

# **Stationary and Emerging Market Fuel Cell System Cost Analysis – Auxiliary Power Units FC097**

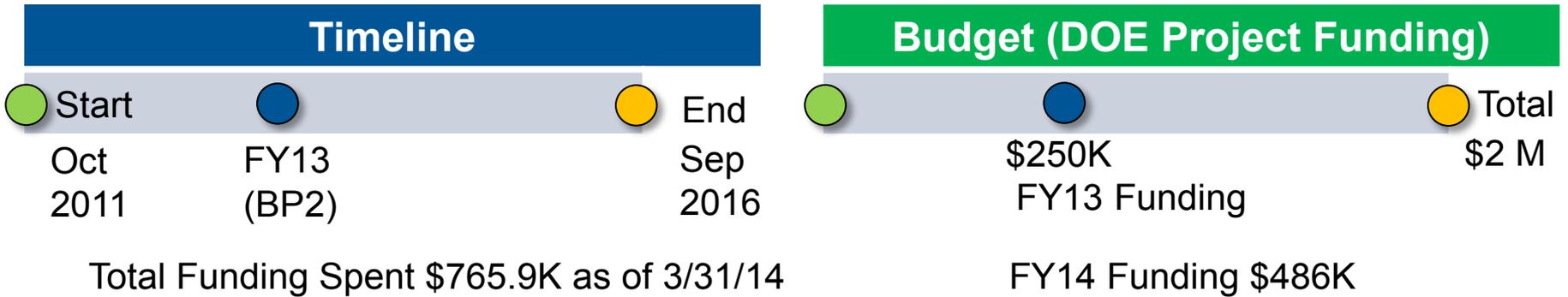
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and Gabe Stout

Battelle

06/19/2014

Washington D.C.

# Overview – Program Details



## Collaborators

have provided design inputs, cost inputs, design review, and manufacturing cost review

- Hydrogenics
- Crown
- Bulk Molding Compounds
- 3M
- AllCell
- NexTech
- Delphi
- American Durafilm
- SonoTek
- Technologies
- Ballard
- Nuvera
- Metro Mold and Design
- PCI

## Barriers Addressed

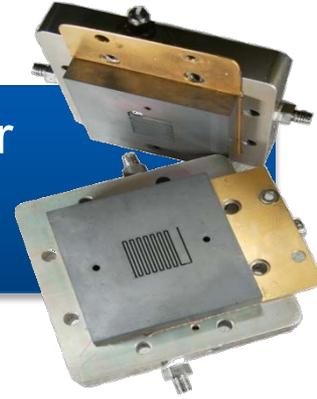
Cost reduction of fuel cell components and materials

Manufacturing capability

Customer acceptance

# Relevance – Program Objective

5-year program to assist DOE in developing fuel cell systems for stationary and emerging markets by developing independent models and cost estimates



- Applications - Primary (including CHP) power, backup power, APU, and material handling equipment
- Fuel Cell Types - 80°C PEM, 180°C PEM, SOFC technologies
- Annual Production Volumes - 100, 1K, 10K and 50K (only for primary production systems)
- Size - 1, 5, 10, 25, 100, 250 kW

## In Budget Period 2 (BP2)

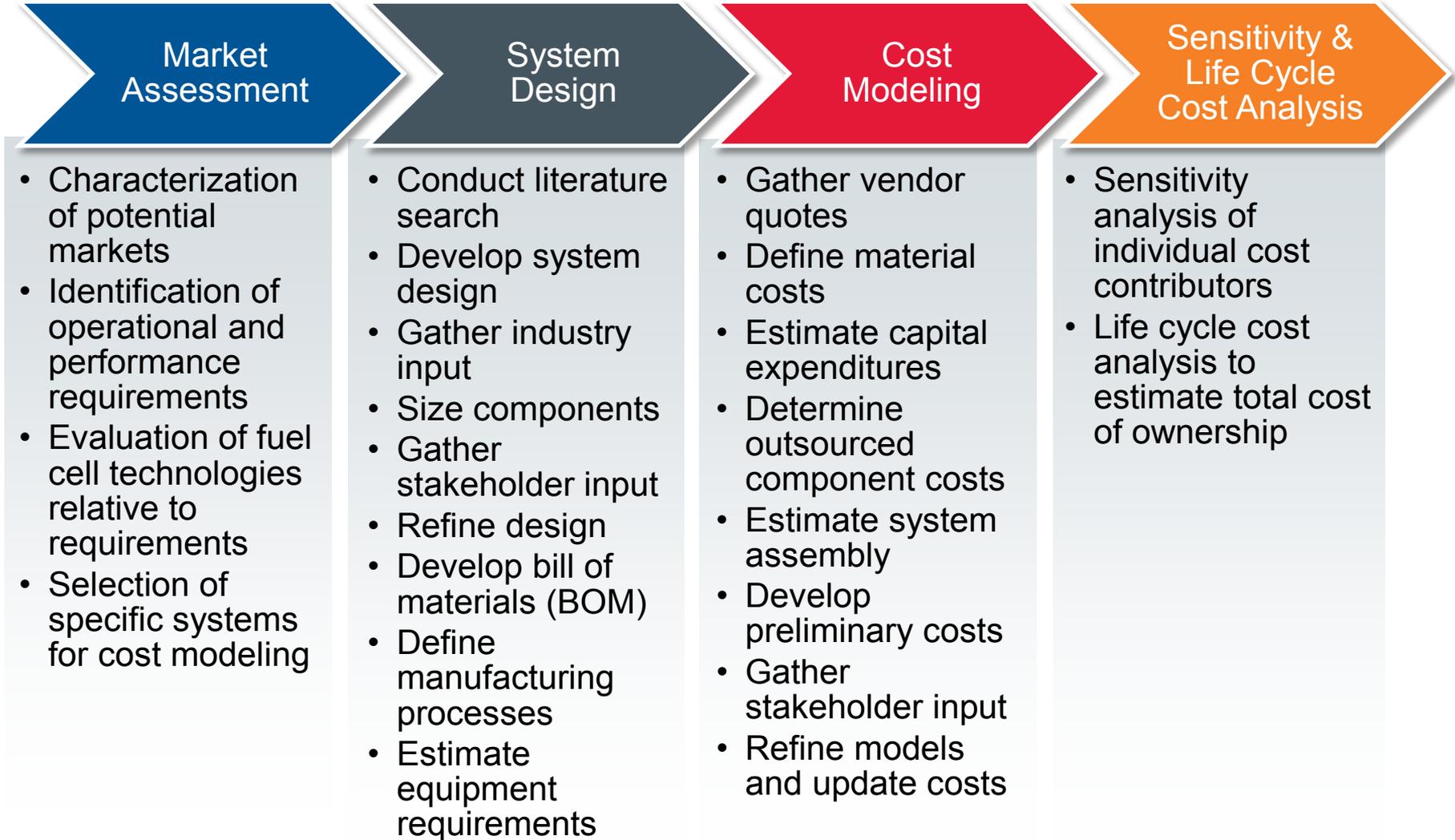
- 1 and 5 kW SOFC for Auxiliary Power Unit (APU) applications
- 1 and 5 kW PEM for Material Handling Equipment (MHE) applications

