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Stationary and Emerging Market Fuel Cell System Cost Analysis – Primary Power and Combined Heat and Power Applications

FC097

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Washington D.C.

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Overview – Program Details

Timeline

Start — FY15 — End

Oct 2011 — FY15 (BP4) — Jan 2017

Total Funding Spent $1,634K as of 3/31/16

Budget (DOE Project Funding)

$343K FY15 Funding

Total $2 M

FY16 Funding $377K

Collaborators

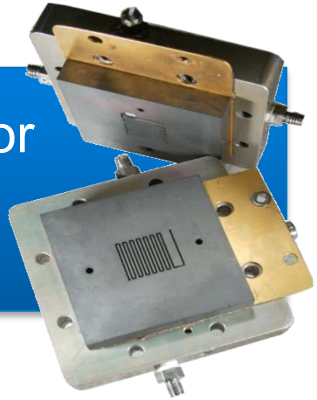
have provided design inputs, cost inputs, design review, and manufacturing cost review

- Hydrogenics
- Nexceris
- Ballard
- Dry Coolers
- Tranter
- Panasonic
- US Hybrid
- Innovatek
- Johnson Matthey/Catacel
- Advanced Power Associates
- Zahn Electronics
- API Heat Transfer
- Watt Fuel Cell
- Vicor Power
- SMA-America
- Cain Industries
- Outback Power Technologies
- Ideal Power

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 4 (BP4) - 2015

- 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications

Relevance – Technical Barriers Addressed

Technical Barriers	Project Goals
Cost reduction of fuel cell components and materials	1. Identify major contributors to fuel cell system cost 2. Identify potential cost reduction opportunities
Manufacturing capability	3. Identify major contributors to fuel cell system manufacturing cost 4. Identify areas for manufacturing R&D to improve quality and/or throughput 5. Provide basis for consideration of transition from other industries
Customer acceptance	6. Develop accurate cost projections that can be used to evaluate total cost of ownership and facilitate early market adoption

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Approach – Manufacturing Cost Analysis Methodology

Market Assessment

- Characterization of potential markets
- Identification of operational and performance requirements
- Evaluation of fuel cell technologies relative to requirements
- Selection of specific systems for cost modeling

System Design

- Conduct literature search
- Develop system design
- Gather industry input
- Size components
- Gather stakeholder input
- Refine design
- Develop bill of materials (BOM)
- Define manufacturing processes
- Estimate equipment requirements

Cost Modeling

- Gather vendor quotes
- Define material costs
- Estimate capital expenditures
- Determine outsourced component costs
- Estimate system assembly
- Develop preliminary costs
- Gather stakeholder input
- Refine models and update costs

Sensitivity & Life Cycle Cost Analysis

- Sensitivity analysis of individual cost contributors
- Life cycle cost analysis to estimate total cost of ownership

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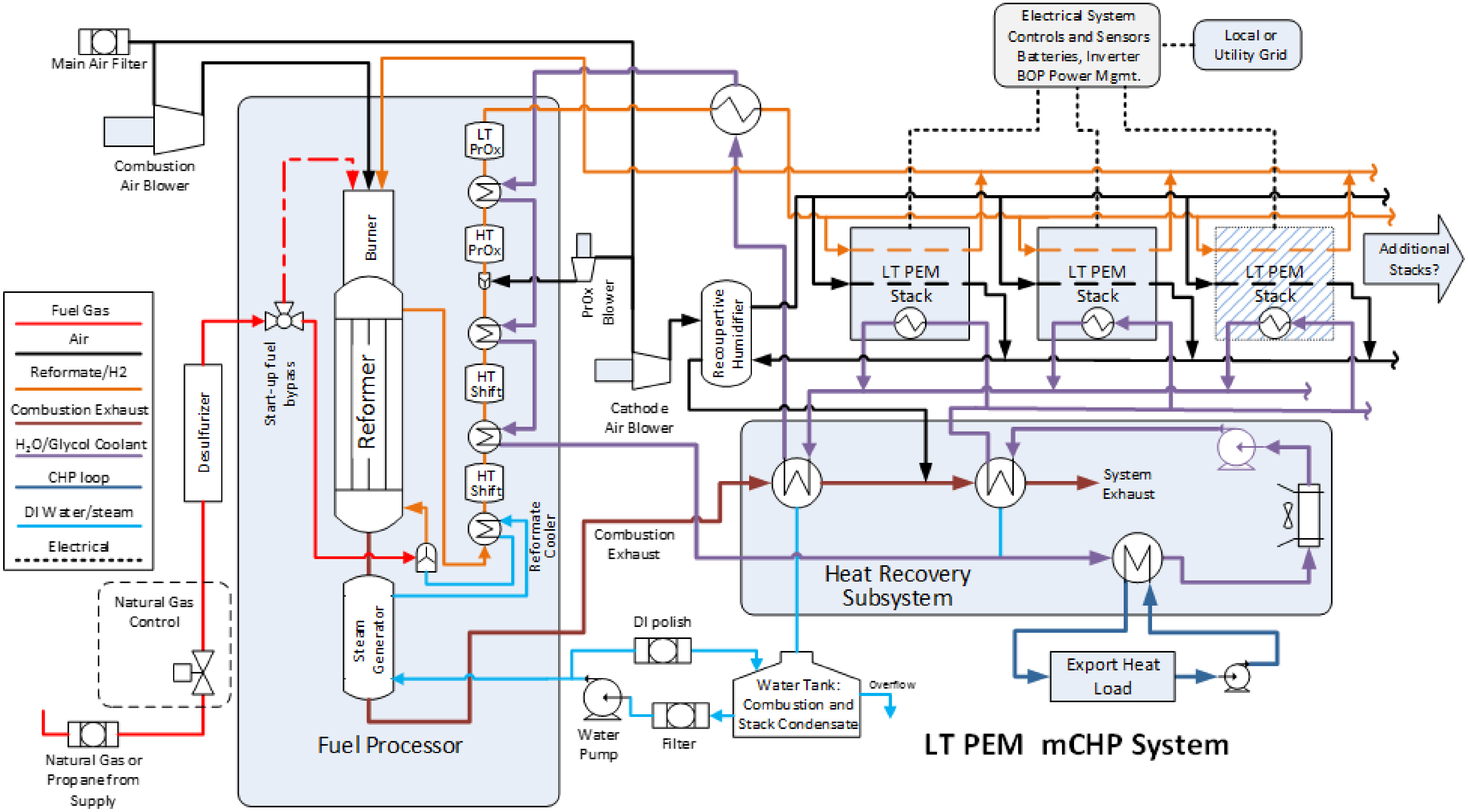
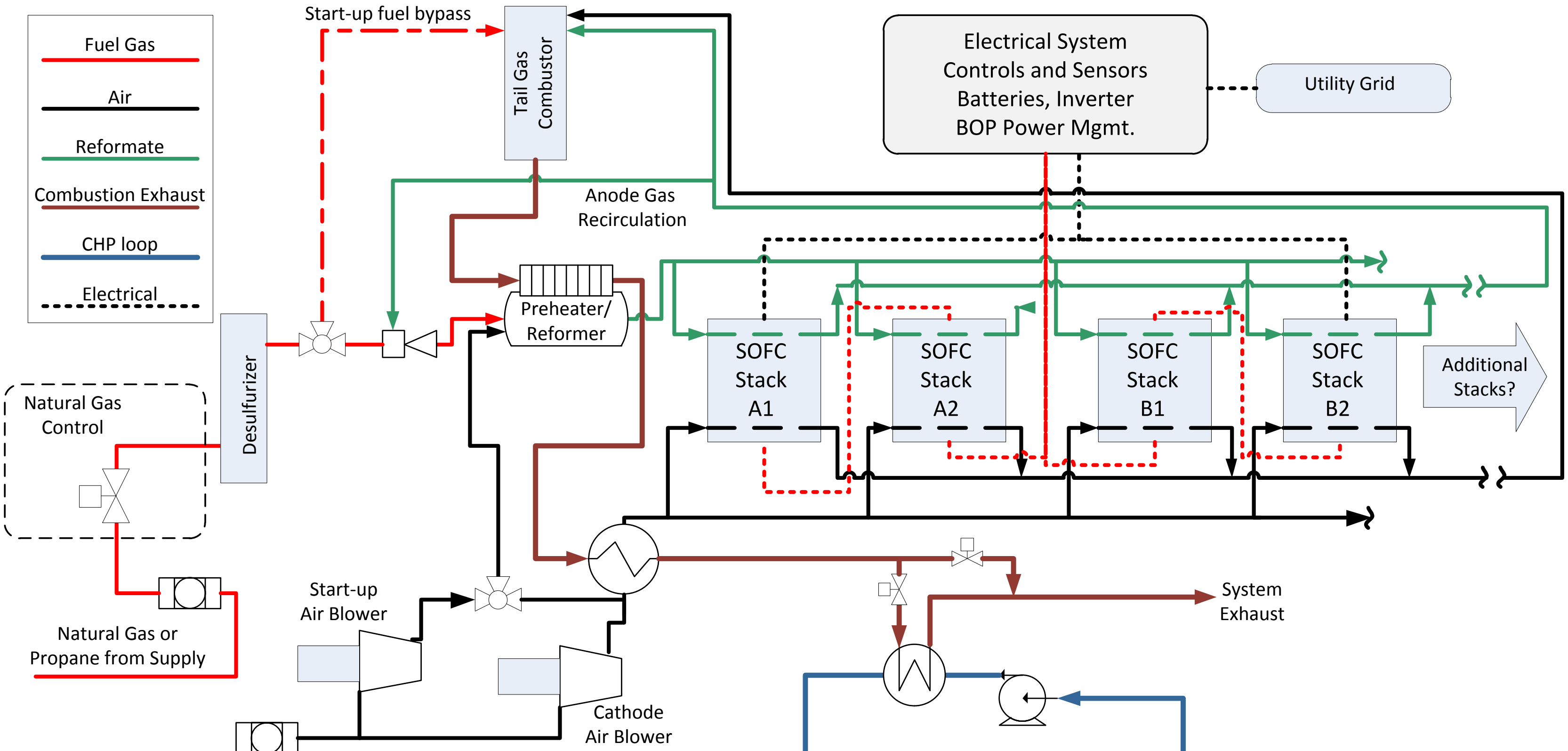
Progress & Accomplishments – Representative LTPEM CHP system

