Overview

Timeline
- Project Start Date: 9/30/16
- Project End Date: 9/30/21
- % complete: 45% of five year project (in Year 3 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
  - ~$685,000 (through Feb. 2019, including Labs)
- Total DOE Project Value
  - $1.25M (over 5 years, including Labs)
  - 0% Cost share

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

Overall Project Objectives:

- Project current (2019) and future cost (2025) of automotive, bus, & truck fuel cell systems at high manufacturing rates.
- Project impact of technology improvements on system cost.
- Identify low cost pathways to achieve the
  - DOE 2025 goal of $40/kW_{net} (automotive) at 500,000 systems per year
  - DOE Interim goal of $80/kW_{net} (MDV/HDV) at 100,000 systems per year
- Benchmark against production vehicle power systems
- Identify fuel cell system cost drivers to facilitate Fuel Cell Technologies Office programmatic decisions.

Impact since 2018 analysis final results:

- 2019 current system decreases $3/kW_{net} for 170 kW MDV System
- 2025 future MDV system cost decreases to < $75/kW_{net}
  - Reaches DOE Interim MDV cost target but not Ultimate cost target $60/kW
## Relevance: Timeline of Analyses

<table>
<thead>
<tr>
<th>Year</th>
<th>Project Year</th>
<th>Technology</th>
<th>Proposed Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Med/Heavy Duty Truck</td>
<td>Scoping Study</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LDV System or Stack Component</td>
<td>Validation Study</td>
</tr>
<tr>
<td>2018</td>
<td>2</td>
<td>LDV</td>
<td>Current (2018), 2020, 2025</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MD/HD Truck #1</td>
<td>Current (2018), 2020, 2025</td>
</tr>
<tr>
<td>2019</td>
<td>3</td>
<td>LDV HDV Truck #1</td>
<td>Current (2019), 2020, 2025</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Buses MDV Truck #2</td>
<td>Current (2019), 2020, 2025</td>
</tr>
<tr>
<td>2020</td>
<td>4</td>
<td>LDV</td>
<td>Current (2020), 2025</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MD/HD Truck System #2 or #3</td>
<td>Current (2020), 2025</td>
</tr>
<tr>
<td>2021</td>
<td>5</td>
<td>LDV</td>
<td>Current (2021), 2025</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Update to Buses &amp; Trucks as needed</td>
<td>Current (2021), 2025</td>
</tr>
</tbody>
</table>

### Automotive LDV Cases

**New Since 2018: All values in 2016$**

- As recommended by DOE, the LDV cases are deferred until 2020 for two reasons.
  - The time period for advancement in technology often takes longer than a year and reporting a small cost change is not of major impact or usefulness to the fuel cell community.
  - Time & resources are better spent on MDV and HDV systems as they are of immediate interest to DOE.

### 2019 Project Analyses:

- Medium & Heavy Duty Fuel Cell Truck Analysis
- Current (2019) and Future Tech (2025) Analysis – 2020 year analysis removed

- Bus to be updated in Year 5
Approach:
Topics Examined Since 2018 AMR

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

**2019/2025 Medium Duty and Heavy Duty Truck Systems**
- **Questionnaire:** Use of feedback from MDV/HDV FC developers for cost modeling
- **Updated Operating Conditions:** Collaboration with ANL and FCPAD
- **Bipolar Plate Material:** Embossed flexible graphite/resin plates (Switch from metallic)
- **Coolant Gasket:** Replace welded BPPs with adhesive coolant gasket

**2018/2019 Side Studies for Automotive/MDV/HDV System (not affecting baseline)**
- **End of Life Disposal and Recycling Cost:** Pt catalyst and BPP coating recycle
- **Impact of Durability on Cost:** Outline of material and system solutions (ongoing)
- **Precors BPP Coating:** carbon-based pre-coating
- **2D Manufacturing:** R2R process for assembly of unitized cell

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**Milestone 1: Validation Study** – Completed in 2017
**Milestone 2,5,8: System Definition** – Completed for 2019/2025 MDV and HDV Systems
**Milestone 3,6,9: DFMA® Cost Analysis** – Initiated for 2019/2025 MDV and HDV Systems
**Milestone 4,7,10: Reporting of Cost Results** – (due Sept 2019) => Go/No-Go Decision
Approach: Fuel Cell Truck Analysis

- DFMA analysis of FC Medium Duty Vehicle (MDV) and Heavy Duty Vehicle (HDV)
- Leverage past work:
  - ANL studies (Ram Vijayagopal et al): 12 truck applications studied
  - 21st Century Truck
  - Questionnaire sent out to FC truck developers (results still coming in)