# Relevance – Technical Barriers Addressed

Technical Barriers	Project Goals
Cost reduction of fuel cell components and materials	<ol style="list-style-type: none"> <li>1. Identify major contributors to fuel cell system cost</li> <li>2. Quantify potential cost reduction based upon technological improvements</li> </ol>
Manufacturing capability	<ol style="list-style-type: none"> <li>3. Identify major contributors to fuel cell system manufacturing cost</li> <li>4. Identify areas for manufacturing R&amp;D to improve quality and/or throughput</li> <li>5. Provide basis for consideration of transition from other industries</li> </ol>
Customer acceptance	<ol style="list-style-type: none"> <li>6. Develop accurate cost projections that can be used to evaluate total cost of ownership and facilitate early market adoption</li> </ol>



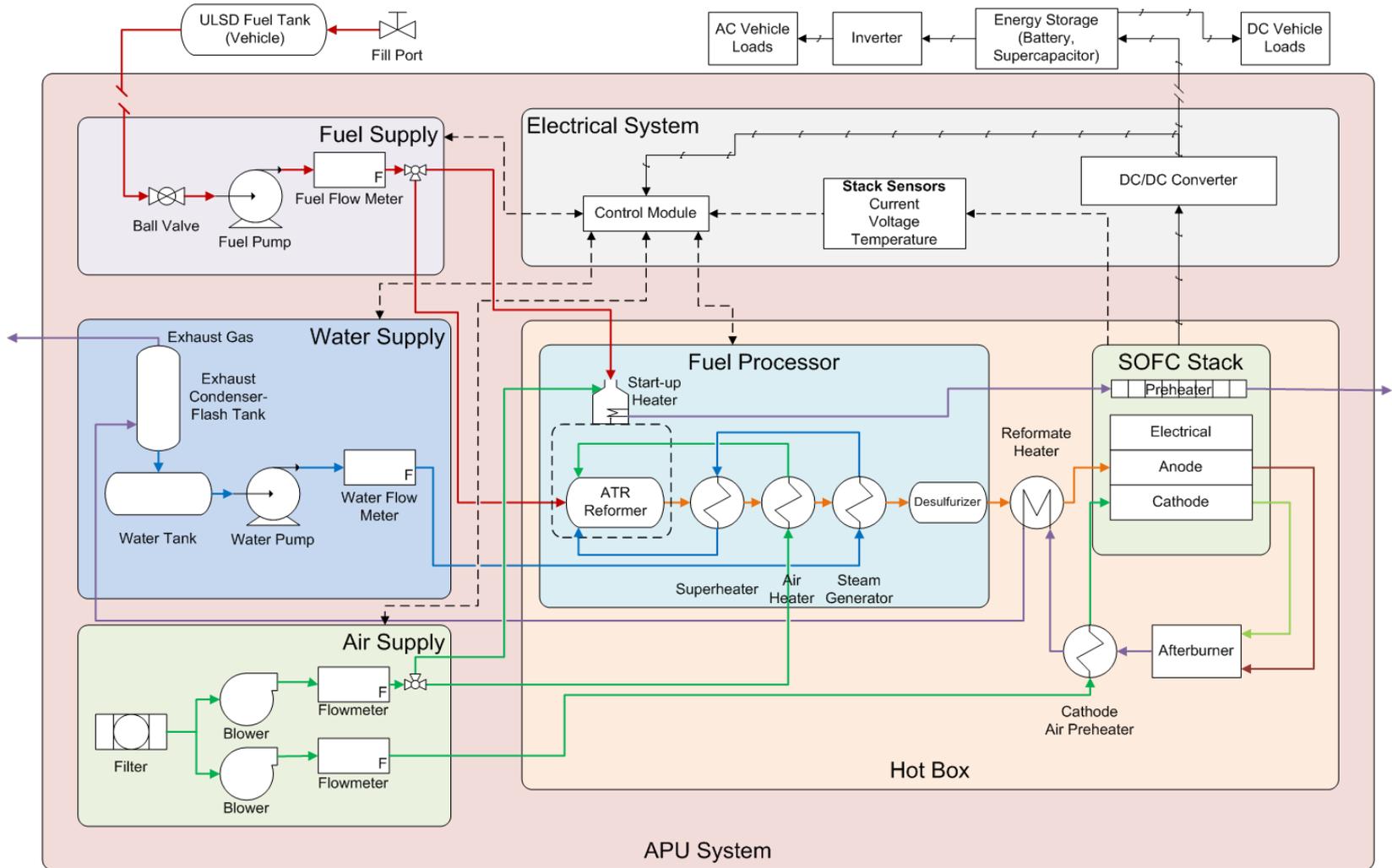
# Approach – Manufacturing Cost Analysis Methodology