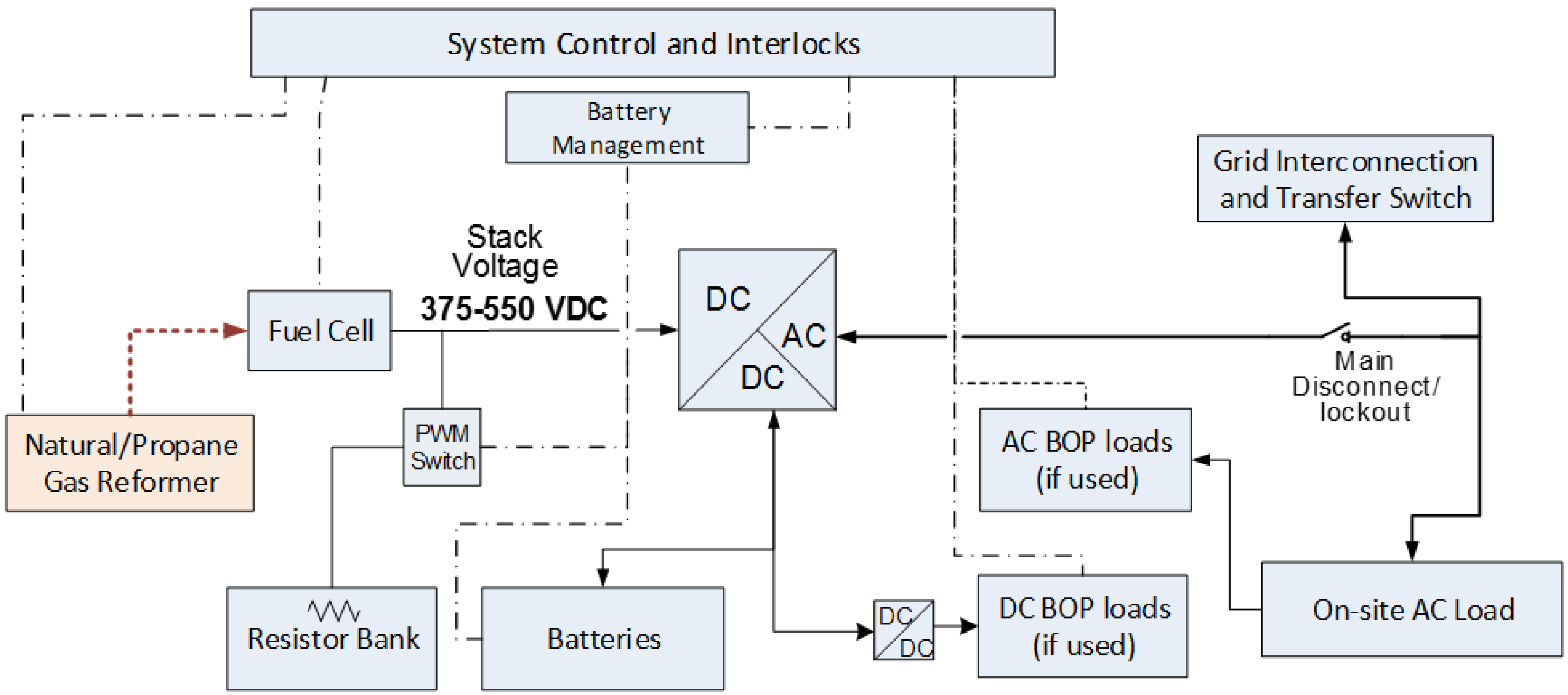


Progress & Accomplishments – Representative SOFC CHP system



SOFC
Multi-Stack mCHP System

Progress & Accomplishments – Electrical System Schematic (Hybrid Inverter)



Progress & Accomplishments – Nominal Design Basis

Metric/Feature	Objective
Input, Fuel	Utility Natural Gas or Propane
	(>30 psig preferred)
Input, Air	Ambient air (-20° to 50°C)
Input, Other	N/A
Output	120/240 VAC
	480 3-phase VAC
Net Power Output	100, 250 kW
System Efficiency (electrical)	
LTPEM	30%
SOFC	40%
System Efficiency Overall	
LTPEM	80%
SOFC	90%
System Life	50,000 hours
System Maintenance Interval (filter change: sulfur trap, air filter, fuel filter)	1 year
Grid Connection	Yes, local and/or utility
Operate off-grid	Yes, critical load back-up
Start off-grid	No

Progress & Accomplishments –PEM Fuel Cell Design Parameters

Parameter	100 kW System	250 kW System
Power Density (W/cm^2)	0.27	
Current Density (A/cm^2)	0.4	
Cell Voltage (VDC)	0.68	
Active Area Per Cell (cm^2)	780	780
System Net Power (kW)	100	250
System Gross Power (kW)	120	300
Number and Size of Stacks per System	2 x 60 kW (gross)	6 x 50 kW (gross)
Number of Cells per stack	283	236
Full Load Stack Voltage (VDC)	192	160
Membrane Base Material	PFSA, 0.2mm thick, PTFE reinforced	
Catalyst Loading	0.4 mg Pt/cm^2 (total) Cathode is 2:1 relative to Anode	
Catalyst Application	Catalyst ink applied with selective slot die coating deposition, heat dried, decal transfer	
Gas diffusion layer (GDL) Base Material	Carbon paper 0.2 mm thick	
GDL Construction	Carbon paper dip-coated with PTFE for water management	
Membrane electrode assembly (MEA) Construction	Hot press and die cut	
Seals	1 mm silicone, injection molded	
Stack Assembly	Hand assembled, Machined pressed before tie rod installation	
Bipolar Plates	Graphite composite, compression molded	
End Plates	Sand cast and machined A356 aluminum	