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

<table>
<thead>
<tr>
<th>Class and Vocation</th>
<th>FHA Vehicle Class Definition</th>
<th>ANL Analysis Assumption/Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test Weight (lbs)</td>
<td>Fuelcell (kW)</td>
</tr>
<tr>
<td>Light Duty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 1</td>
<td>Class 1: &lt; 6,000 lbs</td>
<td>Not eval.</td>
</tr>
<tr>
<td>Class 2 Van</td>
<td>Class 2: 6,001 - 10,000 lbs</td>
<td>7,588</td>
</tr>
<tr>
<td>Medium Duty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 3 Service</td>
<td>Class 3: 10,001 - 14,000 lbs</td>
<td>11,356</td>
</tr>
<tr>
<td>Class 3 SchoolBus</td>
<td>Class 3: 10,001 - 14,000 lbs</td>
<td>11,512</td>
</tr>
<tr>
<td>Class 3 EnclosedVan</td>
<td>Class 3: 10,001 - 14,000 lbs</td>
<td>12,166</td>
</tr>
<tr>
<td>Class 4 Walk-In, Multi-Stop</td>
<td>Class 4: 14,001 - 16,000 lbs</td>
<td>15,126</td>
</tr>
<tr>
<td>Class 5 Utility</td>
<td>Class 5: 16,001 - 19,500 lbs</td>
<td>16,860</td>
</tr>
<tr>
<td>Class 6 Construction</td>
<td>Class 6: 19,501 - 26,000 lbs</td>
<td>22,532</td>
</tr>
<tr>
<td>Heavy Duty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 7 SchoolBus</td>
<td>Class 7: 26,001 - 33,000 lbs</td>
<td>29,230</td>
</tr>
<tr>
<td>Class 8 Construction</td>
<td>Class 8: &gt;33,001 lbs</td>
<td>37,429</td>
</tr>
<tr>
<td>Class 8 Refuse</td>
<td>Class 8: &gt;33,001 lbs</td>
<td>45,291</td>
</tr>
<tr>
<td>Class 8 Nikola One</td>
<td>Class 8: &gt;33,001 lbs</td>
<td>50,870</td>
</tr>
<tr>
<td>Class 8 TractorTrailer</td>
<td>Class 8: &gt;33,001 lbs</td>
<td>54,489</td>
</tr>
<tr>
<td>Class 8 Linehaul</td>
<td>Class 8: &gt;33,001 lbs</td>
<td>70,869</td>
</tr>
</tbody>
</table>
### Accomplishments and Progress:
#### MDV & HDV Operating Parameters

<table>
<thead>
<tr>
<th></th>
<th>2018 MDV System (160kW_{net})</th>
<th>2019 MDV System (170kW_{net})</th>
<th>2019 HDV Line Haul System (237kW_{net})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual Production</strong></td>
<td></td>
<td></td>
<td>200-100k</td>
</tr>
<tr>
<td><strong>Target Stack Durability (hours)</strong></td>
<td></td>
<td></td>
<td>25,000</td>
</tr>
<tr>
<td><strong>FC Conditions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gross Power (kW_{gross})</strong></td>
<td>197</td>
<td>217</td>
<td>315</td>
</tr>
<tr>
<td><strong>Power Density (mW/cm²)</strong></td>
<td>1,178</td>
<td>1,097</td>
<td>1,097</td>
</tr>
<tr>
<td><strong>Total Pt loading (mgPt/cm² total area)</strong></td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>System Voltage (cell voltage)</strong></td>
<td>500V (0.68V)</td>
<td>500V (0.675V)</td>
<td>500V (0.675V)</td>
</tr>
<tr>
<td><strong>Cells per Stack (Stacks per system)</strong></td>
<td>368 (2 x 80kW stacks)</td>
<td>370 (2 x 85kW stacks)</td>
<td>247 (3 x 80kW stacks)</td>
</tr>
<tr>
<td><strong>Operating Pressure (atm)</strong></td>
<td>2.35</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Stack Temp. (Coolant Exit Temp) (°C)</strong></td>
<td>63</td>
<td>85 (peak temp. during 6% grade)</td>
<td>85 (peak temp. during 6% grade)</td>
</tr>
<tr>
<td><strong>Air Stoichiometry</strong></td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Q/ΔT (kW_{th}/°C) (T_{ambient}=25°C)</strong></td>
<td>4.2</td>
<td>3.1</td>
<td>4.5 (approx. diesel HDV value)</td>
</tr>
<tr>
<td><strong>Battery Conditions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Battery Peak Power Req. (kW)</strong></td>
<td>30</td>
<td>30</td>
<td>76</td>
</tr>
<tr>
<td><strong>Battery Energy Req. (kWh)</strong></td>
<td>0.8</td>
<td>0.8</td>
<td>28</td>
</tr>
</tbody>
</table>

- Change in power density, temp., and pressure from 2018 to 2019 MDV system
- New HDV System
  - 40% more FC power than MDV system
  - Q/ΔT based on ANL modeling and set to match heat rejection of diesel truck
Approach:
Flexible Graphite Plates Could Shift Bipolar Plates Closer to $3/kW DOE Target for LDVs at 500k Systems per Year

