturing and Material Cost	$/sys		$655	$470	$446	$419	$405	$380
Markup on Blower and Motor (23%)	$/sys		$104	$68	$63	$58	$56	$52
Total Blower Unit Cost	$/sys		$759	$539	$509	$477	$461	$431
Total Blower Cost (Net)	$/kWnet		$9.48	$5.88	$5.58	$5.24	$5.06	$5.39
Total Blower Cost (Gross)	$/kWgross		$6.67	$4.14	$3.93	$3.69	$3.56	$3.80

Accomplishments and Progress:

2017 Current System and 2020/2025 Future Projections

	2017 Auto System	2020 Auto System	2025 Auto System (High Innovation)
Stack Power Density @ Rated Power ($mW/cm^2_{active\ area}$)	1,095 PtCo/HSC-e after derating to match ANL-optimized stack operating conditions	1,165 Based on PtCo/HSC-f after stack derating	1,500 Consistent with DOE 2020 target of 1,000 at $150kPa_{abs}$
Total Pt loading ($mgPt/cm^2_{total\ area}$)	0.125	0.125 DOE 2020 target	0.088 Reasonable improv. over 2020 target
Pt Group Metal (PGM) Total Content (g/kW_{gross})[1]	0.114	0.107	0.065
Net Power (kW_{net})	80	80	80
Gross Power (kW_{gross})	87.9	87.9	87.9
Cell Voltage (V)	0.66	0.66	0.66
Operating Pressure (atm)	2.5	2.5	2.5
Stack Temp. (Coolant Exit Temp) (°C)	94	94	94
Air Stoichiometry	1.5	1.5	1.5
Q/ΔT (kW_{th}/°C)	1.45	1.45	1.45
Active Cells	377	377	377

2020 and 2025 Projected System Parameters have been vetted with Fuel Cell Technical Team

[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.

Accomplishments and Progress:

2017 Current System and 2020/2025 Future Projections (continued)

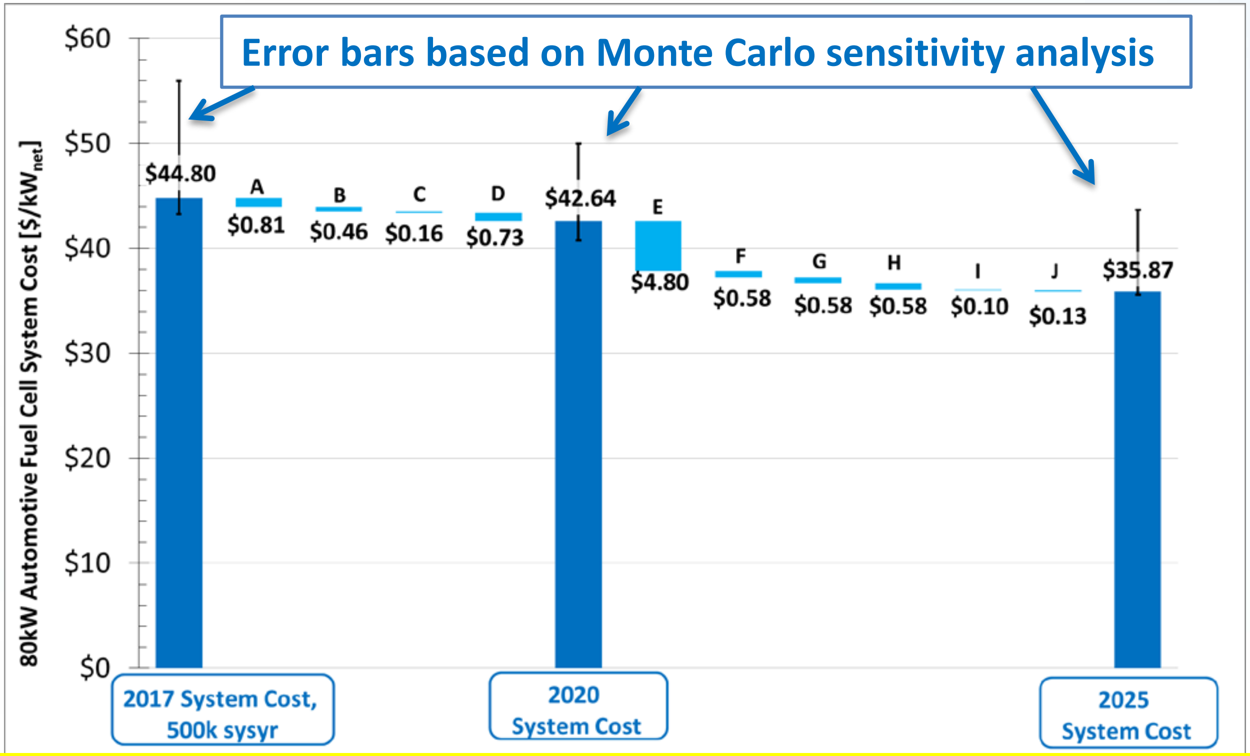
	2017 Auto System	2020 Auto System	2025 Auto System (High Innovation)
Active to Total Area Ratio	0.625	0.625	0.65
Membrane Material & Support	14 µm Nafion (850EW) supported on ePTFE	10 µm Nafion (850EW) supported on ePTFE	High performance membrane (cost based on 10 µm Nafion) on Low-Cost Support (Dimensionally Stable Membrane (DSM)®)
Bipolar Plates and Coating	SS 316 with PVD Coating (modeled as TreadStone DOTS-R)	SS 304 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 304 cost
CEM Efficiencies	Comp: 71% Expand: 73%, Motor/Control. 80%	Comp: 71% Expand: 73%, Motor/Control. 80%	Comp: 71% Expand: 73%, Motor/Control. 80%
Anode Recirculation	2 fixed geometry ejectors	Pulse Ejector with bypass	Pulse Ejector with bypass
Catalyst Durability: ECSA loss after 30k cycles (per 2016 MYPP Table P.1 protocol)	50% (catalyst only, does not capture membrane degradation)	40% (based on achievement of DOE 2020 target)	<40% (exceed DOE 2020 target)
Hydrogen Sensors*	0	0	0
Stack Conditioning (hrs)	2	2	1