Progress & Accomplishments –SOFC Fuel Cell Design Parameters

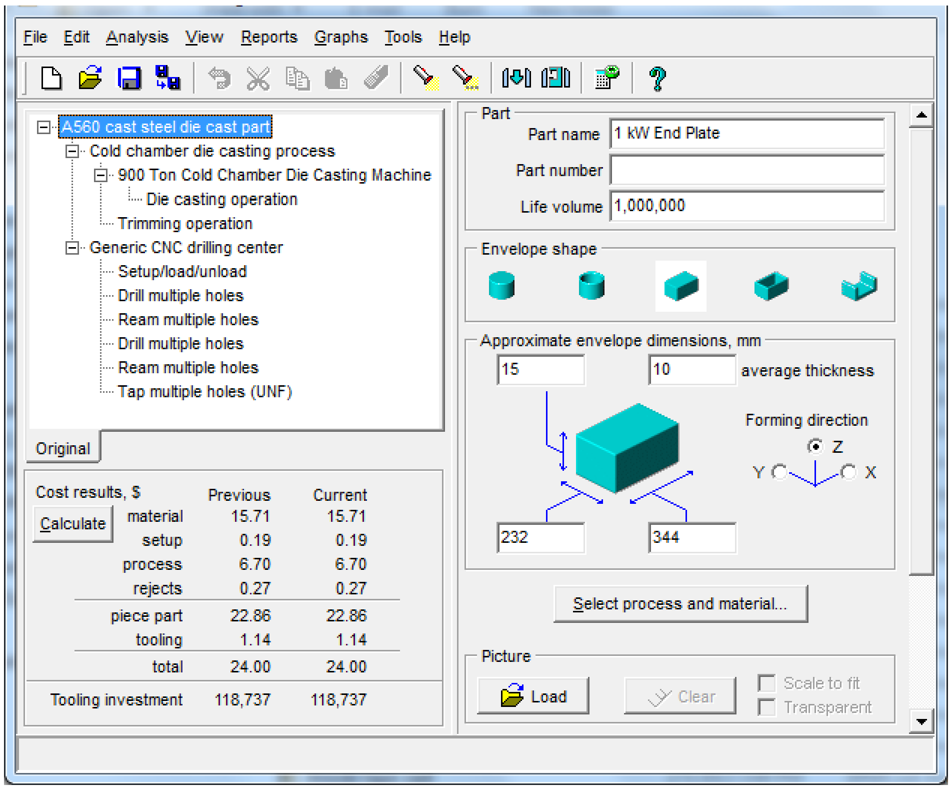
Parameter	100 kW	250 kW
Cell Power Density (W/cm^2)	0.28	
Cell Current Density (A/cm^2)	0.4	
Cell Voltage (VDC)	0.7	
Active Area Per Cell (cm^2)	414	414
System Net Power (kW, continuous)	100	250
System Gross Power (kW, continuous)	120	300
Number and Size of Stacks per System	4 x 30 kW (gross)	10 x 30 kW (gross)
Number of Cells per Stack	259	259
Stack Open Circuit Voltage (VDC)	285	285
Full Load Stack Voltage (VDC)	181	181
Cell Design	Planar, Anode supported	
Anode Material	Ni-YSZ, 500 μm thick (2 layers 250 μm thick)	
Anode Application	Tape cast, kiln fire	
Anode Active Layer Material	Ni-YSZ, 15 μm thick	
Anode Active Layer Application	Screen Print, kiln fire	
Anode Contact Layer Material	Ni-YSZ, 10 μm thick	
Anode Contact Layer Application	Screen Print, kiln fire	

Progress & Accomplishments –SOFC Fuel Cell Design Parameters

Parameter	100 kW	250 kW
Electrolyte Material	YSZ, 8 μm thick	
Electrolyte Application	Screen print, kiln fire	
Cathode Active Layer Material	YSZ/LSM, 5μm thick	
Cathode Active Layer Application	Screen Print, kiln fire	
Cathode Material	LSCF, 30 μm thick	
Cathode Application	Screen Print, kiln fire	
Cathode Contact Layer Material	LSM/YSZ, 10 μm thick	
Cathode Contact Layer Application	Screen Print, kiln fire	
Seals	Wet application bonded glass/ceramic	
Stack Assembly	Hand Assembled, tie rods, furnace brazed	
Interconnects	Ferritic Stainless Steel (SS-441) with Perovskite coating, 2-3 μm thick	
Anode/Cathode Spacer Frames	Ferritic Stainless Steel (SS-441)	
Anode/Cathode Mesh	Corrugated expanded foil (SS-441)	
End Plates	Sand Cast and Machined Hastelloy X	

Progress & Accomplishments – Methodology for Calculating Manufacturing Costs

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



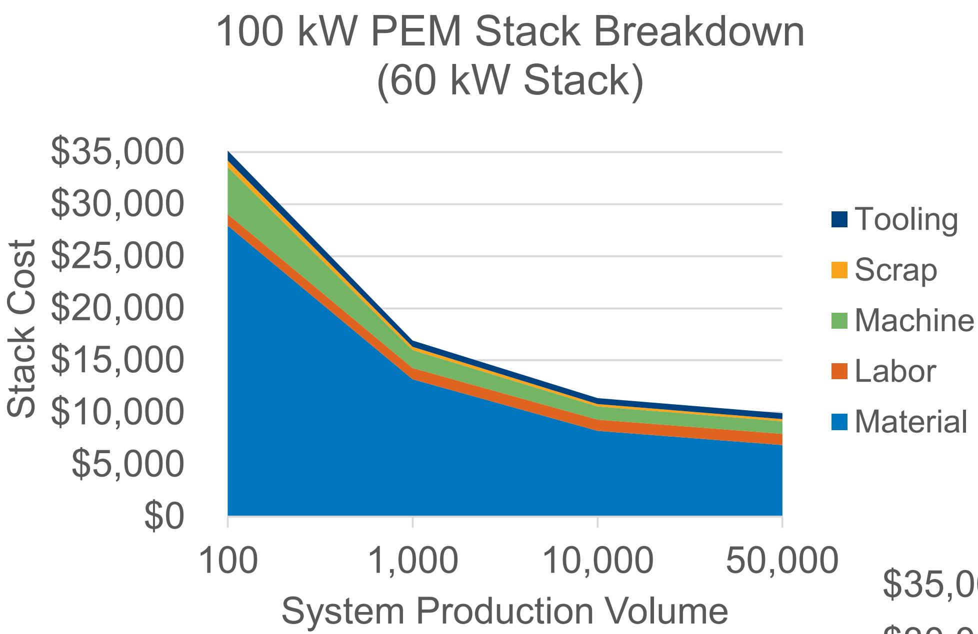
- Custom Model Development Process
  - Develop model approach and process flow
  - Perform preliminary model analysis
    - Inputs and calculations required to produce cost outputs
    - Independent verification of viability and accuracy
  - Implement model in Excel
    - Develop model using DFMA® principles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

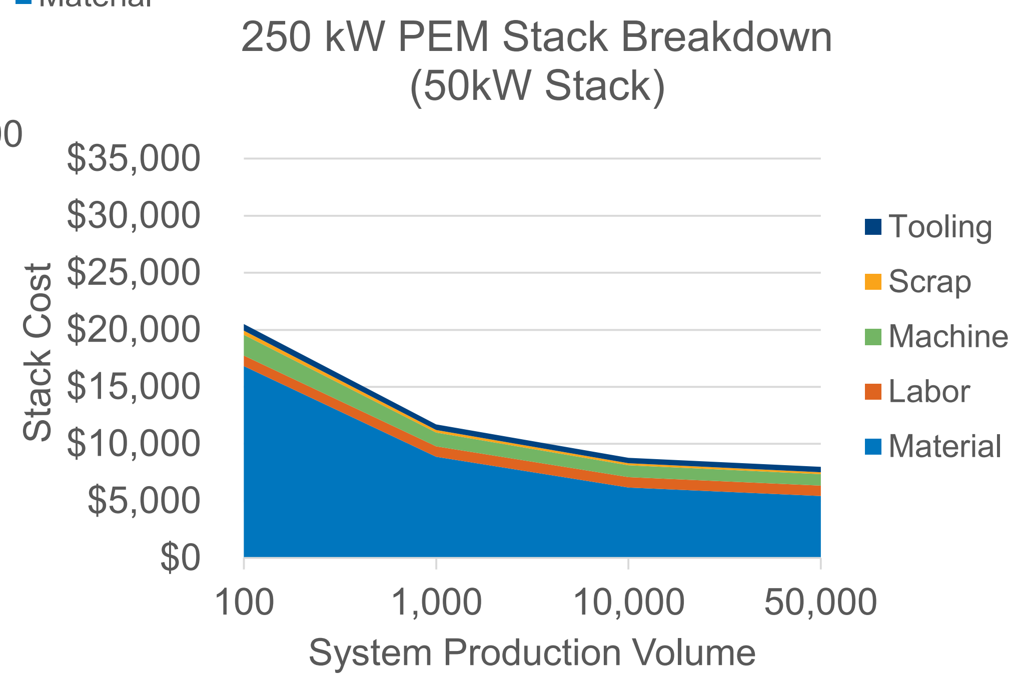
Progress & Accomplishments – PEM Stack Component Cost Summary