## **Progress & Accomplishments – BP2**

- Completed the manufacturing cost analysis for SOFC fuel cells for APU applications
  - Presented these results at the Fuel Cell Seminar
- Completed the manufacturing cost analysis for small PEM systems for MHE applications

# Progress & Accomplishments – SOFC Fuel Cell System Design for APU Applications



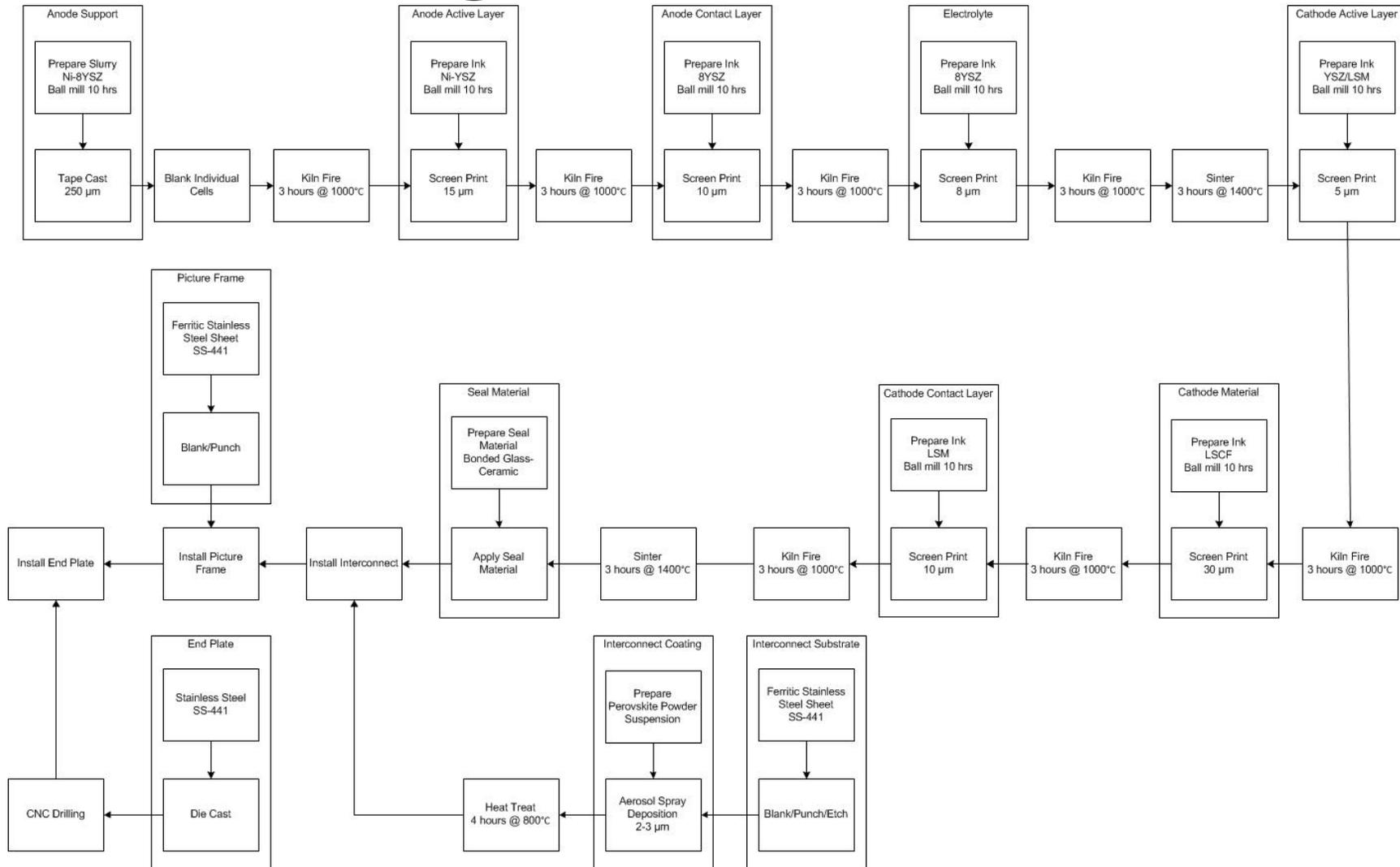
# Progress & Accomplishments – Additional Design Details