2020 and 2025 Projected System Parameters have been vetted with Fuel Cell Technical Team

*Removed H_2 sensors from fuel cell system per FCTT recommendation

Accomplishments and Progress:

Waterfall Chart Showing Cost Impact of Changes from 2017 to 2020 and 2025



A: Increase of power density from 1,095 to 1,165mW/cm^2

B: Switched from SS316 to SS304 for BPP base material and switched from TreadStone DOTS Gen 2 to TIOX coating

C: Reduction in membrane thickness from 14 to 10 microns thick

D: Switch from Dual Ejector System to Pulsed Ejector with Bypass for hydrogen recirculation system

E: Increase of power density from 1,165 to 1,500mW/cm^2 and reduced Pt loading from 0.125mg/cm^2 to 0.088mg/cm^2

F: Switched from TreadStone TIOX to no coating on BPPs

G: Switched from ePTFE-supported membrane to Giner DSM-supported membrane

H: Switched to more advanced CEM design

I: Reduced stack conditioning time from 2hrs to 1hr

J: Increased active to total area ratio from 0.625 to 0.65

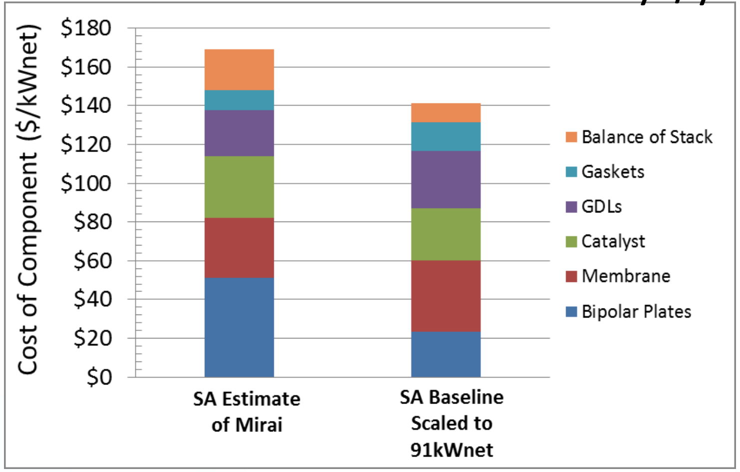
Account for >60% of Cost Reduction

Accomplishments and Progress:

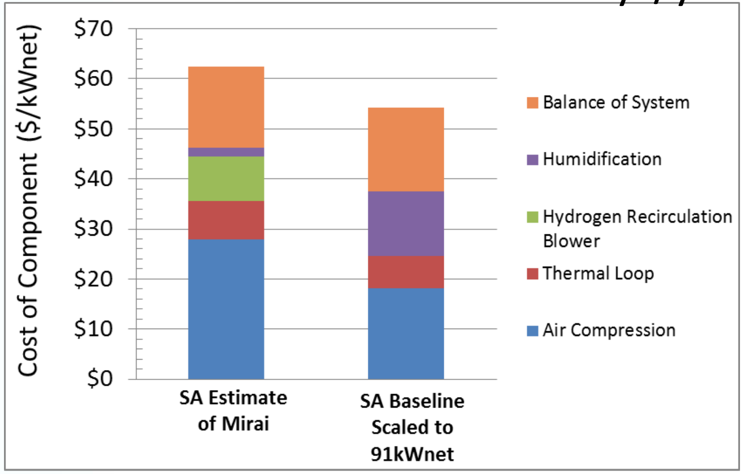
Validation Study (to confirm SA costing methodology)

- Toyota Mirai system under consideration
- SA’s 2017 Mirai fuel cell system estimate: ~\$233/kW$_{net}$ at 1k sys/yr

Breakdown in Stack Cost at 1k sys/yr



Breakdown in BOP Cost at 1k sys/yr



Estimated Mirai Operating Condition	
Stack Power Net/Gross	91 kW/114 kW
Cell Voltage	0.67 V, 370 cells/stack
Current Density	1.9 A/cm^2
Power Density	1,295 mW/cm^2
Stack Pressure	est. <=2.5 atm
Total Pt loading	0.3 mg/cm^2
Peak Cell Temp	est. <86 °C
Total Active Area/system	8.78 m^2
Active to Total Area ratio	0.4
Active/Total plate area	237 cm^2/593 cm^2
Q/ΔT	2.5 kW/°C

Major sources of cost difference with Baseline:

Stack: - BPP material (Titanium vs. SS316)
- Catalyst loading

BOP: - No humidifier
- Large H_2 recirculation blower
- Higher-cost Roots air compressor

Accomplishments and Progress:

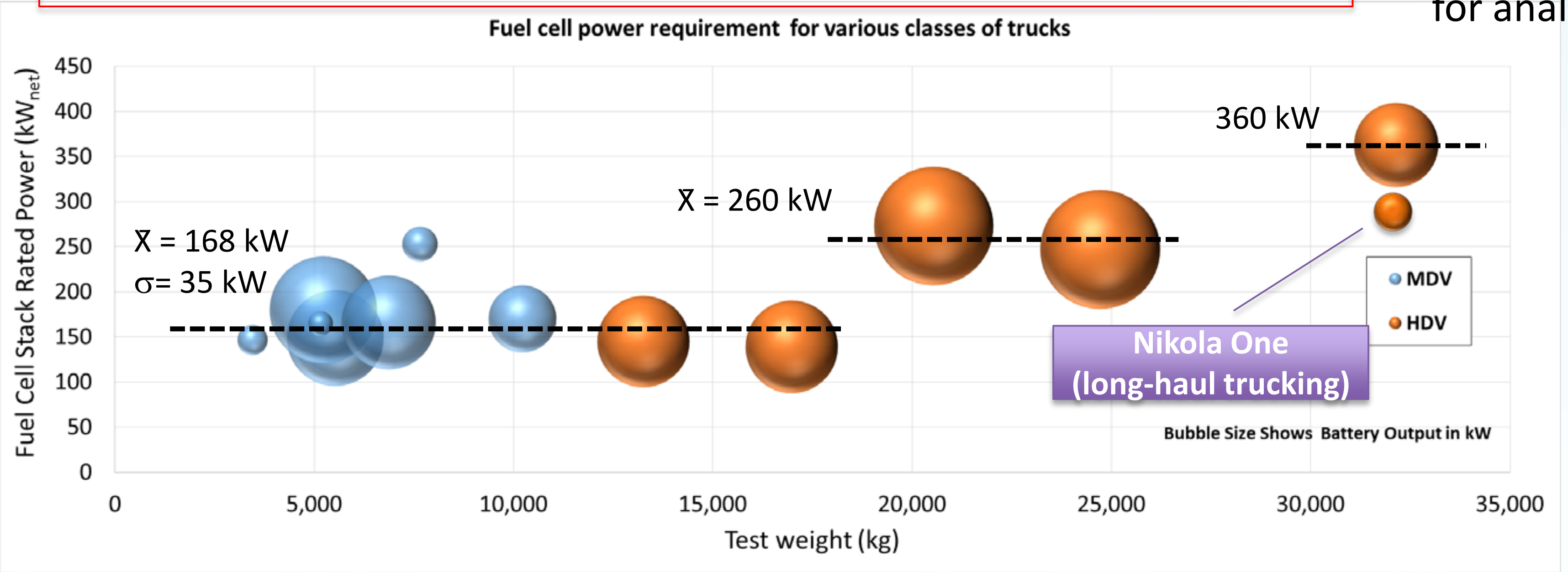
Fuel Cell Truck Scoping Study

- Consideration of fuel cell Medium Duty Vehicle (MDV) and Heavy Duty Vehicle (HDV)
- Objective: Determine system configurations for detailed cost analysis in 2018
- Leverage past ANL studies (Ram Vijayagopal et al): 12 truck applications studied
- Develop system definitions (power level, architecture, level of hybridization)

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



Study Findings:

- Two power levels capture most MDV/HDV applications
- Stacks can be built-up from ~80 kW modules
- Only minor differences between Bus/MDV/HDV operating-conditions & stack designs

Ram Vijayagopal, “Fuel cell electric truck (FCET) component sizing” Annual Merit Review, Washington DC (2016).

Accomplishments and Progress:

Preliminary Analysis Suggests MDV/HDV Similar to FC Bus

	2017 LDV System	2016 Bus System	2017 MDV System	2017 HDV System
Annual Production (fuel cell systems/year)	1,000-500,000	200-1,000	Up to 150k[1]	Up to 250k[1]
Target Stack Durability (hours)	5,000	25,000[2]	25,000[2]/5,000[3]	25,000[2]
Total Pt loading ($mgPt/cm^2_{total\ area}$)	0.125	0.5	0.5	0.5
Pt Group Metal (PGM) Total Content (g/kW_{gross})	0.114	0.719	0.719	0.719
Cell Voltage (V/cell)	0.663	0.659	prelim. 0.659 (subject to time-at-power analysis)	prelim. 0.659 (subject to time-at-power analysis)
Net Power (kW_{net})	80	160	~160	240/360
Gross Power (kW_{gross})	88	TBD	TBD	TBD
Operating Pressure (atm)	2.5	1.9	prelim. 1.9 (to be cost optimized)	prelim. 1.9 (to be cost optimized)
Stack Temp. (Coolant Exit Temp) (°C)	94	72	72[4]	72[4]
Air Stoichiometry	1.5	1.8	1.8	1.8
Q/ΔT (kW_{th}/°C)	1.45	5.4	5.4	5.4

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:

Responses to Previous Year’s Reviewers’ Comments

Reviewer’s Comments	Response to Reviewer’s Comment
Adding a section highlighting areas, components, and processes that can be improved (in a pre-competitive environment) to enhance cost-affordability would be helpful.	1) In a pre-competitive environment, roll-to-roll cell assembly may be an area of interest. Multiple FC developers have commented on the difficulty of managing very thin, expensive repeat units. To reach 500,000 vehicle/year volumes, a roll-to-roll system (similar to batteries) seems the most feasible way to maintain repeatability and reduce time and scrap. See Slide 32. 2) Investigation of alternative BPP materials that can meet the DOE cost target $3/kW. See Slide 8.
It might be good to add details about which balance-of-plant (BOP) costs are driving the overall system cost, and how what type of work at the stack level can bring the BOP costs to less than $\$15/kW_{net}$.	The air compressor drives the bulk of the BOP component costs. At the stack level, a lower operating pressure can significantly lower the air compressor sizing and cost. Additional work on water removal in the anode could help offset costs in the H_2 recirculation system. See Slide 34.

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, particularly XRF for 2017. • Reviews and provides feedback on SA's assumptions for MEA processing and techniques (including CCM acid wash) • Provided feedback on 2020 and 2025 analysis systems and manufacturing processes.
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 pressures, mass flows, CEM efficiencies, and membrane area requirements for optimized system. • Provided feedback and small modeling efforts on 2020 and 2025 analysis systems. • Contributed to H2 recirculation blower sizing and operation • Will provide H2 ejector performance for H_2 recirc. configs. • Provided information on FC Med/Hvy Duty Truck Analysis
2016/2017 DOE Sponsored Collaborators	• Gore participated heavily in the re-evaluation of the Gore Direct-Coat MEA process. A much greater amount of detail has been defined for this type of process because of them.
Vendors/Suppliers	See back-up material for list of ~30 other companies with which we have consulted.

Remaining Barriers and Challenges

Automotive System

- Uncertainty of PFSA ionomer cost: some suggest that ionomer may be ~$500/kg even at high volumes. May require alternative formulation or fabrication process.
- Base material 316SS contributes ~$3/kW$_{net}$ making it difficult to reach DOE's 2020 cost target of $3/kW total BPP (material/forming/coating).
- Presence of ammonia in air feed of FC vehicles presents difficulty in maintaining membrane air humidifier performance.
- Even with advancements projected for 2020 fuel cell system cost, it is not in alignment with DOE's 2020 $40/kW target cost.
- 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).
- Even with ~2sec/plate forming speed, many parallel BPP production lines are needed for 500k systems/year. This presents part uniformity problems.

Validation Study

- Difficulty in finding company who will supply actual system/component cost data to SA to compare against SA projections.

Proposed Future Work

Automotive System

- Investigate alternatives to ePTFE membrane support (i.e. electrospinning)
- Investigate ionomer material process cost (determine uncertainty in cost)
- Cost model amorphous carbon BPP coating for high volume production
- Cost model PtCo cathode catalyst synthesis process
- Investigate advanced roll-to-roll manufacturing for cell assemblies
- Compare H_2 recirculation systems on a cost and performance basis
- Finalize 2020/2025 Analysis by incorporating feedback from Tech Team & AMR
- Conduct cost sensitivity studies on 2017/2020/2025 automotive systems

Medium/Heavy Duty Truck Scoping Study

- Determine variation in system operating conditions and bill of materials
- Have finalized systems reviewed by collaborators (ANL, NREL), DOE, FCTT, and stakeholders

Validation Study

- Determine whether Toyota Mirai system or component(s) can be used for study
- Complete analysis

Complete 2017 Final Report

Technology Transfer Activities

Not applicable for SA’s Cost Analysis

Summary of Findings

- New contract expands analysis to future 2020/2025 auto, bus, med/heavy duty truck fuel cell systems, and Validation Study
- Baseline auto cost results show continued slight annual decline:
    - ~\$55/kW_{net} (2014), \$53/kW_{net} (2015/2016), and \$45/kW_{net} (2017)
- Use of PtCo/HSC-e from GM increases perform. by 48% and reduces cost by \$7.50/kW_{net}
- Bipolar plate base material 316 SS cost alone is the same as the DOE 2020 target of \$3/kW. (~3,000mW/cm^2 power density would be required to reach DOE target.)
- Focused on reduction of BPP stamping simultaneous prod. lines (110 to <30).
- Multiple BPP coating approaches examined:
    - Each generation of TreadStone BPP coating shows lower cost (TIOX is <\$1/kW)
    - Sandvik pre-forming coating provides advantage of reduced parts handling
- Pulsed ejector H_2 recirc. config. lowest cost, vol., & weight out of 4 configs. modeled.
- Projected cost for 2020 does not meet DOE Target of \$40/kW (but is close).
- >60% of 2020 & 2025 cost reductions due to increased mW/cm^2 and lower mgPt/cm^2.
- Three FC power levels (168kW, 260kW, & 360kW) capture most MDV/HDV applications.
- Toyota Mirai fuel cell system preliminarily selected as Validation Study system
    - SA DFMA® system cost projection: ~\$233/kW_{net} (at 1k sys/yr)

Project Summary

- **Overview**
  - Annually updated cost analysis of automobile, bus, and truck fuel cell systems
  - Exploring subsystem alternative configurations and benchmark cost where possible
  - In year 1 of 5 year transportation 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
- **Approach**
  - Process-based cost analysis methodologies (e.g. DFMA®)
- **Accomplishments**
  - 2016 Automobile & Bus analysis completed (report available)
  - Automotive 2017, 2020, 2025, FC truck, and validation study analysis underway
  - Components newly analyzed or revisited:
    - Bipolar plate stamping, TreadStone DOTS-R and TIOX BPP coating, Amorphous Carbon BPP Coating, Sandvik pre-forming BPP coating
    - Four H_2 recirculation systems
    - Gore Direct-Coat MEA
- **Collaborations**
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
- **Future Work**
  - Complete studies and final report.