- Leverage LDV work conducted in collaboration with Ballard
- Bipolar Plate Assembly (BPA) cost includes base material/coating, forming, and joining of two individual bipolar plates at 315cm² total area
- Automotive plate sizing and production volumes, assuming the same performance
- Metallic plates utilizing SS316 have base material cost ~$2.70/kW
- Flexible Graphite expected to be slightly higher mass and volume than metallic
• Initial feedback from multiple FC developers suggest that carbon plates are more desirable than metallic plates, especially when trying to reach 25,000 hrs operation
• Increased FC power to $170\text{ kW}_\text{net}$ and switched from PtCo/HSC to annealed Pt/C for improved durability

=> Reduced power density based on ANL modeling of higher Pt loading (0.35mgPt/cm$^2$)
Accomplishments and Progress:
Preliminary Cost Results for 2019 MDV & HDV Systems

- MDV/HDV cost curves more shallow than LDV due to low-volume manufacturing assumptions
- Large cost difference between LDV and MDV/HDV at 100k sys/year due to:
  - Pt loading (0.125 vs 0.35mgPt/cm²)
  - CEM/gross power
  - Non-vertical integration (application of extra markup and job shop for truck)
Accomplishments and Progress: Quantifying the Cost Impact of Durability Measures

- Review of possible durability-enhancing actions
  - Collaborated with NREL, ANL, and LANL to create list of mitigation steps
  - List broken into two categories: Materials and System Solutions

<table>
<thead>
<tr>
<th>Mitigation Step</th>
<th>Hardware</th>
<th>Other Impacts</th>
<th>Currently in Models?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material Solutions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase Pt loading</td>
<td>Increase total Pt loading to 0.35mgPt/cm²</td>
<td>Enhances power density</td>
<td>✓</td>
</tr>
<tr>
<td>Use radical scavengers</td>
<td>Add 9 micrograms Ce/cm² (in form of CeO₂ nanopowder) to cathode catalyst ink</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Manage particle agglomeration</td>
<td>Novel catalyst geometries and formulations</td>
<td>Probable increase in synthesis costs. Potential water management issues.</td>
<td>X</td>
</tr>
<tr>
<td>Limit leaching</td>
<td>Mirai approach: use &lt;10%mol Co (in cathode catalyst)</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Bipolar Plate Base Material</td>
<td>LDV: Ti plates (used in Mirai)</td>
<td>Ti material would increase material cost.</td>
<td>✓</td>
</tr>
<tr>
<td>Other material solutions</td>
<td>Eg. Use of high performance, inherently durable catalysts with high surface area carbon supports</td>
<td>Unknown</td>
<td>X</td>
</tr>
</tbody>
</table>
## Accomplishments and Progress: Quantifying the Impact of Durability on Cost

<table>
<thead>
<tr>
<th>Mitigation Step</th>
<th>Hardware</th>
<th>Other Impacts</th>
<th>Currently in Models?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System Solutions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thicker membrane to delay failure due to membrane thinning</td>
<td>25 micron membrane (instead of &lt;14 micron)</td>
<td>Lower power density</td>
<td>X</td>
</tr>
<tr>
<td>Limit temperature to &lt;90°C</td>
<td>Larger radiator: at peak 85°C 18% increase [(93°-40°)/(85°+40°)]=1.18</td>
<td>Lower power-density/larger-stack</td>
<td>✓</td>
</tr>
<tr>
<td>Clip voltage at 0.85V/cell</td>
<td>No hardware change needed</td>
<td>Do not operate stacks at low powers where voltage exceed threshold. (rough est. 0.85V @50mA/cm(^2) is ~4% of peak power). May want to avoid/limit numerous FC on/off cycles by running in Range Extender mode. May need larger battery.</td>
<td>X</td>
</tr>
<tr>
<td>Limit voltage slew rate</td>
<td>No hardware change needed</td>
<td>Time delay expected to be ~1 second. Impact on battery sizing expected to be negligible.</td>
<td>X</td>
</tr>
<tr>
<td>Run wetter/ Run with less RH variability</td>
<td>Possibly larger humidifier. Ballard Bus approach: “run wetter” Approach: avoid RH swings that cause tearing/pin-holes at inlet and outlet</td>
<td>Impacts power density</td>
<td>X</td>
</tr>
<tr>
<td>Run load through shut down and don’t let voltage go up</td>
<td>No hardware change needed</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Oversize stack</td>
<td>Increase in stack size</td>
<td>Increase in stack size would increase cost but also increase fuel economy for much of vehicle life.</td>
<td>X</td>
</tr>
<tr>
<td>Accept &gt;10% power degradation over system lifetime</td>
<td>No/limited hardware impact</td>
<td>System will provide &lt;90% rated power in later years of lifetime</td>
<td>X</td>
</tr>
<tr>
<td>Air purge of Anode at shut down (Not in use by OEMs)</td>
<td>Add 3-way valve, $24-$50 each, 1 per stack</td>
<td>Additional H(_2) loss during each shutdown. Shutdowns more frequent than current/baseline system. Partially offset by reduced anode purges (of N(_2) and water buildup)</td>
<td>X</td>
</tr>
</tbody>
</table>
Accomplishments and Progress: End of Life Vehicle (ELV) Recycle and Disposal Cost Analysis