Component	Specification
<b>Fuel (Anode)</b>	<ul style="list-style-type: none"> <li>• ULSD (approx 15 ppm Sulfur, EPA regulated)</li> <li>• Reformed and desulfurized to &lt;0.1 ppmv sulfur and &lt;1% hydrocarbons</li> <li>• Fuel supplied from onboard diesel tanks</li> <li>• No input water</li> <li>• Air filtered for particulates and chemicals (passive)</li> </ul>
<b>Air (Cathode)</b>	<ul style="list-style-type: none"> <li>• Filtered for particulates and chemicals (passive)</li> <li>• Flow is 2X stoichiometric</li> </ul>
<b>Electric</b>	<ul style="list-style-type: none"> <li>• 12 VDC regulated output</li> <li>• Buck DC/DC converter</li> <li>• 1 kW hybridized system with on-board truck battery to supply short bursts of peak power</li> </ul>
<b>General</b>	<ul style="list-style-type: none"> <li>• 10,000 hr lifetime</li> <li>• &lt; 2% degradation per 1000 hours of operation</li> <li>• 30% Electrical efficiency at rated power(Complete System)</li> </ul>

# Progress & Accomplishments – APU SOFC Fuel Cell System Specification

Parameter	1kW System	5kW System
Power Density (W/cm <sup>2</sup> )	0.32	
Current Density (A/cm <sup>2</sup> )	0.4	
Cell Voltage (VDC)	0.8	
Active Area Per Cell (cm <sup>2</sup> )	200	500
Net Power (kW)	1	5
Gross Power (kW)	1.22	6.08
Number of Cells (#)	19	38
Full Load Stack Voltage (VDC)	15.2	30.4
Cell Design	Planar, Anode supported	
Anode Application	Ni-8YSZ, 250 μm thick, tape cast, kiln fired	
Subsequent Cell Layer Application	5-30 μm thick, screen print, kiln fire	
Seals	Wet application bonded glass ceramic	
Interconnects	Ferritic Stainless Steel (SS-441) with Perovskite coating, 2-3 μm thick	
End plates	A560 cast steel	
Stack Assembly	Hand assembled, tie rods, furnace braze	
Test and Condition	2 hr. warm-up 5% H <sub>2</sub> /95% N <sub>2</sub> , 2 hr. test 50% H <sub>2</sub> /50% N <sub>2</sub> , 2 hr. cool down 100% N	

# Progress & Accomplishments – SOFC Fuel Cell Stack Manufacturing Process Overview



# Progress & Accomplishments – Methodology for Calculating Manufacturing Costs

- Use the Boothroyd-Dewhurst DFMA<sup>®</sup> estimating software for standard process models whenever they exist
- Developed custom models as needed

The screenshot shows the Boothroyd-Dewhurst DFMA software interface. On the left, a tree view shows the process hierarchy for 'A560 cast steel die cast part', including 'Cold chamber die casting process' and 'Generic CNC drilling center'. Below this is a 'Cost results, \$' table with columns for 'Previous' and 'Current' values. A 'Calculate' button is visible. On the right, a 3D model of a '1 kW End Plate' is shown with dimensions: 15 mm average thickness, 232 mm length, and 344 mm width. The 'Forming direction' is indicated as Z. A 'Select process and material...' button is located below the model.

Cost results, \$	Previous	Current
material	15.71	15.71
setup	0.19	0.19
process	6.70	6.70
rejects	0.27	0.27
piece part	22.86	22.86
tooling	1.14	1.14
total	24.00	24.00
Tooling investment	118,737	118,737

## • Custom Model Development Process

- Develop model approach and process flow
- Perform preliminary model analysis
  - Inputs and calculations required to produce cost outputs
  - Independent verification of viability and accuracy
- Implement model in Excel
  - Develop model using DFMA principles and methods
  - Validate model results against preliminary cost analysis results

# Progress & Accomplishments – Manufacturing Processes Evaluated

Process	Method Evaluated	Alternatives Not Evaluated
<b>Ceramic Deposition</b>	Screen Printing Tape Casting	<ul style="list-style-type: none"> <li>• Plasma Spray Coating</li> </ul>
<b>Interconnect</b>	Sheet Metal Stamping Etching Spray Deposition Coating	<ul style="list-style-type: none"> <li>• Laser Cutting</li> <li>• Water Jet Cutting</li> <li>• Chemical Etching</li> </ul>
<b>Sealing</b>	Bead Deposition	<ul style="list-style-type: none"> <li>• Screen Printing</li> <li>• Tape Casting</li> </ul>
<b>Picture Frame</b>	Sheet Metal Stamping	<ul style="list-style-type: none"> <li>• Laser cutting</li> <li>• Injection molding</li> </ul>
<b>End Plate</b>	Die Casting	<ul style="list-style-type: none"> <li>• Machining</li> <li>• Stamping, Welding</li> </ul>

# Progress & Accomplishments – Major Stack Material & Process Assumption

Material	Cost (\$)	Measure
NiO	32	kg
8YSZ	50	kg
Ni-YSZ	35	kg
LSM-YSZ	150	kg
LSCF	150	kg
Lanthanum Oxide	15	kg
Perovskite Coating	150	kg
441 Stainless Steel	5.31	kg
A560 Stainless Steel	5.64	kg

Process Assumptions	Value
Custom process scrap rate	3.0%
Standard process scrap rate	0.5%
Inspection steps included in processing	None
Labor cost	\$45/hr
Machine cost*	\$25/hr
Energy cost	\$0.07/kW-h
Overall plant efficiency	85%
Operators per line	1

\*note that energy cost of high power machines is included in processing cost

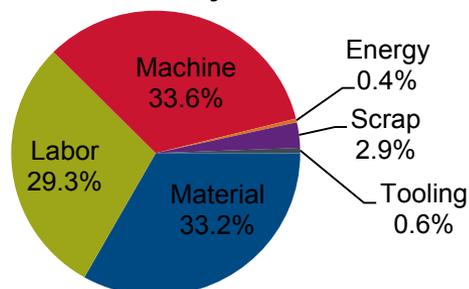
# Progress & Accomplishments – Capital Cost Assumptions