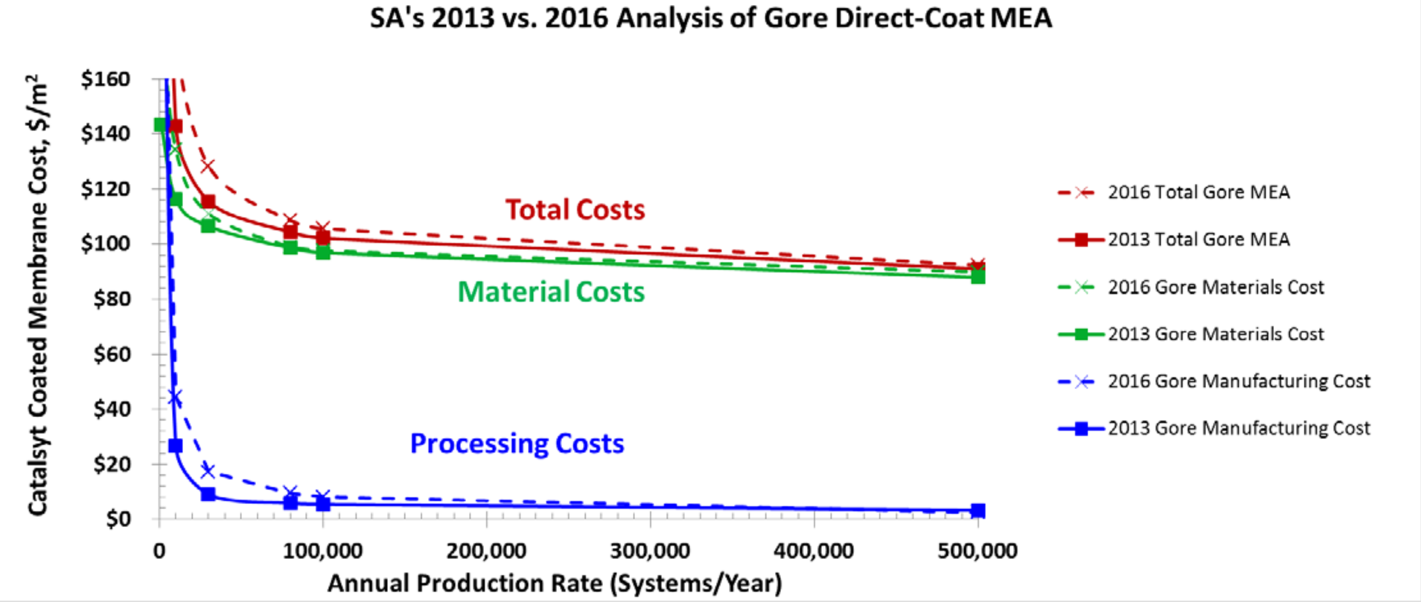
Thank you!

Questions?

Technical Backup Slides

Accomplishments and Progress:

Re-Evaluation of Gore Direct-Coat MEA



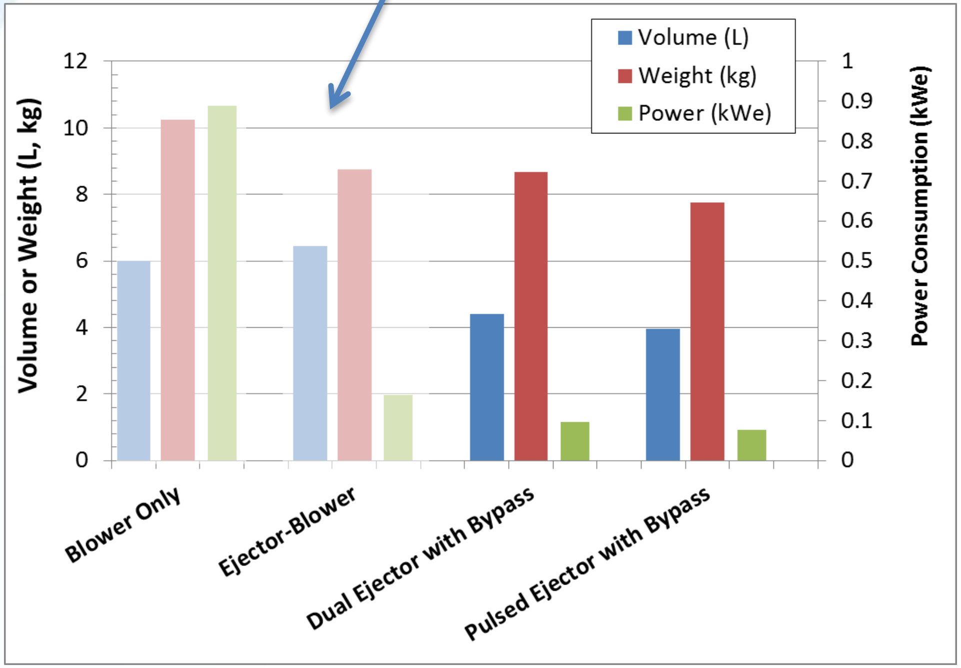
Differing Parameters	2013 Analysis	2016 Analysis	Effect on 2016 Cost
Membrane Area per Stack	12.93m^2	11.71m^2	Material Cost ↑ Processing Cost ↑
Membrane Thickness	15 microns	10 microns	Material Cost ↓
Ionomer EW & Cost (500k sys/yr)	EW Not specified (\$85/kg)	750EW (\$120/kg)	Material Cost ↑
Catalyst Processing Cost	Not Accounted For	\$1.20/m^2	Material Cost ↑
Capital Cost of Equipment	\$5M	\$20M	Processing Cost ↑
Line Speed	10m/min	19-25m/min	Processing Cost ↓
Overall Cost at 500k sys/yr	\$91.07/m^2	\$92.35/m^2	