Investigation of recycling or disposal of fuel cell system components

- **Fuel Cell Stack**
  - MEA - Recycling of Pt. Multiple patented pathways (see backup slides).
  - Ionomer at EOL not expected to have much value due to degradation, however fluorine capture could be a lucrative business.
  - Recycling of bipolar plates and coatings: SS, Au, Ru, Ti, & TiO₂

- **Balance of Plant Components**
  - Components similar to EV/ICE vehicles (so recycle/disposal is also the same)

- **Complex processes requiring specific separation methods**
  - Ideally have single stream process that can handle different stack designs

- **Extensive Pt/metals recycling currently conducted for autos**
  - FCV’s would most likely leverage that recycling infrastructure

- **Plan to incorporate feedback from Pt experts**: Umicore, Johnson Matthey, Heraeus, AngloAmerican, etc.
Accomplishments and Progress:
Recovered Value from Pt Recycle are Much Higher than

Values shown in nominal year dollars

Recycled BPP Materials Preliminary Results

<table>
<thead>
<tr>
<th>Total Pt loading at 0.125mg/cm²</th>
<th>Fuel Cell Stack Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Pt Recycled kg/year</td>
<td>1,000 10,000 20,000 50,000 100,000 500,000</td>
</tr>
<tr>
<td>Annual System Recycling Rate</td>
<td>9 88 176 439 878 4,389</td>
</tr>
<tr>
<td>Cell Singulation &amp; Separation Cost $/year</td>
<td>($37,283) ($153,348) ($333,673) ($669,350) ($1,469,610) ($6,642,615)</td>
</tr>
<tr>
<td>Pt Recycle Cost $/year</td>
<td>($618,593) ($1,121,904) ($1,761,337) ($2,701,757) ($3,970,120) ($14,331,416)</td>
</tr>
<tr>
<td>BPP Materials Recycle Cost $/year</td>
<td>($801,230) ($2,386,491) ($1,545,541) ($2,165,249) ($4,234,666) ($19,745,009)</td>
</tr>
<tr>
<td>Revenue from Pt $/year</td>
<td>$423,305 $4,233,053 $8,466,105 $21,165,264 $42,330,527 $211,652,636</td>
</tr>
<tr>
<td>Revenue from BPP Base Material and Coating $/year</td>
<td>$512,256 $512,256 $1,025,122 $2,562,806 $5,125,611 $25,628,057</td>
</tr>
<tr>
<td>Total Annual Recovered Value $/year</td>
<td>($1,042,545) $1,051,811 $5,830,676 $18,191,716 $37,781,649 $196,561,654</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Pt loading at 0.025mg/cm²</th>
<th>Fuel Cell Stack Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Pt Recycled kg/year</td>
<td>1,000 10,000 20,000 50,000 100,000 500,000</td>
</tr>
<tr>
<td>Annual System Recycling Rate</td>
<td>2 18 35 88 176 878</td>
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<td>($37,283) ($153,348) ($333,673) ($669,350) ($1,469,610) ($6,642,615)</td>
</tr>
<tr>
<td>Pt Recycle Cost $/year</td>
<td>($533,080) ($737,479) ($876,648) ($1,560,148) ($2,198,064) ($4,547,673)</td>
</tr>
<tr>
<td>BPP Materials Recycle Cost $/year</td>
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</tr>
<tr>
<td>Total Annual Recovered Value $/year</td>
<td>($1,295,676) ($1,950,146) ($37,717) $2,401,116 $5,689,175 $37,023,287</td>
</tr>
</tbody>
</table>

End of Life Recycle of MEA and BPP at 500k stacks/year

- Above 1k stacks per year recycled, one can have net positive recovered value from recycling Pt at 0.125mgPt/cm²
- Recovered value of metals to be split between FCV owner, salvager, & recycler.
  - Split driven by market forces
Accomplishments and Progress:
Precors BPP Coating: Deposition of Functionalized Carbon (High Volume)
Vacuum-free in-line process for pre-coating and post-coating

- Water
- Functionalized Carbon Powder ($1,000/kg)
- Ultrasonic Dispersion by Sonotrode
- <30 min/1L
- At 50W/cm² of sonotrode

1-2mg powder/ml

- Ultrasonic Spray Coating
- Pre-treatment in ambient air (wash/degrease, other cleanse)
- Photochemical Activation
- In-line Optical Detection and Conductivity QC
- Flotation Oven Dry
- Re-Roll Coated Coil
- Heater