Stack Components	60kW Stack – 100 kW System				50kW Stack – 250 kW System			
	100 Units ($/each)	1,000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)	100 Units ($/each)	1,000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
MEA	$27,345	$12,351	$7,270	$5,867	$16,173	$8,072	$5,295	$4,543
Anode / Cooling Gasket	$517	$438	$394	$388	$405	$347	$325	$324
Cathode Gasket	$266	$196	$173	$169	$174	$155	$143	$140
Anode Bipolar Plate	$2,488	$1,591	$1,461	$1,456	$1,340	$1,241	$1,214	$1,212
Cathode Bipolar Plate	$2,350	$1,450	$1,320	$1,315	$1,222	$1,123	$1,096	$1,095
End plates	$111	$73	$49	$40	$83	$70	$49	$38
Assembly hardware	$438	$410	$383	$366	$424	$397	$371	$354
Assembly labor	$188	$166	$164	$164	$144	$138	$138	$138
Test and conditioning	$1,436	$231	$160	$159	$542	$169	$153	$151
Total Cost per Stack	**$35,140**	**$16,906**	**$11,375**	**$9,925**	**$20,507**	**$11,713**	**$8,784**	**$7,994**
Cost per kW_{net}	**$703**	**$338**	**$227**	**$198**	**$492**	**$281**	**$211**	**$192**

All costs include manufacturing scrap

PEM Fuel Cell Stack Volume Trends

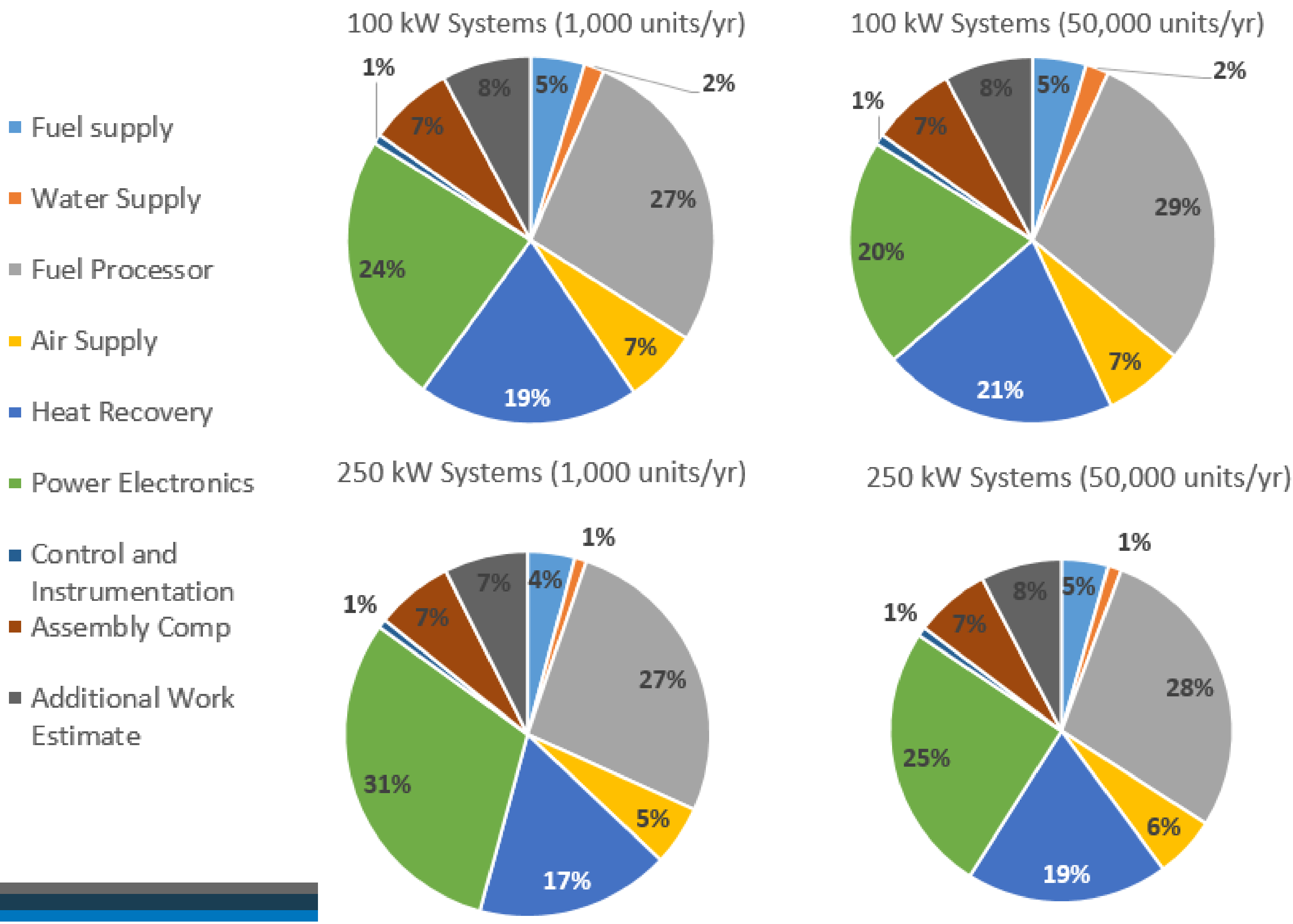




Progress & Accomplishments – CHP PEM BoP Manufacturing Cost

BoP Components	100 kW				250 kW			
	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Fuel Supply	$10,102	$8,286	$7,324	$6,741	$14,879	$12,452	$11,166	$10,358
Water Supply	$3,341	$3,095	$2,980	$2,872	$3,340	$3,144	$3,023	$2,915
Fuel Processing	$55,616	$48,005	$43,629	$41,395	$94,462	$79,221	$70,458	$66,491
Air Supply	$12,390	$11,476	$10,590	$10,009	$17,254	$15,851	$14,473	$13,607
Heat Recovery	$37,440	$33,994	$30,868	$29,466	$56,215	$51,218	$46,680	$44,665
Power Electronics	$50,894	$41,757	$33,934	$28,568	$114,436	$91,898	$72,617	$59,454
Instrumentation and Control	$1,642	$1,464	$1,324	$1,291	$2,622	$2,340	$2,108	$2,055
Assembly Components	$14,400	$13,090	$11,780	$10,605	$22,540	$20,490	$18,440	$16,600
Additional Work Estimate	$15,100	$13,700	$12,300	$11,100	$24,300	$22,100	$19,900	$17,900
BOP Total	$200,924	$174,868	$154,728	$142,047	$350,048	$298,714	$258,865	$234,045

Progress & Accomplishments – CHP PEM BoP Manufacturing Cost



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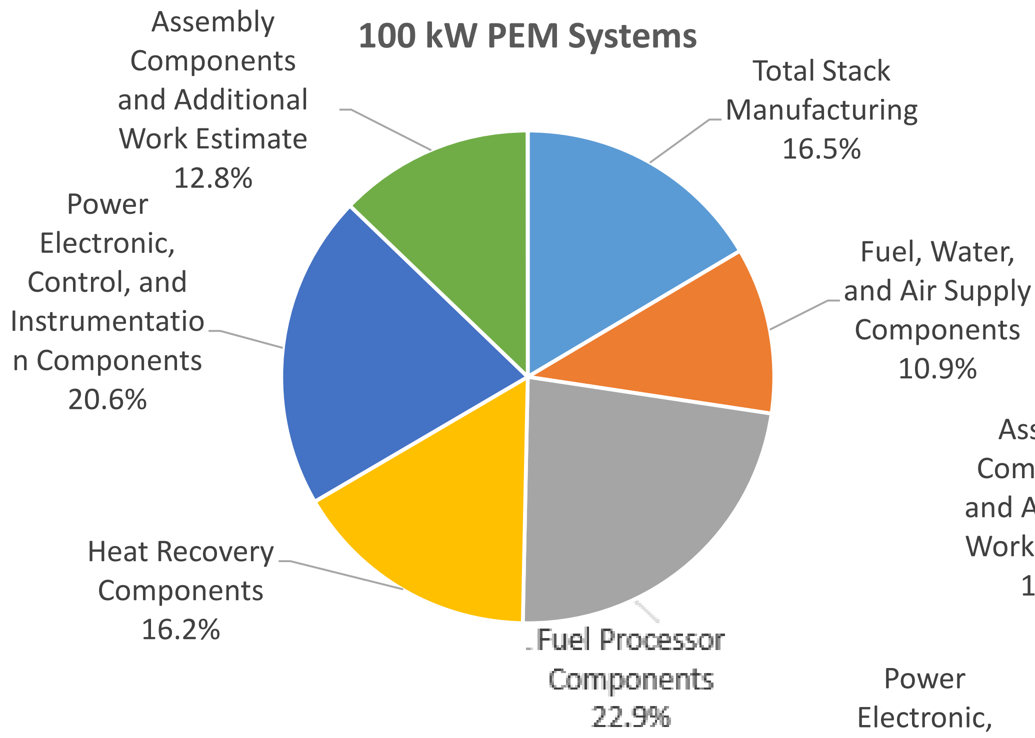
Progress & Accomplishments – 100 kW CHP PEM Fuel Cell System Cost Summary