Capital Cost	Unit Cost (2013\$)	Units	Total Cost (2013\$)	Assumption/Reference
<b>Factory Total Construction Cost</b>	250	\$/sq ft	751,723 to 1,348,055	<ul style="list-style-type: none"> <li>Includes Electrical Costs (\$50/sq ft)</li> <li>Total plant area based on line footprint plus 1.5x line space for working space, offices, shipping, etc.</li> <li>Varies with anticipated annual production volumes of both 1 kW and 5 kW stacks</li> </ul>
<b>Production Line Equipment Cost</b>	Varies by component		1,537,495 to 2,890,680	<ul style="list-style-type: none"> <li>Varies with anticipated annual production volumes of both 1 kW and 5 kW stacks</li> </ul>
<b>Forklifts</b>	25,000	\$/lift	50,000	<ul style="list-style-type: none"> <li>Assumes 2 forklifts with extra battery and charger</li> </ul>
<b>Cranes</b>	66,000	\$/crane	198,000	<ul style="list-style-type: none"> <li>Assumes 3 cranes, 5 ton capacity, 20' wide per line</li> </ul>
<b>Real Estate</b>	125,000	\$/acre	125,000	<ul style="list-style-type: none"> <li>Assumes 1 acre of vacant land, zoned industrial Columbus, OH</li> </ul>
<b>Contingency</b>	10% Capital Cost		266,222 to 461,174	<ul style="list-style-type: none"> <li>Construction estimation assumption</li> </ul>
<b>Total</b>			<b>2,928,440 to 5,072,909</b>	<ul style="list-style-type: none"> <li>Varies with anticipated annual production volumes of both 1 kW and 5 kW stacks</li> </ul>

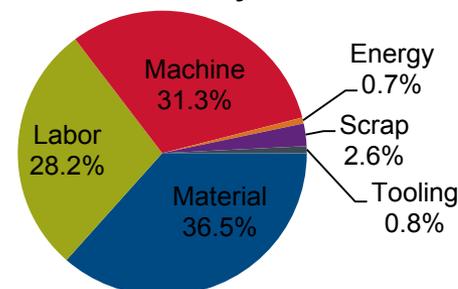
# Progress & Accomplishments – 1 kW SOFC Stack Manufacturing Cost

Stack Component	100 Units (\$/each)	1000 Units (\$/each)	10,000 Units (\$/each)	50,000 Units (\$/each)
Cells	246	177	149	142
Interconnects	170	167	167	167
Picture Frame	5	5	5	5
Sealing	28	26	25	25
End plates	50	44	44	44
Stack assembly	15	12	12	12
Stack brazing	3	6	6	6
Stack test and conditioning	353	353	353	353
<b>Stack Total (less testing)</b>	<b>590</b>	<b>511</b>	<b>481</b>	<b>473</b>

**1 kW Stack - Cost by Category**  
100 stacks/year



**1 kW Stack - Cost by Category**  
50,000 stacks/year



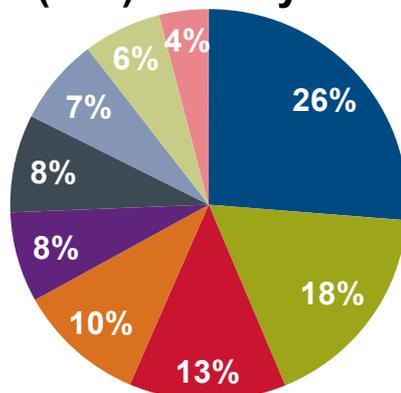
All costs include manufacturing scrap

# Progress & Accomplishments – 1 kW APU SOFC BoP Manufacturing Cost

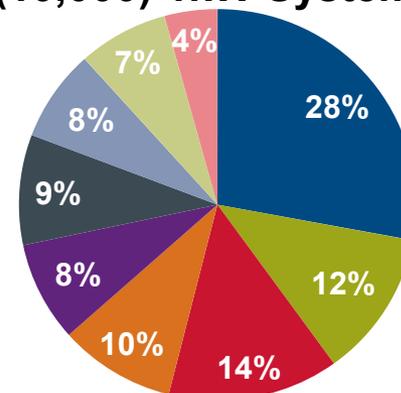
BoP Components	100 Units (\$/each)	1000 Units (\$/each)	10,000 Units (\$/each)	50,000 Units (\$/each)
Fuel Supply	610	542	542	542
Air Supply	1,226	1,059	1,027	1,027
Water Supply	715	638	608	608
Power Electronics and Controls	1,673	1,220	895	895
Heat Transfer Components	2,522	2,267	2,061	2,061
Instruments and Sensors	777	703	673	673
Fuel Reformer/Desulfurizer	388	353	318	318
Additional Components	685	623	559	559
Additional Work Estimate	1,000	800	700	700
<b>BOP Total</b>	<b>9,597</b>	<b>8,205</b>	<b>7,383</b>	<b>7,383</b>

- Heat Transfer
- Electronics & Controls
- Air Supply
- Additional Work Estimate
- Water Supply
- Instrumentation
- Assembly Components
- Diesel Fuel Supply
- Fuel Processing