Unroll SS Coil

SA Capital Cost & Power Estimates
- $29k, ~2kW $240k, ~10kW
- $820k, ~200kW $800k, 40kW $1.2M, 36kW
- $400k, ~2kW
- $26k, ~2kW

- Total = $3.5M, 290kW

- Final coating
  - 10nm thick coating is ~0.02g carbon/m²
  - Projected high volume process coats both sides simultaneously.
    - one-sided coating demonstrated (currently building R2R two-sided coating line)
Accomplishments and Progress:

Project Low Cost for Precors BPP Coating at High Volume

$0.58/kW at high production volume (assuming same performance as baseline system)

• $0.12/bipolar plate assembly (BPA) (coated on both sides simultaneously)
• High cost at low production due to low utilization of equipment
• Above 4M BPAs/year, lower cost to use $3.5M machinery for 2-sided coating
• Majority of cost associated with capital investment (minor material cost)
• Maintenance & Spare Parts assume 15% of capital cost per year

Breakdown in Cost per BPA at 500k systems/year
Accomplishments and Progress: Possible Cost Reduction with High Volume 2D Manufacturing Concept

• Concept from Takuya Hasegawa of Nissan
  – Batteries and fuel cells assemblies can benefit from fast line speeds
  – Currently has lab in Oppama, Japan, making 4kW stacks

• Features of roll-to-roll operation for unit cell fab/assembly
  – Avoid 3D stacking of individual pieces and long cycle-time batch processes
  – Delay singulation as long as possible to minimize handling of parts
  – Flow field formation on the MEA/GDL would be an enabling technology
  – Mechanical forming of flow fields can be avoided => Thinner separators (1-2mils rather than 3mils thick) reduce stack weight and modestly reduces cost

• Many different conceptual ideas to explore

• SA chose one design pathway, vetted the design with NREL and industry, and conducted a DFMA® analysis of the R2R concept

Other work and patents on similar process
• American Fuel Cell 2018 SBIR: Over-Molded Plate for Reduced Cost and Mass PEM Fuel Cells
Accomplishments and Progress: SA’s Roll-to-Roll Manufacturing Concept Final Cell and Stack Assembly

All 6 sub-assembly components are combined together in a R2R process to form a repeat cell. Repeat cells are stacked to form a FC stack.

1. Unwind Cathode Bpp Sub-Assembly
   - Unwind Cathode Carrier Web

2. Unroll, die cut and vacuum timed transfer cathode GDL

3. Unwind CCM Sub-Assembly
   - Vacuum Die
   - Cutting Die
   - Anvil

4. Unroll, die cut and vacuum timed transfer anode GDL

5. Unwind Anode Bpp Sub-Assembly
   - Vacuum Die
   - Cutting Die
   - Anvil
   - Porous Al Mesh

6. Unroll, die cut and vacuum timed transfer Coolant Cell

Repeat Cell Concept

Stack Compression

Stack Cells
Accomplishments and Progress:
Cost Reduction Based on 2D Manufacturing Concept is Highly Dependent on Material Selection and Pricing

- **2D Manufacturing** can be ~$3.50/kW lower cost than 2018 baseline system
- Final Assembly has the largest manufacturing cost and it’s driven by capital cost ($3.5M)
- Material assumptions have the greatest impact on final cost
## Accomplishments and Progress:
### Responses to Previous Year’s Reviewers’ Comments

<table>
<thead>
<tr>
<th>2018 Reviewer’s Comments</th>
<th>Response to Reviewer’s Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>“The model should also integrate system durability and take into account the impact of “degraded modes” on the performance and cost.”</td>
<td>SA is working with ANL, LANL (both part of FCPAD) to identify sources of degradation. We are currently assessing the cost impact by altering stack materials or system operating techniques that can improve durability. See slides 11-12.</td>
</tr>
<tr>
<td>“The team should revisit seals and gasket costs because SA’s current projections are too low.”</td>
<td>Feedback from multiple sources have similar concerns. SA evaluated the difference between PET and PEN material for MEA subgaskets for 2019. PET degrades under FC operating conditions while PEN does not. From one supplier, PEN is currently 4-5x the cost of PET. Further investigation of PEN cost and alternative low cost gasket materials is planned.</td>
</tr>
</tbody>
</table>
| “Ways to further reduce system complexity, such as removing the humidifier or using only a compressor instead of a compressor/expander module, should be taken into consideration.” | 1. In collaboration with ANL, SA has looked into removing the air humidifier and shows minimal cost reduction within current system (see slide 13 of 2018 AMR presentation: FC017_Ahluwalia_2018_0)  
2. Removing the expander for an LDV system is not ideal because of the significant increase in gross power. For lower pressure systems like the bus or MDV/HDV systems, the expander is removed. |
<table>
<thead>
<tr>
<th>Partner/Collaborator/Vendor</th>
<th>Project Role</th>
</tr>
</thead>
</table>
| **National Renewable Energy Laboratory (NREL)** *(sub on contract)* | - Provided knowledge and expertise on QC systems for FC manufacturing lines.  
- Reviewed and provided feedback on SA’s assumptions for MEA & R2R processing and techniques (2D Manufacturing for 2019).  
- Provided feedback on current 2019 and 2025 analysis systems and manufacturing processes.  
- Participates in researching the affect of durability on cost. |
| **Argonne National Laboratory (ANL)** *(sub on contract)* | - Supplied detailed modeling results for optimized fuel cell operating conditions (based on experimental cell data).  
- Provided SA with model results for system pressure, mass flows, CEM $\eta$, and membrane area requirements for optimized system.  
- Provided feedback and small modeling efforts on 2025 systems.  
- Provided modeling data on durability for various Pt loadings. |
| **2018/2019 Collaborators** | - Ballard supplied information on cutting-edge graphite bipolar plate design and manufacturing methods.  
- Mike Yandrasits (3M) and Matt Fronk (former GM, now consultant) provided detailed reviews of 2D Manufacturing analysis.  
- Vitali Weissbecker at Precors gave processing and capital cost information on carbon coating for metallic bipolar plates. |
| **Vendors/Suppliers** | See back-up material for list of ~30 other companies with which we have consulted. |
Remaining Barriers and Challenges