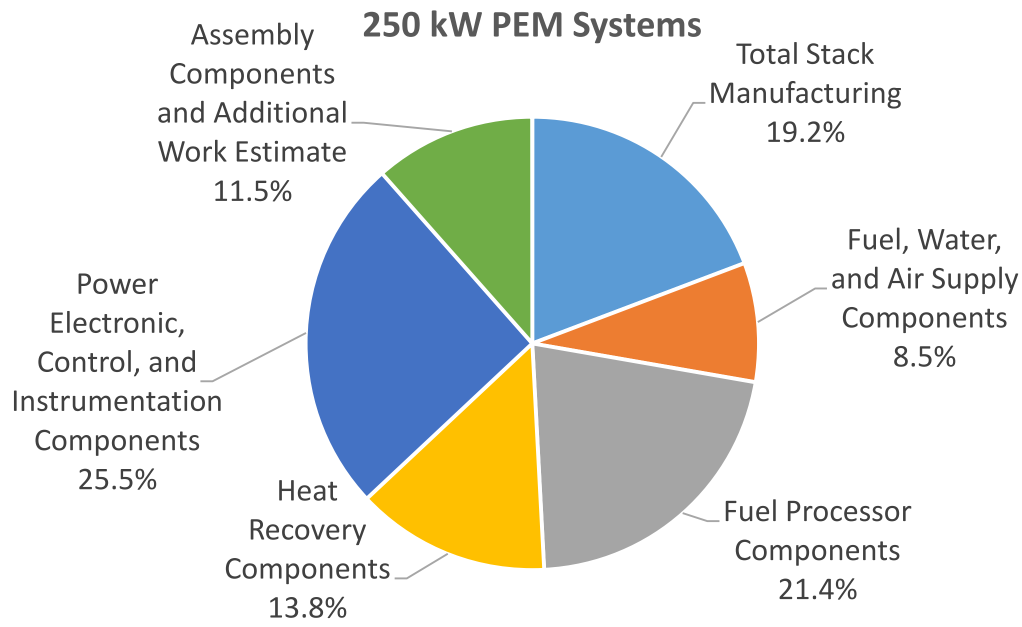
Description	100 Units/Year	1,000 Units/year	10,000 Units/Year	50,000 Units/Year
Total Stack Manufacturing	$73,522	$34,480	$23,303	$20,390
Fuel, Water, and Air Supply Components	$25,832	$22,857	$20,894	$19,622
Fuel Processor Components	$55,616	$48,005	$43,629	$41,395
Heat Recovery Components	$37,440	$33,994	$30,868	$29,466
Power Electronic, Control, and Instrumentation Components	$52,536	$43,221	$35,258	$29,859
Assembly Components and Additional Work Estimate	$29,500	$26,790	$24,080	$21,705
Total system cost, pre-markup	**$274,446**	**$209,348**	**$178,032**	**$162,438**
System cost per KW_{net}, pre-markup	**$2,744**	**$2,093**	**$1,780**	**$1,624**
Sales markup	50%	50%	50%	50%
Total system cost, with markup	**$411,670**	**$314,021**	**$267,048**	**$243,657**
System cost per KW_{net}, with markup	**$4,117**	**$3,140**	**$2,670**	**$2,437**

Progress & Accomplishments – 250 kW CHP PEM Fuel Cell System Cost Summary

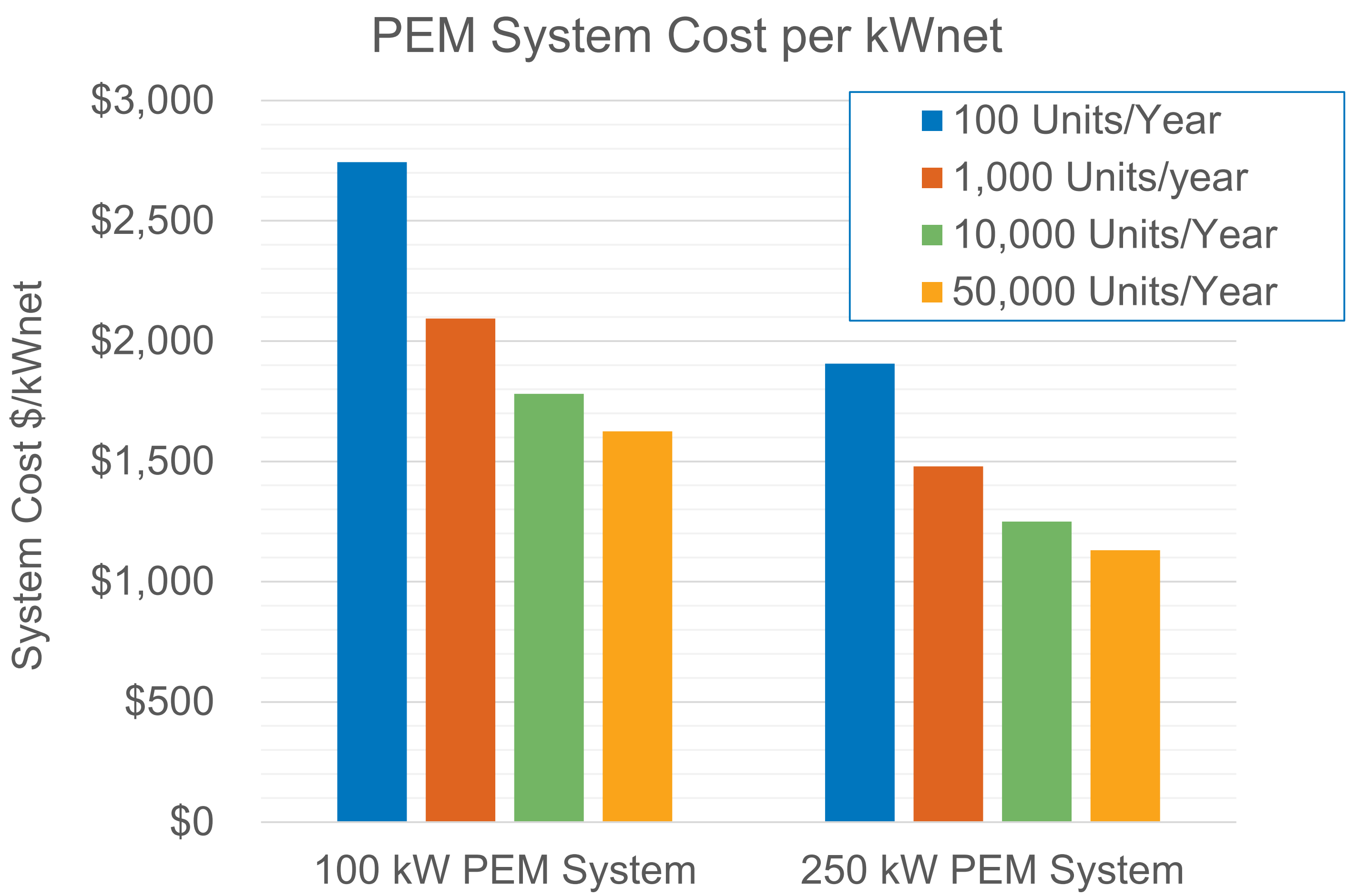
Description	100 Units/Year	1,000 Units/year	10,000 Units/Year	50,000 Units/Year
Total Stack Manufacturing	$126,587	$71,151	$53,494	$48,737
Fuel, Water, and Air Supply Components	$35,472	$31,447	$28,662	$26,881
Fuel Processor Components	$94,462	$79,221	$70,458	$66,491
Heat Recovery Components	$56,215	$51,218	$46,680	$44,665
Power Electronic, Control, and Instrumentation Components	$117,058	$94,238	$74,725	$61,509
Assembly Components and Additional Work Estimate	$46,840	$42,590	$38,340	$34,500
Total system cost, pre-markup	**$476,635**	**$369,865**	**$312,359**	**$282,782**
System cost per KW_{net}, pre-markup	**$1,906**	**$1,479**	**$1,249**	**$1,131**
Sales markup	50%	50%	50%	50%
Total system cost, with markup	**$714,952**	**$554,797**	**$468,538**	**$424,174**
System cost per KW_{net}, with markup	**$2,860**	**$2,219**	**$1,874**	**$1,697**