(100) 1kW Systems



(10,000) 1kW Systems



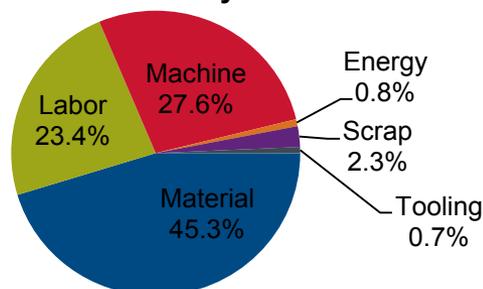
# Progress & Accomplishments – 1 kW APU SOFC Fuel Cell System Cost Summary

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	\$590	\$511	\$481	\$473
Stack manufacturing capital cost	\$4,757	\$495	\$69	\$43
Balance of plant	\$9,597	\$8,204	\$7,383	\$7,383
System assembly, test, and conditioning	\$475	\$451	\$448	\$448
<b>Total system cost, pre-markup</b>	<b>\$15,419</b>	<b>\$9,661</b>	<b>\$8,381</b>	<b>\$8,347</b>
<b>System cost per net KW, pre-markup</b>	<b>\$15,419</b>	<b>\$9,661</b>	<b>\$8,381</b>	<b>\$8,347</b>
Sales markup	50.00%	50.00%	50.00%	50.00%
<b>Total system cost, with markup</b>	<b>\$23,129</b>	<b>\$14,491</b>	<b>\$12,571</b>	<b>\$12,520</b>
<b>System cost per net KW, with markup</b>	<b>\$23,129</b>	<b>\$14,491</b>	<b>\$12,571</b>	<b>\$12,520</b>

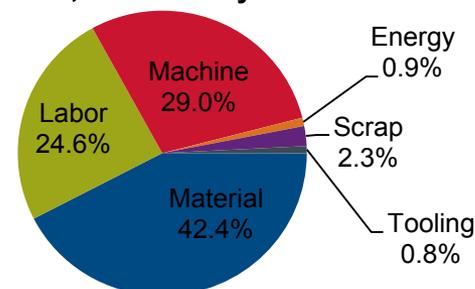
# Progress & Accomplishments – 5 kW SOFC Stack Manufacturing Cost

Stack Component	100 Units (\$/each)	1000 Units (\$/each)	10,000 Units (\$/each)	50,000 Units (\$/each)
Cells	618	483	425	416
Interconnects	586	583	583	583
Picture Frame	14	14	14	14
Sealing	73	72	70	64
End plates	72	65	64	64
Stack assembly	27	21	21	21
Stack brazing	12	16	16	16
Stack test and conditioning	359	359	359	359
<b>Stack Total (less testing)</b>	<b>1,476</b>	<b>1,327</b>	<b>1,267</b>	<b>1,257</b>

**5 kW Stack - Cost by Category**  
100 stacks/year



**5 kW Stack - Cost by Category**  
50,000 stacks/year



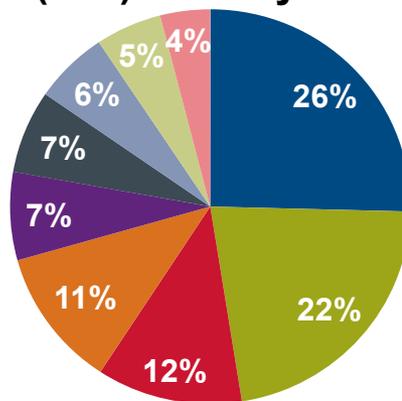
All costs include manufacturing scrap

# Progress & Accomplishments – 5 kW APU SOFC BoP Manufacturing Cost

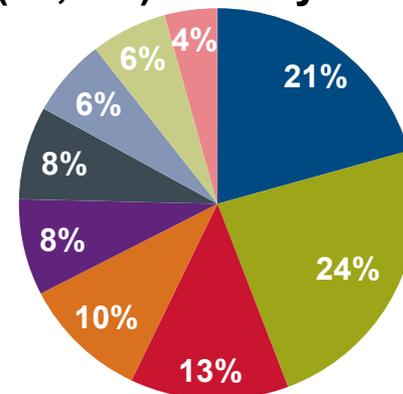
BoP Components	100 Units (\$/each)	1,000 Units (\$/each)	10,000 Units (\$/each)	50,000 Units (\$/each)
Fuel Supply	610	542	542	542
Air Supply	1,342	1,160	1,128	1,128
Water Supply	825	737	696	696
Power Electronics & Controls	2,901	2,351	1,802	1,802
Heat Transfer Components	2,522	2,267	2,061	2,061
Instruments and Sensors	777	703	673	673
Fuel Reformer/Desulfurizer	461	419	377	377
Additional Components	685	623	559	559
Additional Work Estimate	1,200	1,000	900	900
<b>BOP Total</b>	<b>11,323</b>	<b>9,802</b>	<b>8,738</b>	<b>8,738</b>

- Electronics & Controls
- Heat Transfer
- Air Supply
- Additional Work Estimate
- Water Supply
- Instrumentation
- Assembly Components
- Diesel Fuel Supply
- Fuel Processing

(100) 5kW Systems



(10,000) 5kW Systems



# Progress & Accomplishments – 5 kW APU SOFC Fuel Cell System Cost Summary

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	\$1,476	\$1,327	\$1,267	\$1,257
Stack manufacturing capital cost	\$4,757	\$495	\$82	\$73
Balance of plant	\$11,323	\$9,802	\$8,738	\$8,738
System assembly, test, and conditioning	\$481	\$456	\$454	\$454
<b>Total system cost, pre-markup</b>	<b>\$18,037</b>	<b>\$12,080</b>	<b>\$10,541</b>	<b>\$10,522</b>
<b>System cost per net KW, pre-markup</b>	<b>\$3,607</b>	<b>\$2,416</b>	<b>\$2,108</b>	<b>\$2,104</b>
Sales markup	50.00%	50.00%	50.00%	50.00%
<b>Total system cost, with markup</b>	<b>\$27,056</b>	<b>\$18,120</b>	<b>\$15,812</b>	<b>\$15,783</b>
<b>System cost per net KW, with markup</b>	<b>\$5,411</b>	<b>\$3,624</b>	<b>\$3,162</b>	<b>\$3,156</b>