- **Gasket material cost**: Low-cost PET material degrades under FC conditions. Polyethylene Naphthalate (PEN) is a recommended alternative, but may lead to ~$5/kW cost increase.

- **PFSA ionomer cost uncertainty**: Some in industry suggest ionomer may be ~$500/kg even at high volumes. May require alternative formulation or fabrication process.

**Automotive System**

- **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/HDV Study**

- Better understanding of the FCV truck preferred operating mode (how much hybridization).
Proposed Future Work

• Incorporate feedback from MDV/HDV questionnaire (system diagrams and preferred vocation)
• Continue to investigate ways to incorporate durability into cost modeling
• Investigate the value of recovering fluorine from waste ionomer
• Investigate synthesis cost of PFSA ionomers
• Synthesis cost analysis of PGM-Free catalyst
• Conduct sensitivity analyses for MDV and HDV systems

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

• **MDV 170kW_{net} System**
  – Interim results: \(\sim$89/kW_{net}\) (current 2019) and \(\sim$72/kW_{net}\) (2025) at 100k sys/year

• **HDV Line Haul 363kW_{net} System**
  – Interim results: \(\sim$86/kW_{net}\) (current 2019) and \(\sim$69/kW_{net}\) (2025) at 100k sys/year

• **Impact of Durability on Cost**
  – Material and System Solutions (qualitative and quantitative) incorporated into system cost models
  – Further FCPAD testing results will help quantify the impact of some solutions

• **Recycle and Disposal Cost Analysis**
  – Pt recycling is profitable for greater than 1,000 stacks recycled per year
  – Pt is more profitable than BPP base material and coating

• **Precors Bipolar Plate Coating**
  – Potentially lower cost functionalized carbon pre-coating for metallic bipolar plates
  – May be restricted to non-welded plates

• **2D Manufacturing**
  – Current SA design projected to reduce stack cost by \(\sim$3.50/kW\)
  – Most uncertainty in material selection and pricing
Project Summary

• Overview
  – Exploring subsystem alternative configurations and benchmark cost where possible
  – In year 3 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
  – 2018 Automobile analysis documented (report available)
  – MDV and HDV 2019 & 2025 fuel cell systems analysis results (LDV updated every other year)
  – Side Analyses:
    • Impact of Durability on Cost
    • Recycle and Disposal of Fuel Cell System components
    • Precors Bipolar Plate Coating
    • 2D Manufacturing

• Collaborations
  – ANL and NREL provide cooperative analysis and vetting of assumptions/results
  – Extensive discussions, interviews, feedback with 30+ industry vendors/suppliers

• Future Work
  – Continue to incorporate durability into cost analysis, evaluate cost of ionomer synthesis, initiate PGM-free catalyst cost analysis, and draft 2019 final report.
Thank you!

Questions?
Technical Back-up Slides
2019 MDV System
(Diagram shows system components included in baseline cost analysis model)

Dotted lines refer to FC exhaust lines

Added BOP Components

2019 Medium Duty Truck System

Hydrogen From Tanks
Compressed Hydrogen Tanks
Not Included in Cost Analysis

Anode Exhaust

Mixer

Exhaust Air to Tail Pipe

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Accomplishments and Progress:
Detailed Process Flow Diagram of
Pt & PFSA Recovery

Breakdown of membrane in butanol/water mixture under microwave heat at 100°C for 30min (75kW, 915mHz microwave generator)

Delamination Tank:
Separate GDL from CCM in 25wt %butanol/75wt %water

Sieve (GDL collection)

Microwave Vessel

Remove Pt Catalyst through Filter Press

Heated line to maintain ionomer particle sizes between 100-500µm

Recycle of butanol/water mixture

Gasketed MEA*

Shredder

Removal of concentrated polymer (100-500µm) by ultrafiltration

Disposal of ionomer through incineration or landfill (Future study may look at capture/resale of fluorine)

<0.2% Pt loss

<0.2% Pt loss

*GDLs are hot pressed to CCM, so care must be taken to not prematurely remove GDL to which Pt may be affixed.