Progress & Accomplishments – CHP PEM Fuel Cell System Cost Summary (1,000 units/year)





Progress & Accomplishments – CHP PEM Fuel Cell System Cost Comparison



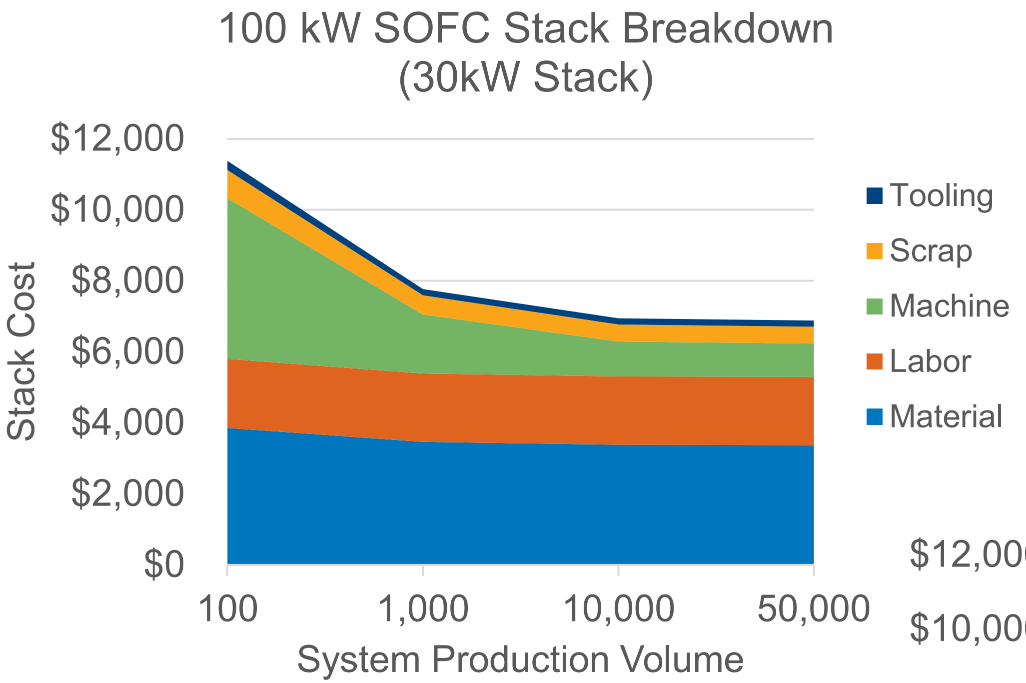
DOE Target (2015) – $2,300/kW, (2020) – $1,000/kW

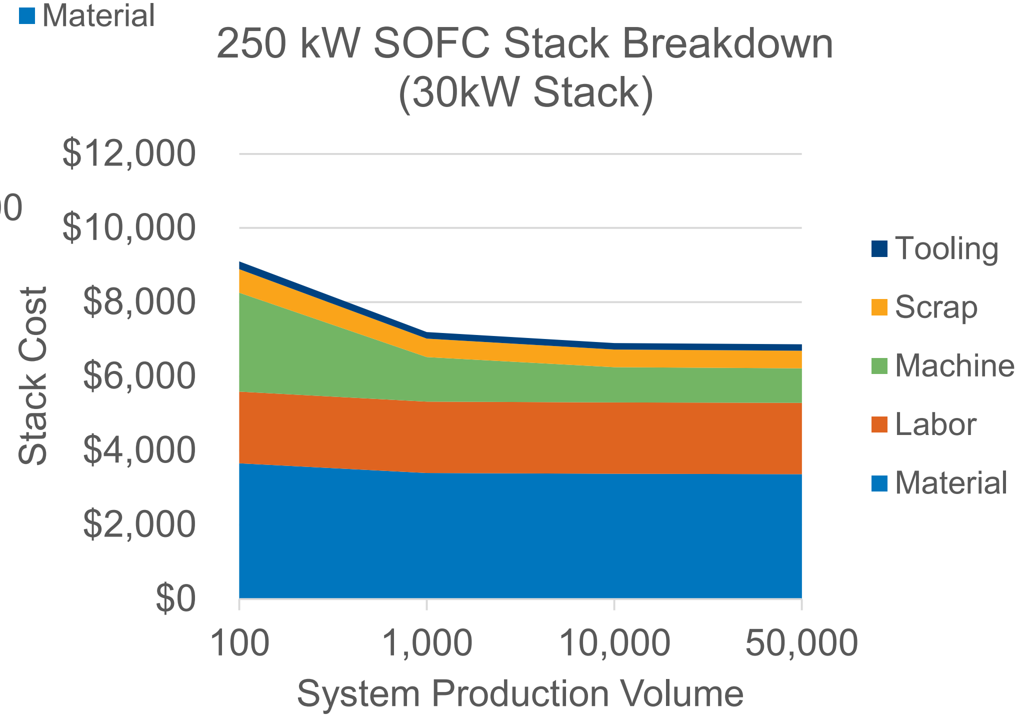
Progress & Accomplishments – SOFC Stack Manufacturing Cost

	30 kW Stack - 100 kW System				30 kW Stack - 250 kW System			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Ceramic Cells	$4,749	$3,476	$3,147	$3,110	$3,912	$3,229	$3,115	$3,103
Interconnects	$987	$610	$413	$413	$852	$477	$418	$411
Anode Frame	$375	$356	$349	$348	$364	$357	$349	$348
Anode Mesh	$301	$214	$183	$183	$269	$186	$184	$183
Cathode Frame	$131	$114	$109	$108	$121	$114	$109	$108
Cathode Mesh	$304	$217	$186	$186	$272	$189	$186	$186
Picture Frame	$149	$126	$121	$121	$136	$126	$121	$120
Laser Weld	$355	$84	$84	$84	$142	$84	$84	$84
Glass Ceramic Sealing	$1,295	$557	$504	$501	$742	$522	$501	$501
End Plates	$885	$803	$735	$733	$878	$764	$733	$733
Assembly hardware	$207	$194	$181	$173	$202	$188	$176	$168
Assembly labor	$200	$188	$187	$187	$192	$187	$187	$187
Stack Brazing	$82	$78	$56	$50	$80	$67	$50	$50
Test and conditioning	$1,360	$750	$688	$685	$934	$705	$686	$684
Total Cost per Stack	**$11,380**	**$7,767**	**$6,945**	**$6,882**	**$9,101**	**$7,195**	**$6,899**	**$6,866**