Although there are many parameters that changed between 2013 and 2016 analyses, the overall cost did not change more than 2% at 500k sys/yr. The small increase for 2016 reflects more accurate ionomer and capital costs, and reflects a better representation of the Gore Direct-Coat MEA process based on their patent application.

Hydrogen Recirculation Configuration Study

(Preliminary Results)

Blower-Only and Ejector-Blower configurations are not used in the current baseline system cost models



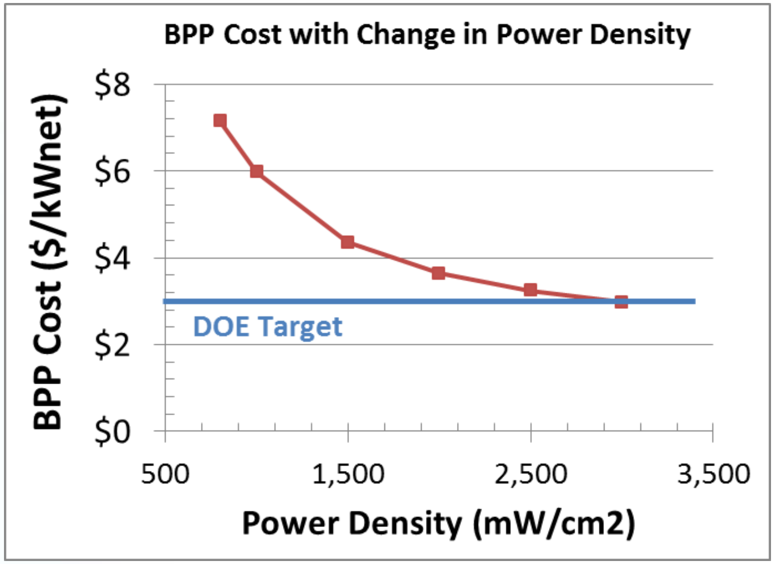
Dual Ejector configuration contains more components equating to longer piping, more bends/fittings, and higher weight.