Pt catalyst Filter Cake

(continued on next slide)

Accomplishments and Progress: Detailed Process Flow Diagram of Pt & PFSA Recovery

**Filter Cake:**
Pt catalyst on carbon support

**Base Leaching with NaOH (1):**
- Oxidation of carbon & other organic materials in air (1,000°C for 6 hrs)
- Base Leaching: 50wt% NaOH dissolves non-Pt metal oxides formed in oxidation step (in Teflon vessel at 170°C and 9bar for 4hrs) x 2

**Filter Press & Wash with Water:**
- NaOH, CoO, Co₃O₄

**Oxidation of carbon & other organic materials in air (1,000°C for 6 hrs):**

**Base Leaching with NaOH (2):**
- Co(NO₃)₂, Ni(NO₃)₂

**Filter Cake:**
- HNO₃

**Dissolve Co, Ni & other metals in Nitric Acid at 100°C at 1atm:**
- Co(NO₃)₂, Ni(NO₃)₂

**Filter Press & Wash with Water:**
- > 99.6% Pt Recovered at x% purity

Detailed cost breakdown in Technical Backup Slides shows the Oxidation of Carbon as the highest cost process step followed by Base Leaching.

Accomplishments and Progress:
Pt Catalyst Recycling
Preliminary Cost Results

<table>
<thead>
<tr>
<th>PtCo/HSC Cathode Catalyst Recycling</th>
<th>Component Costs per gram of Pt recycled</th>
<th>1,000</th>
<th>10,000</th>
<th>20,000</th>
<th>50,000</th>
<th>100,000</th>
<th>500,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1: Shred and Delamination</td>
<td>$/g</td>
<td>$(11.87)</td>
<td>$(1.31)</td>
<td>$(0.79)</td>
<td>$(0.40)</td>
<td>$(0.22)</td>
<td>$(0.08)</td>
</tr>
<tr>
<td>Step 2: Microwave Dissolution</td>
<td>$/g</td>
<td>$(18.70)</td>
<td>$(1.99)</td>
<td>$(1.08)</td>
<td>$(0.88)</td>
<td>$(0.45)</td>
<td>$(0.11)</td>
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<tr>
<td>Step 3: Pt Catalyst Filtration</td>
<td>$/g</td>
<td>$(3.95)</td>
<td>$(0.40)</td>
<td>$(0.21)</td>
<td>$(0.09)</td>
<td>$(0.06)</td>
<td>$(0.03)</td>
</tr>
<tr>
<td>Step 4: Ultrafiltration</td>
<td>$/g</td>
<td>$(4.69)</td>
<td>$(0.56)</td>
<td>$(0.35)</td>
<td>$(0.33)</td>
<td>$(0.26)</td>
<td>$(0.16)</td>
</tr>
<tr>
<td>Step 5: Combustion of HSC</td>
<td>$/g</td>
<td>$(4.62)</td>
<td>$(1.40)</td>
<td>$(1.40)</td>
<td>$(0.90)</td>
<td>$(0.84)</td>
<td>$(0.69)</td>
</tr>
<tr>
<td>Step 6: Base Leaching with NaOH (1)</td>
<td>$/g</td>
<td>$(2.60)</td>
<td>$(1.19)</td>
<td>$(1.10)</td>
<td>$(0.65)</td>
<td>$(0.55)</td>
<td>$(0.48)</td>
</tr>
<tr>
<td>Step 7: Leaching Filter Press (1)</td>
<td>$/g</td>
<td>$(3.30)</td>
<td>$(0.63)</td>
<td>$(0.50)</td>
<td>$(0.30)</td>
<td>$(0.25)</td>
<td>$(0.20)</td>
</tr>
<tr>
<td>Step 8: Leaching Wash (1)</td>
<td>$/g</td>
<td>$(2.14)</td>
<td>$(0.52)</td>
<td>$(0.52)</td>
<td>$(0.24)</td>
<td>$(0.15)</td>
<td>$(0.12)</td>
</tr>
<tr>
<td>Step 9: Base Leaching with NaOH (2)</td>
<td>$/g</td>
<td>$(2.60)</td>
<td>$(1.19)</td>
<td>$(1.10)</td>
<td>$(0.65)</td>
<td>$(0.55)</td>
<td>$(0.48)</td>
</tr>
<tr>
<td>Step 10: Leaching Filter Press (2)</td>
<td>$/g</td>
<td>$(3.30)</td>
<td>$(0.63)</td>
<td>$(0.50)</td>
<td>$(0.30)</td>
<td>$(0.25)</td>
<td>$(0.20)</td>
</tr>
<tr>
<td>Step 11: Leaching Wash (2)</td>
<td>$/g</td>
<td>$(2.14)</td>
<td>$(0.52)</td>
<td>$(0.52)</td>
<td>$(0.24)</td>
<td>$(0.15)</td>
<td>$(0.12)</td>
</tr>
<tr>
<td>Step 12: Dissolution in Nitric Acid</td>
<td>$/g</td>
<td>$(1.56)</td>
<td>$(0.50)</td>
<td>$(0.42)</td>
<td>$(0.30)</td>
<td>$(0.24)</td>
<td>$(0.21)</td>
</tr>
<tr>
<td>Step 13: Nitric Acid Filter Press</td>
<td>$/g</td>
<td>$(3.08)</td>
<td>$(0.47)</td>
<td>$(0.34)</td>
<td>$(0.17)</td>
<td>$(0.11)</td>
<td>$(0.08)</td>
</tr>
<tr>
<td>Step 14: Nitric Acid Wash</td>
<td>$/g</td>
<td>$(1.95)</td>
<td>$(0.42)</td>
<td>$(0.35)</td>
<td>$(0.20)</td>
<td>$(0.12)</td>
<td>$(0.09)</td>
</tr>
<tr>
<td>Step 15: Dry</td>
<td>$/g</td>
<td>$(3.97)</td>
<td>$(1.04)</td>
<td>$(1.00)</td>
<td>$(0.52)</td>
<td>$(0.34)</td>
<td>$(0.25)</td>
</tr>
</tbody>
</table>