All costs include manufacturing scrap

SOFC Fuel Cell Stack Volume Trends

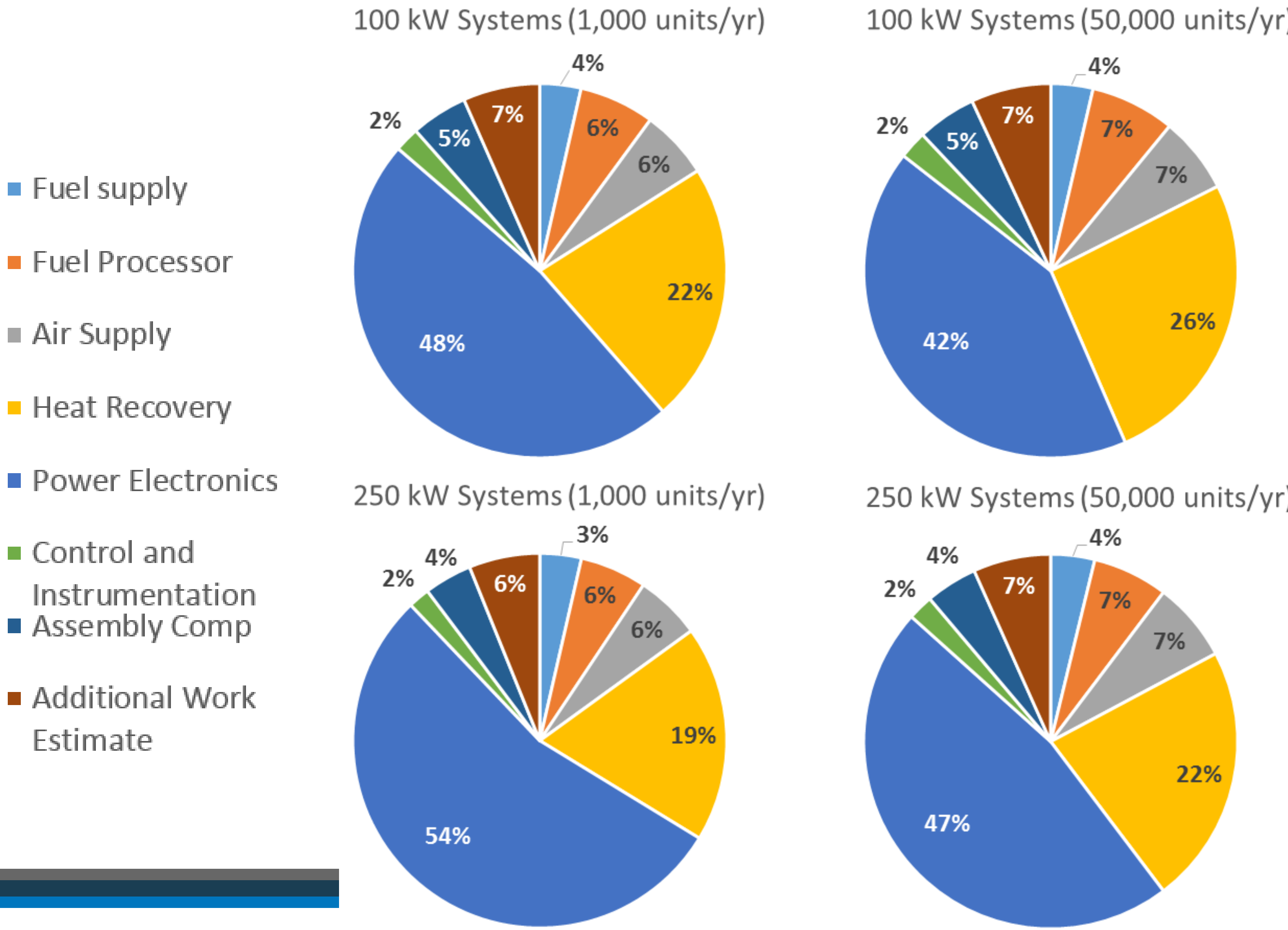




Progress & Accomplishments – CHP SOFC BoP Manufacturing Cost

BoP Components	100 kW				250 kW			
	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Fuel Supply	$4,449	$3,106	$2,663	$2,470	$7,953	$6,093	$5,372	$4,815
Fuel Processing	$8,245	$5,693	$5,247	$4,962	$14,347	$9,797	$8,604	$8,253
Air Supply	$5,659	$5,200	$4,801	$4,486	$10,345	$9,607	$8,937	$8,741
Heat Recovery	$21,057	$19,698	$18,430	$17,621	$33,857	$31,718	$29,718	$28,470
Power Electronics	$50,894	$41,757	$33,934	$28,568	$114,436	$91,898	$72,617	$59,454
Instrumentation and Control	$2,094	$1,870	$1,688	$1,645	$3,526	$3,152	$2,836	$2,763
Assembly Components	$4,705	$4,280	$3,855	$3,475	$7,710	$7,010	$6,310	$5,680
Additional Work Estimate	$6,400	$5,800	$5,200	$4,700	$11,400	$10,400	$9,400	$8,500
BOP Total	**$103,503**	**$87,405**	**$75,818**	**$67,927**	**$203,575**	**$169,675**	**$143,793**	**$126,677**

Progress & Accomplishments – CHP SOFC BoP Manufacturing Cost



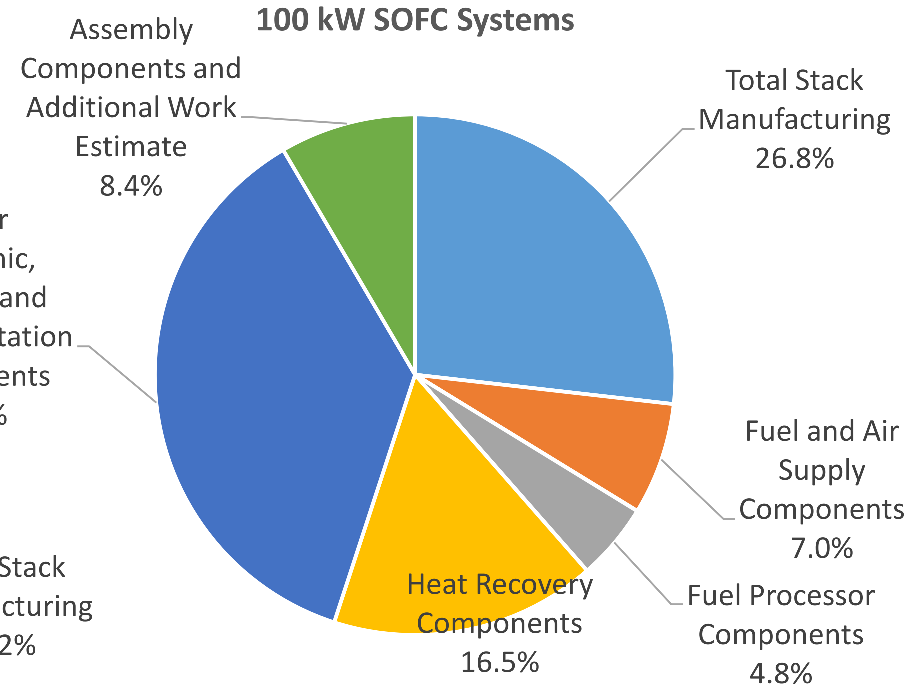
Progress & Accomplishments – 100 kW CHP SOFC Fuel Cell System Cost Summary

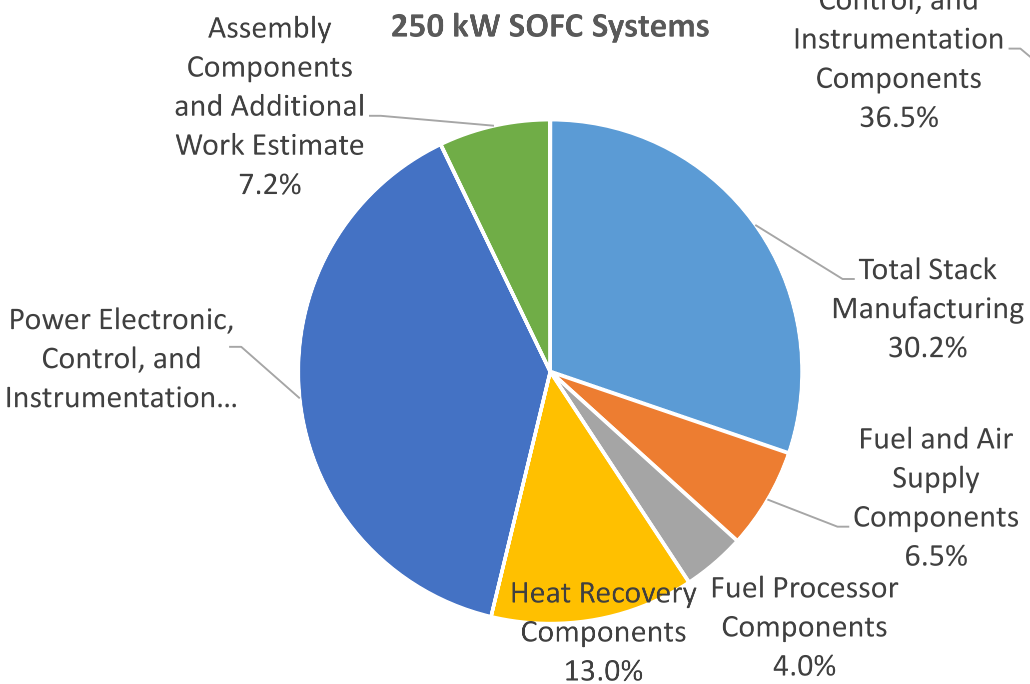
Description	100 Units/Year	1,000 Units/year	10,000 Units/Year	50,000 Units/Year
Total Stack Manufacturing	$48,191	$32,005	$28,537	$28,273
Fuel and Air Supply Components	$10,108	$8,306	$7,465	$6,956
Fuel Processor Components	$8,245	$5,693	$5,247	$4,962
Heat Recovery Components	$21,057	$19,698	$18,430	$17,621
Power Electronic, Control, and Instrumentation Components	$52,988	$43,627	$35,622	$30,213
Assembly Components and Additional Work Estimate	$11,105	$10,080	$9,055	$8,175
Total system cost, pre-markup	**$151,694**	**$119,410**	**$104,354**	**$96,200**
System cost per KW_{net}, pre-markup	**$1,517**	**$1,194**	**$1,044**	**$962**
Sales markup	50%	50%	50%	50%
Total system cost, with markup	**$227,541**	**$179,115**	**$156,532**	**$144,300**
System cost per KW_{net}, with markup	**$2,275**	**$1,791**	**$1,565**	**$1,443**