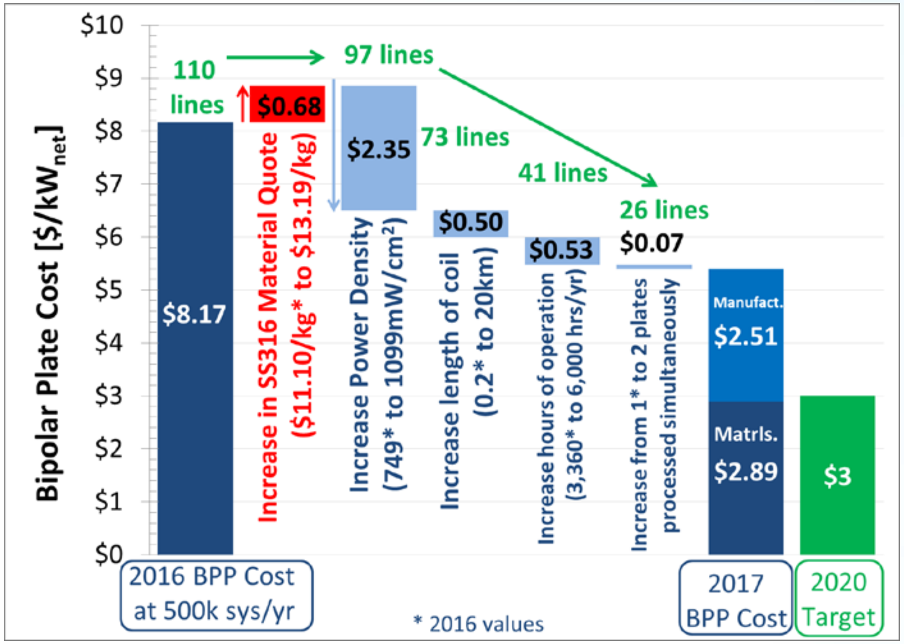
	Cost ($/system)								
Annual Production	1,000	10,000	20,000	50,000	100,000	500,000	Volume (L)	Weight (kg)	Power (kW)
Blower Only	$1,176	$802	$745	$675	$643	$590	6.00	10.24	0.89
Blower	$740	$521	$492	$460	$445	$415	3.6	6.0	0.84
Injector	$60	$36	$30	$27	$22	$20	0.16	0.6	0.018
Pressure Sensor	$57	$44	$40	$36	$33	$27	0.03	0.2	0.01
Over-Pressure Cut-Off	$25	$22	$20	$15	$14	$12	0.01	0.1	0.01
Demister	$132	$33	$26	$17	$15	$13	0.57	0.1	0.00
Drain & Purge Valve	$80	$70	$64	$48	$45	$38	0.6	0.1	0.01
Inline Filter	$15	$15	$15	$15	$15	$15	0.9	1.8	0.00
Piping	$68	$62	$60	$56	$54	$50	0.2	1.4	0.00
Dual Ejector with Bypass	$675	$466	$425	$375	$349	$321	4.4	8.7	0.1
Low Flow Fixed Ejector	$44	$31	$29	$26	$25	$24	0.3	0.5	0.0
High Flow Fixed Ejector	$51	$38	$36	$33	$31	$31	1.2	1.4	0.0
Diverter Valve	$16	$16	$16	$16	$16	$16	0.1	0.2	0.01
Injector A	$60	$36	$30	$27	$22	$20	0.16	0.6	0.018
Injector B Bypass	$60	$36	$30	$27	$22	$20	0.16	0.6	0.018
Pressure Sensor	$57	$44	$40	$36	$33	$27	0.03	0.2	0.01
Check Valve (1)	$5	$5	$5	$5	$5	$5	0.03	0.2	0.01
Check Valve (2)	$5	$5	$5	$5	$5	$5	0.03	0.2	0.01
Over-Pressure Cut-Off	$25	$22	$20	$15	$14	$12	0.01	0.1	0.01
Demister	$132	$33	$26	$17	$15	$13	0.57	0.1	0.00
Drain & Purge Valve	$80	$70	$64	$48	$45	$38	0.6	0.1	0.01
Inline Filter	$15	$15	$15	$15	$15	$15	0.9	1.8	0.00
Piping	$127	$115	$112	$106	$101	$95	0.3	2.7	0.00
Ejector-Blower	$986	$748	$704	$647	$619	$579	6.45	8.749	0.2
Variable Area Ejector	$71	$52	$48	$44	$42	$41	1.2	1.4	0.0
Blower	$272	$272	$272	$272	$272	$272	2.8	1.95	0.065
Injector	$60	$36	$30	$27	$22	$20	0.16	0.6	0.018
Pressure Sensor (1)	$50	$38	$35	$31	$29	$24	0.03	0.2	0.01
Pressure Sensor (2)	$50	$38	$35	$31	$29	$24	0.03	0.2	0.01
Pressure Sensor (3)	$50	$38	$35	$31	$29	$24	0.03	0.2	0.01
Temperature Sensor (1)	$30	$11	$9	$6	$4	$2	0.02	0.2	0.01
Temperature Sensor (2)	$30	$11	$9	$6	$4	$2	0.02	0.2	0.01
Check Valve	$5	$5	$5	$5	$5	$5	0.03	0.2	0.01
Over-Pressure Cut-Off	$25	$22	$20	$15	$14	$12	0.01	0.1	0.01
Demister	$132	$33	$26	$17	$15	$13	0.57	0.1	0.00
Drain & Purge Valve	$80	$70	$64	$48	$45	$38	0.6	0.1	0.01
Inline Filter	$15	$15	$15	$15	$15	$15	0.9	1.8	0.00
Piping	$117	$106	$102	$97	$93	$87	0.108	1.4	0.00
Pulsed Ejector with Bypass	$600	$405	$366	$319	$295	$267	4.0	7.7	0.1
Injector (A)	$60	$36	$30	$27	$22	$20	0.16	0.6	0.018
Injector (B) (bypass)	$60	$36	$30	$27	$22	$20	0.16	0.6	0.018
Fixed Ejector	$51	$38	$36	$33	$31	$31	1.2	1.4	0.0
Pressure Sensor	$57	$44	$40	$36	$33	$27	0.03	0.2	0.01
Check Valve	$5	$5	$5	$5	$5	$5	0.03	0.2	0.01
Over-Pressure Cut-Off	$25	$22	$20	$15	$14	$12	0.01	0.1	0.01
Demister	$132	$33	$26	$17	$15	$13	0.57	0.1	0.00
Drain & Purge Valve	$80	$70	$64	$48	$45	$38	0.6	0.1	0.01
Inline Filter	$15	$15	$15	$15	$15	$15	0.9	1.8	0.00
Piping	$116	$106	$102	$97	$92	$87	0.3	2.7	0.00

Reconsideration of Bipolar Plate Forming

- **Progressive stamping used in baseline system**
  - 100+ processing lines at 2016 assumptions
  - Reduce to <30 simultaneous lines for 2017
    - Increase in length of coil reduces the total number of roll changes (change-out time is 15 minutes)
    - 2016 Value: 3,360 hrs/yr: 2x 7hr shifts, 240 days/year
    - 2017 Value: 6,000 hrs/yr: 3x 8hr shifts, 250 days/year

- ➢ 3,000mW/cm² power density required to meet $3/kW (assuming current system)





In Response to Review Comment:

Adding a section highlighting areas, components, and processes that can be improved (in a pre-competitive environment) to enhance cost-affordability would be helpful.