| Pt Catalyst Recycling Cost         | $/g                                    | $(70.47) | $(12.78) | $(10.15) | $(6.16) | $(4.52) | $(3.27) |
| Total Catalyst Recycling Cost $/year | $(6,183.56) | $(1,121.96) | $(1,781.33) | $(2,701.75) | $(3,970.01) | $(4,133.44) |
| Pt Price                           | $/g                                    | $48.23 | $48.23 | $48.23 | $48.23 | $48.23 | $48.23 |
| Total Annual Revenue of Recycled Pt $/year | $423,306 | $4,233,053 | $8,468,105 | $21,165,264 | $42,330,527 | $211,662,636 |
| Recovered Value per gram of Pt     | $/g                                    | $(22.25) | $(36.44) | $(38.08) | $(42.07) | $(43.70) | $(44.96) |
| Total Annual Recovered Value $/year | $(195,288) | $3,111,089 | $6,684,768 | $18,463,507 | $38,360,615 | $197,321,220 |

Values shown in nominal year dollars

- Cost includes ionomer disposal in landfill
- Profit based on Pt resale price of $1,500/tr.oz at all recycling volume rates and 0.125mgPt/cm² loading (9.3g/system)
  - Current Pt price is ~$800/tr.oz.
Accomplishments and Progress:

Detailed Process Flow Diagram of Removal of Corrosion-Resistant and Conductive Coatings on Bipolar Plates

- Singulate unit cells (by solvent or cutting)
- Remove titanium/titanium oxide and gold or ruthenium coatings by submerging BPP in acid solution of 25% Nitric Acid (HNO₃) and 2% Hydrogen Fluoride (HF)
  - Heat acid solution via heat exchanger evaporator to obtain powdered titanium/titanium oxide material (about 5 min)
  - Reuse titanium/titanium oxide on new BPPs
- Remove gold or ruthenium that will sit on top of solution
  - Skimmed Materials
  - Recycle gold or ruthenium materials
- Remove SS BPPs from solution
  - Recycle SS
  - Gold can be melted and sputtered onto new BPPs
  - Ruthenium oxide can be converted to ruthenium chloride and dissolved in ethanol to be reused.

Acid Scrubber
- Acid Vapor

Bipolar Plate Recycling
Preliminary Cost Results

- Stainless Steel, although having a low recycle price, makes up the majority of BPP revenue due to the sheer mass of material recycled.
- Although gold coating is quite small amount, makes up almost the same amount of revenue as SS.
- Titanium purchase price is extremely high for 99.9% purity PVD target

<table>
<thead>
<tr>
<th>Material</th>
<th>Purchased Price ($/kg)</th>
<th>Recycled Price ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>316 SS</td>
<td>$13.19</td>
<td>$1.43</td>
</tr>
<tr>
<td>Gold</td>
<td>$42,439 ($1,320/tr.oz)</td>
<td>$20,000 ($622/tr.oz)</td>
</tr>
<tr>
<td>Ruthenium</td>
<td>$1,620 ($50/tr.oz)</td>
<td>$1,350 ($42/tr.oz)</td>
</tr>
<tr>
<td>Titanium</td>
<td>$230</td>
<td>$17.64</td>
</tr>
</tbody>
</table>

Values shown in nominal year dollars