Progress & Accomplishments – 250 kW CHP SOFC Fuel Cell System Cost Summary

Description	100 Units/Year	1,000 Units/Year	10,000 Units/Year	50,000 Units/Year
Total Stack Manufacturing	$94,814	$73,566	$70,452	$70,113
Fuel and Air Supply Components	$18,298	$15,700	$14,309	$13,556
Fuel Processor Components	$14,347	$9,797	$8,604	$8,253
Heat Recovery Components	$33,857	$31,718	$29,718	$28,470
Power Electronic, Control, and Instrumentation Components	$117,962	$95,050	$75,453	$62,217
Assembly Components and Additional Work Estimate	$19,110	$17,410	$15,710	$14,180
Total system cost, pre-markup	**$298,389**	**$243,241**	**$214,244**	**$196,789**
System cost per KW_{net}, pre-markup	**$1,194**	**$973**	**$857**	**$787**
Sales markup	50%	50%	50%	50%
Total system cost, with markup	**$447,583**	**$364,861**	**$321,367**	**$295,184**
System cost per KW_{net}, with markup	**$1,790**	**$1,459**	**$1,285**	**$1,181**

Progress & Accomplishments – CHP SOFC Fuel Cell System Cost Summary (1,000 units/year)





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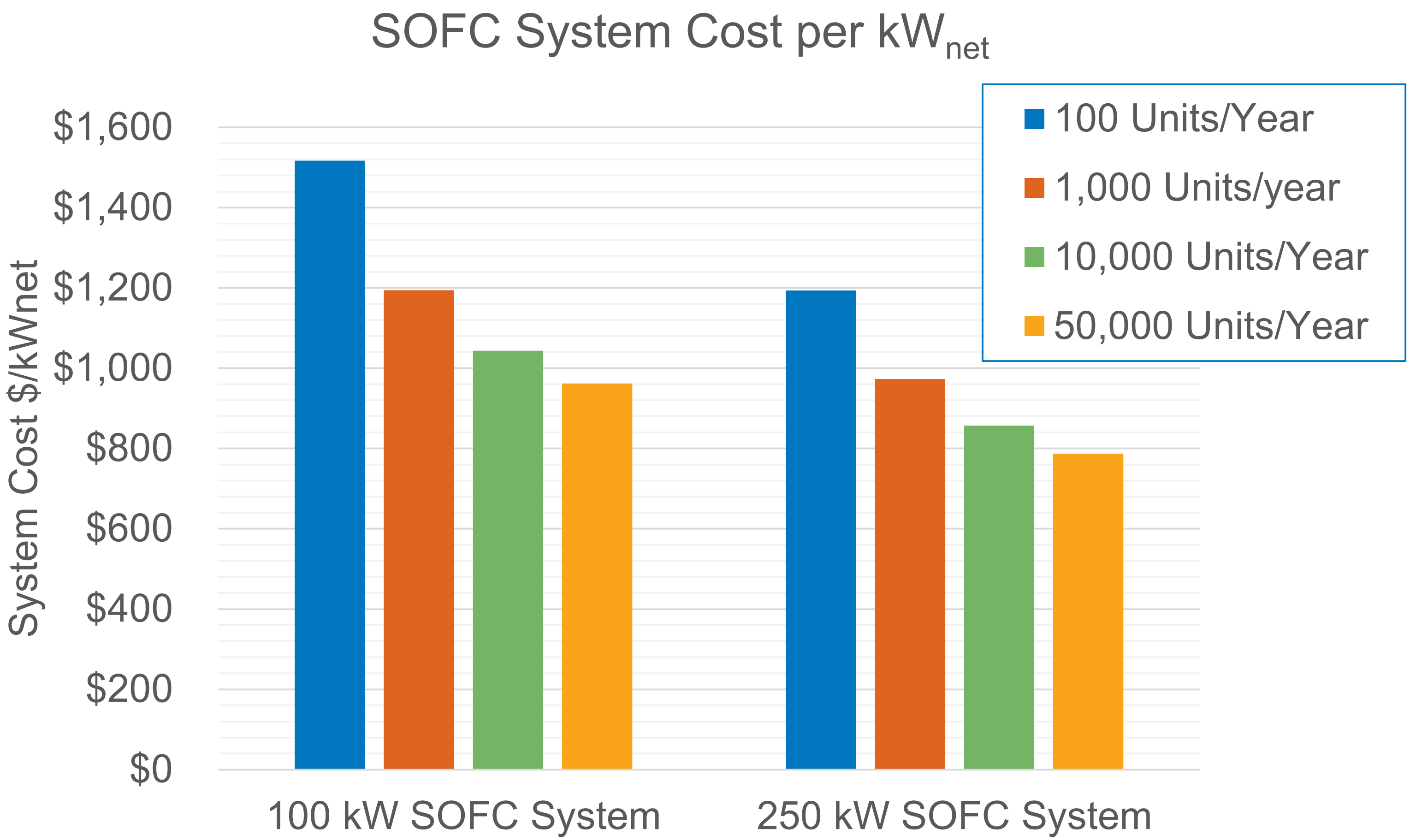
Progress & Accomplishments – CHP SOFC Fuel Cell System Cost Comparison



DOE Target (2015) – $2,300/kW, (2020) – $1,000/kW

Progress & Accomplishments – Results Summary

- BOP costs dominate system cost
- Within BOP costs
  - Power electronics is a major contributor for both technologies
  - Heat recovery and fuel processing contribute significantly for PEM systems
- An attractive value proposition exists
  - Under high spark-spread utility rate conditions
  - Improved if able to utilize waste heat
- Manufacturing Readiness Level (MRL) for many BOP components not ready for mass production – significant cost driver
  - DFMA® performed on specific components (Fuel Processing, Stack) assumes technology > MRL 9

Progress & Accomplishments – Response to Previous Year Reviewers' Comments

- FY15 Reviewer comment: *"Batteries are used only in cases of black-start capability and off-grid operation. Those are rather exotic applications, especially for urban markets. The majority of urban markets are rather unlikely to have such systems and would not justify the expense."*
  - Clarification – Batteries are not for black start, but rather to accommodate load following. Although the grid could assist with this, overwhelming feedback suggests that back-up power (covering critical loads) would be an important feature.
- FY15 Reviewer comment: *"Overall efficiency of 80% for LT-PEM seems excessive. The low-quality heat from the PEM system makes thermal recovery limited."*
  - Although the heat quality of the PEM system is not as high as with the SOFC system, because of the reformer, the temperatures available are higher than with a direct hydrogen system. Feedback has been mixed on this subject, with some saying 80% is too high and other saying it is too low."
- FY15 Reviewer comment: *"It was unclear whether the project used any thermodynamic process modeling. If not, there is plenty to tap into, and these models are absolutely necessary for component sizing."*
  - We agree…ChemCad was used for thermodynamic process modeling and incorporated into component sizing.

Collaborations

The following list of companies is a sampling of those that provided support for the CHP and Primary Power effort. A complete list is on slide 2.

- Johnson Matthey/Catacel
  - System Design Review/Feedback
  - Fuel Processing technology review/feedback
- Nexceris
  - System Design Review/Feedback
  - SOFC technology assessment
- Tranter
  - BOP design guidance
- Ballard
  - System Design Review/Feedback
- Panasonic
  - System Design Review/feedback
  - BOP design guidance

Proposed Future Work

Budget Period 5
• Revisit all applications in previous 4 budget periods and update reports

Summary

- **Relevance:** Help answer questions on opportunities for cost reduction to penetrate non-automotive applications
- **Approach:** Perform cost modeling including DFMA® analysis of a generic fuel cell system design developed for the application
- **Technical Accomplishments and Progress:** Completed cost analysis of 100 and 250 kW fuel cell systems for primary power and combined heat and power applications
- **Technology Transfer/Collaborations:** Working with a number of industry collaborators (e.g., Johnson Matthey/Catacel, Nexceris, Ballard) for design inputs, cost inputs, design review and results review
- **Proposed Future Research:** Revisit all applications in previous 4 budget periods and update all reports