# Progress & Accomplishments – APU SOFC BoP Cost Comparison

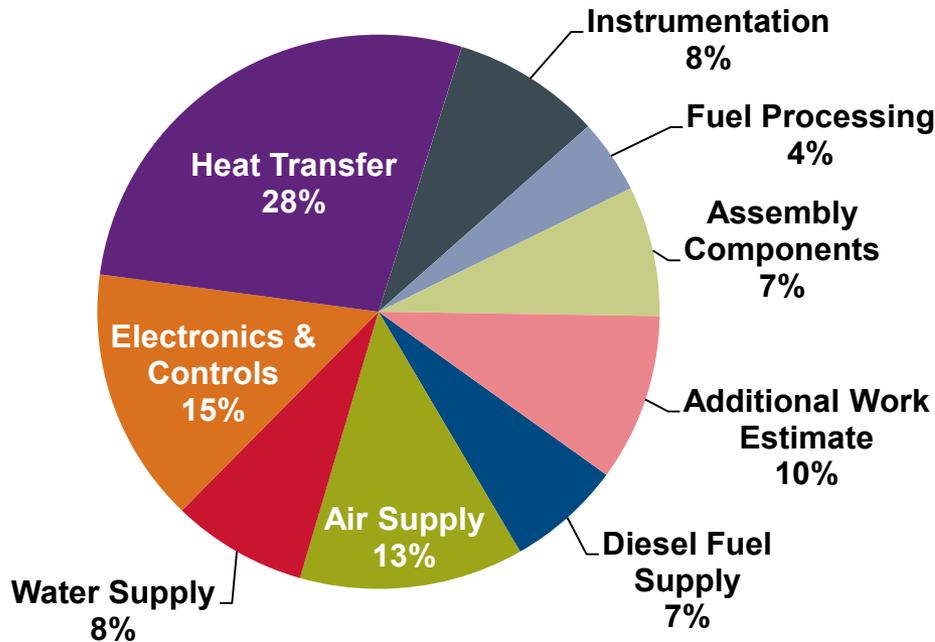
- 3 Dominant Cost Drivers

- Heat Transfer Components

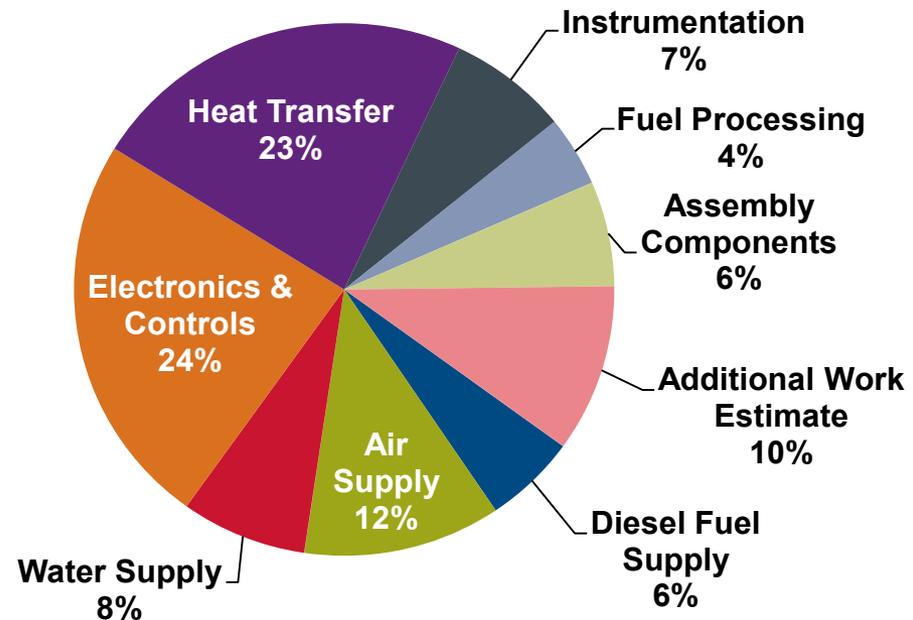
- Electronics & Controls

- Air Supply

1kW Systems - 1000 units/yr



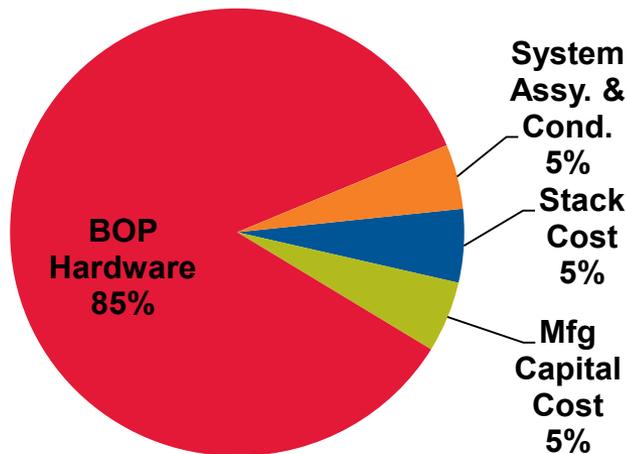
5kW Systems - 1000 units/yr



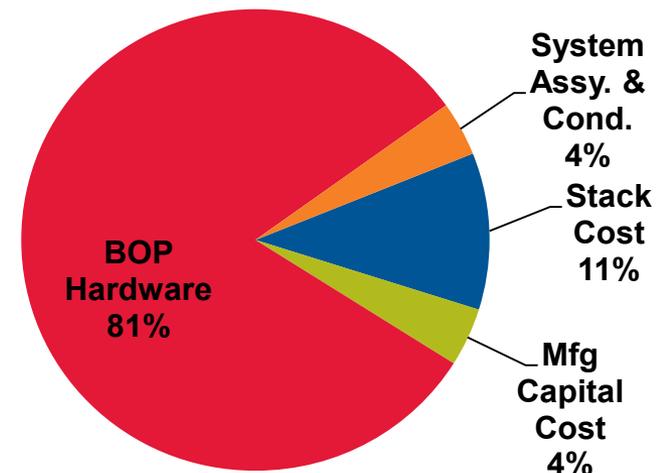
# Progress & Accomplishments – APU System Cost Comparison

- Largest System Expense = Balance of Plant (BOP) Hardware
- Avenues for BOP Cost Reductions:
  - Improved heat exchanger manufacturing
  - Reduce number of heat exchangers in system
  - Eliminate DC/DC converter
  - Alternative make-up water management – Anode Gas Recirculation?

**1 kW Units - 1000 units/yr**



**5 kW Units - 1000 units/yr**



# Progress & Accomplishments – Life Cycle Cost Analysis Assumptions

	Fuel Cell	ICE Genset	Idling Truck Engine
<b>Retail Cost of Power System *</b>	\$10,541	\$7,500	-
<b>Power Source</b>	5 kW SOFC Stack	15hp Diesel Engine	400hp Diesel Engine
<b>Hours of Operation per Year (Hrs)</b>	2,000	2,000	2,000
<b>Energy Efficiency</b>	30%	25%	3-4%
<b>Fuel Consumption per Hour (gal/hr)</b>	0.22	0.30	0.72
<b>Maintenance Cost (per hour)</b>	\$0.05	\$0.07	\$0.15
<b>Fuel Cost (per hour)</b>	\$0.77	\$1.05	\$3.50
<b>Heater and Air Conditioner</b>	\$1,800	Included in cost of system	\$1,800
<b>Installation Cost</b>	\$1,500	\$1,500	-
<b>O &amp; M Cost over 3 Years</b>	\$300	\$420	\$900
<b>Fuel Cost over 3 Years</b>	\$4,620	\$6,300	\$15,120
<b>Total Cost over 3 Years</b>	\$18,761	\$15,720	\$17,820

\* Based on 10,000 units per year

# Progress & Accomplishments – Results Summary

- Production volume has negligible effect on stack cost
  - Ceramic material and commodity cost constant across all volumes
  - Material processing requirements limit throughput
- Manufacturing Readiness Level (MRL) for many BOP components not ready for mass production – significant cost driver
  - DMFA performed on specific components (Reformer, Desulfurizer, Stack) assumes technology > MRL 9

# Progress & Accomplishments – Response to Previous Year Reviewers’ Comments

- Reviewer comment: “I don't see Plug Power in the list of collaborators. I believe they are one of the leaders in forklift sales”