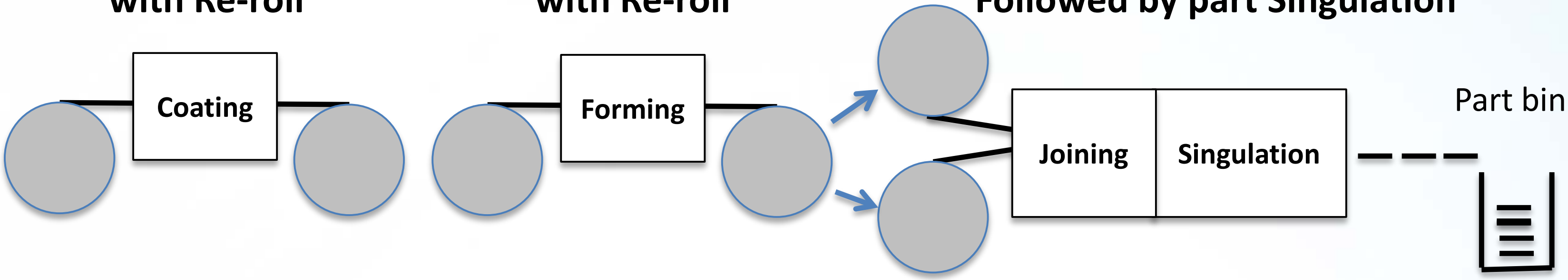
Ideal BPP Fabrication (inspired by Nissan concept)

Option #1:

Coating from Coil with Re-roll

Forming from Coil with Re-roll

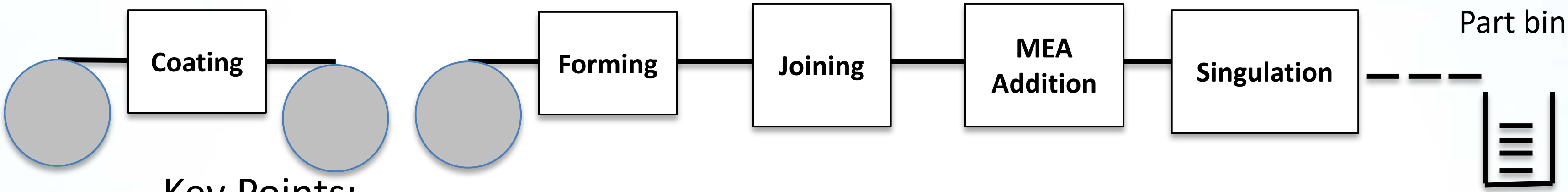
Joining from Coil Followed by part Singulation



Option #2:

Coating from Coil with Re-roll

Forming/Joining/MEA-Addition/Sing. All on Continuous Line



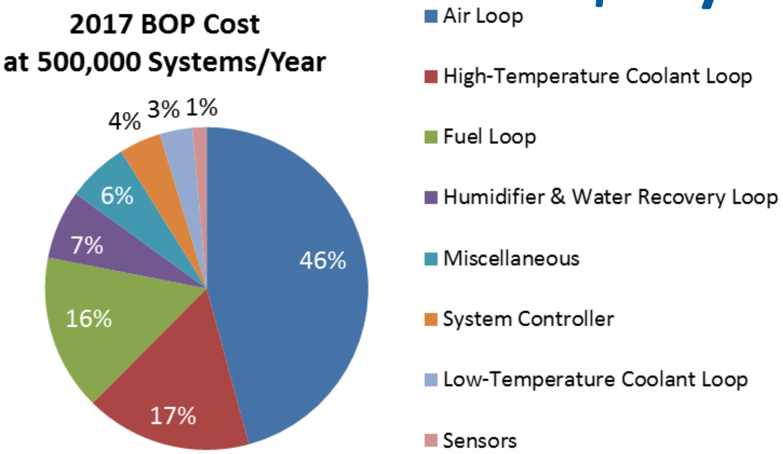
Key Points:

1) Delay singulation as long as possible.
2) Re-roll of formed plates would be an enabling technology.
3) Flow-field formation on the MEA would be an enabling technology.
4) R2R creation of a unitized cell (BPP plus MEA) would be an enabling technology.
5) Numerous configurations are possible.

In Response to Review Comment:

"It might be good to add details about which balance-of-plant (BOP) costs are driving the overall system cost, and how what type of work at the stack level can bring the BOP costs to less than \$15/kW_{net}."

Very Difficult to Achieve BOP < \$15/kWnet



\$24.62/kWnet
(at 2.5 atm stack pressure)

\$21.19/kWnet at 1.5 atm stack pressure (w/out expander)

\$20.27/kWnet with alternative water removal (H_2 pulse ejector w/out bypass for H_2 purge)

\$19.86/kWnet with higher temperature stack (94°C to 110°C) (Reduced high temp coolant loop)

\$19.38/kWnet with stack operation in order to combine LT and HT coolant loops

\$17.61/kWnet with alternative stack humidification (removal of air humidifier)

\$15.75/kWnet at 1 atm stack pressure (smaller air compressor)

Very difficult to reach <\$15/kW for BOP by only making changes to stack operation & design.