  - Battelle made various efforts to include Plug Power in this effort, however they have chosen not to contribute. Alternatively Ballard provided support for MHE applications. Additionally, several collaborators have participated in the APU work.
- Reviewer comment: “We can only assume that there has been collaboration. There were no slides describing the degree of collaboration so difficult to judge. It would have been useful if the project followed the format requested”
  - A specific collaboration slide has been included to highlight collaborators and their role in the APU work.
- Reviewer comment: “Progress in the SOFC APU area has not been as good as in the MHE area.”
  - Unlike MHE applications, SOFC APU systems are less technically mature and lack significant market share. FY13 work focused specifically on the SOFC APU application.

# Collaborations

The following companies provided support for APU costing effort:

- **NexTech Materials**
  - System Design Review/Feedback
  - SOFC technology assessment
- **Precision Combustion, Inc.**
  - Fuel Processing Technology Review/Feedback
- **Delphi**
  - System Design Review/Feedback
  - BOP Design Comments
- **AVL**
  - System Design Review and Application feedback

# Proposed Future Work

Budget Period 3	Budget Period 4
<ul style="list-style-type: none"> <li>• Primary Power and CHP (PEMFC, High Temp PEMFC, SOFC)</li> <li>• 1 kW, 5 kW, 10 kW, 25 kW</li> </ul>	<ul style="list-style-type: none"> <li>• Large Scale Primary Power and CHP Applications (PEMFC, High Temp PEMFC, SOFC)</li> <li>• 100 kW, 250 kW</li> </ul>

# Summary

- **Relevance:** Help answer questions on opportunities for cost reduction to penetrate non-automotive applications
- **Approach:** Perform cost modeling including DFMA<sup>®</sup> analysis of a generic fuel cell system design developed for the application
- **Technical Accomplishments and Progress:** Completed cost analysis of SOFC for APU applications. Completed cost analysis of small PEM for MHE systems
- **Technology Transfer/Collaborations:** Working with a number of industry collaborators (e.g., Delphi, NexTech Materials, PCI) for design inputs, cost inputs, design review and results review
- **Proposed Future Research:** Primary Power and CHP Applications (PEMFC, High Temp PEMFC, SOFC)