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

FC097

06/11/2015

Washington D.C.

Overview – Program Details

Timeline

Start: Oct 2011

FY14 (BP3)

End: Sep 2016

Budget (DOE Project Funding)

$486K FY14 Funding

Total $2 M

Total Funding Spent $1,277K as of 3/31/15

FY15 Funding $343K

Collaborators

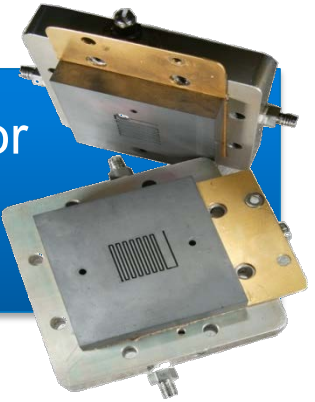
have provided design inputs, cost inputs, design review, and manufacturing cost review

- Hydrogenics
- NexTech
- Ballard
- Innovatek
- Panasonic
- US Hybrid
- Johnson Matthey/Catacel
- Advanced Power Associates
- Zahn Electronics
- Watt Fuel Cell
- Vicor Power
- SMA-America
- Outback Power Technologies

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 3 (BP3)

- 1, 5, 10 and 25 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. Quantify potential cost reduction based upon technological improvements
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

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

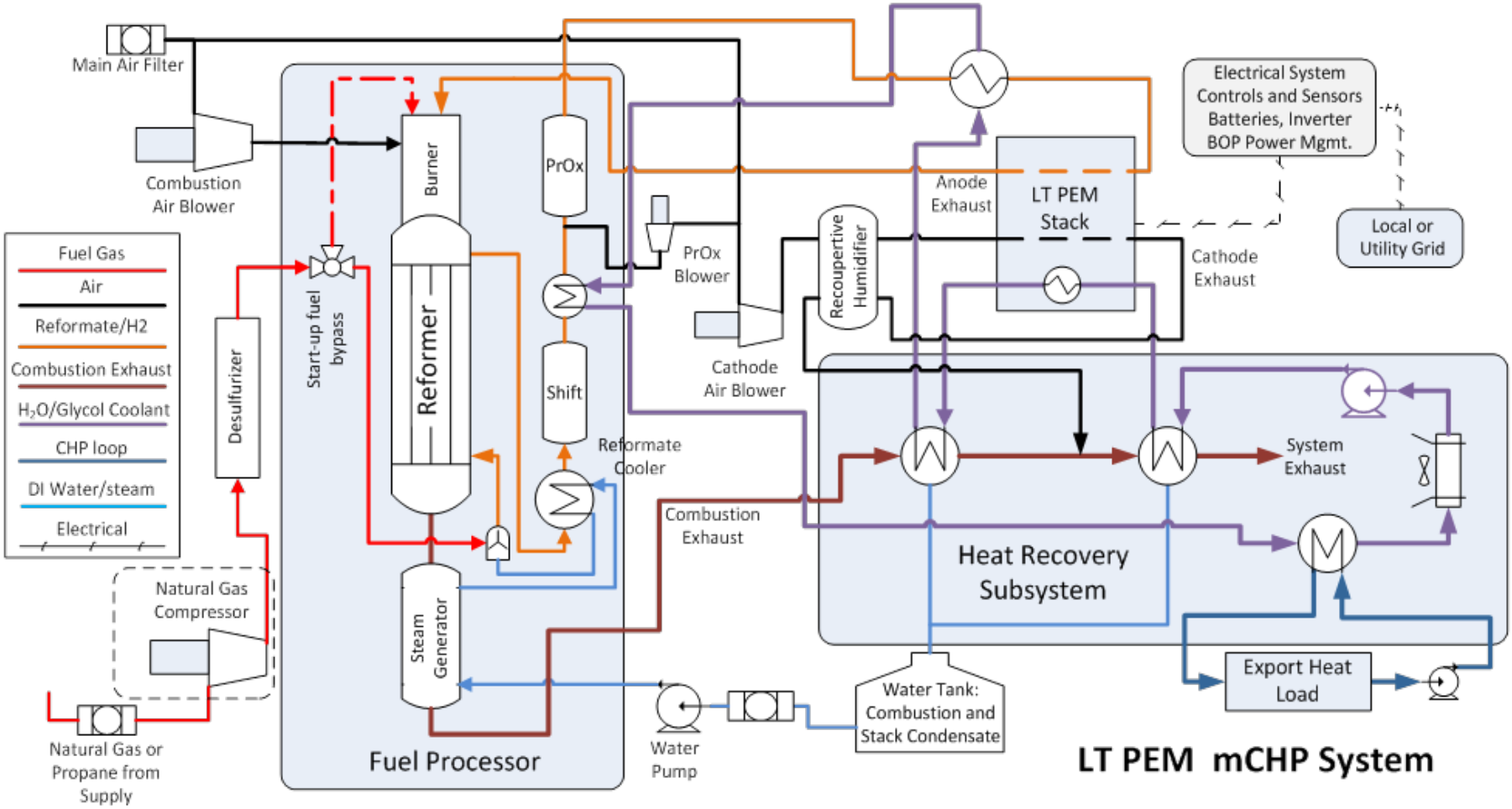
Cost Modeling

- 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

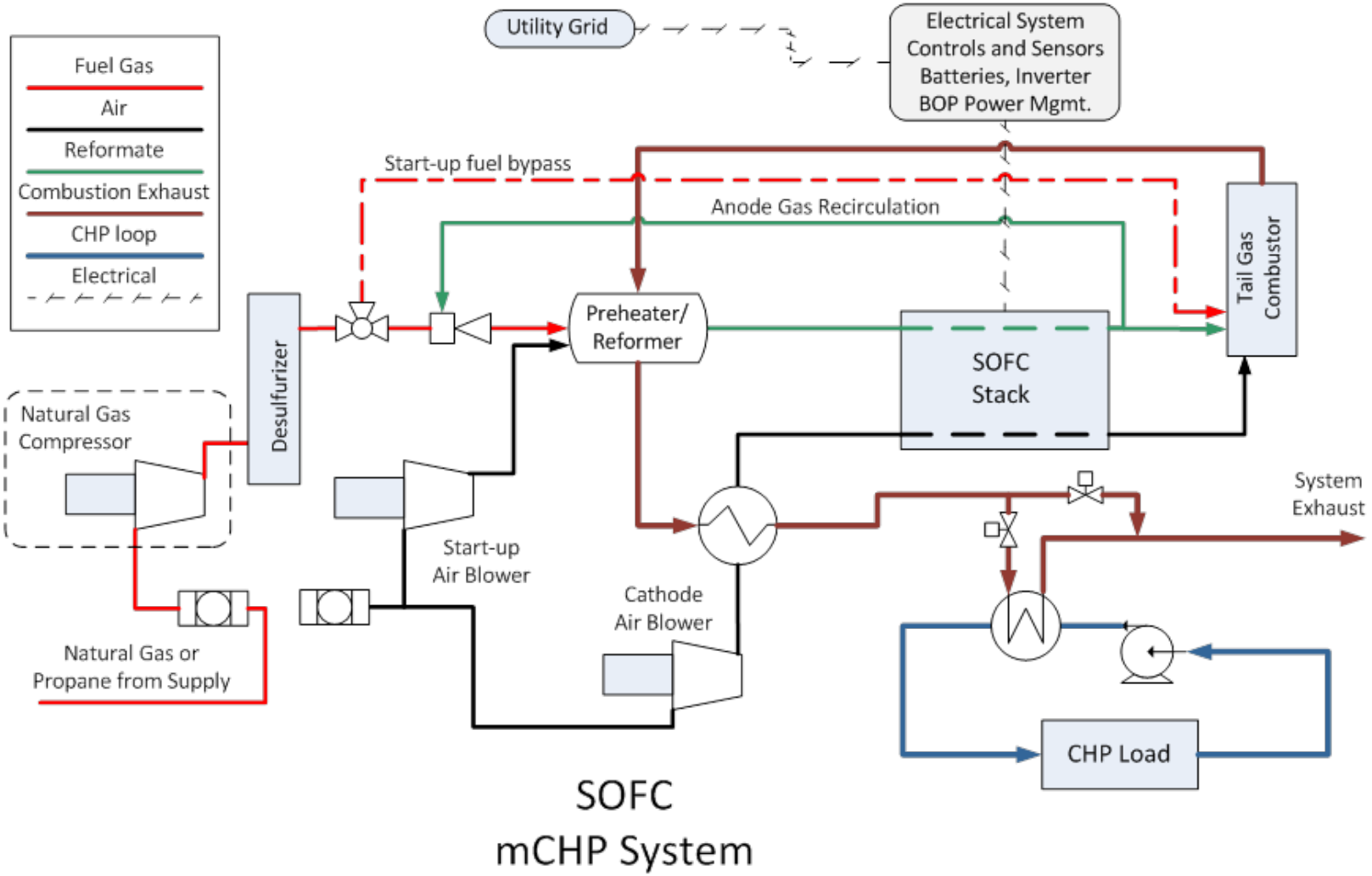
Sensitivity & Life Cycle Cost Analysis

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

Progress & Accomplishments – Representative LTPEM CHP system

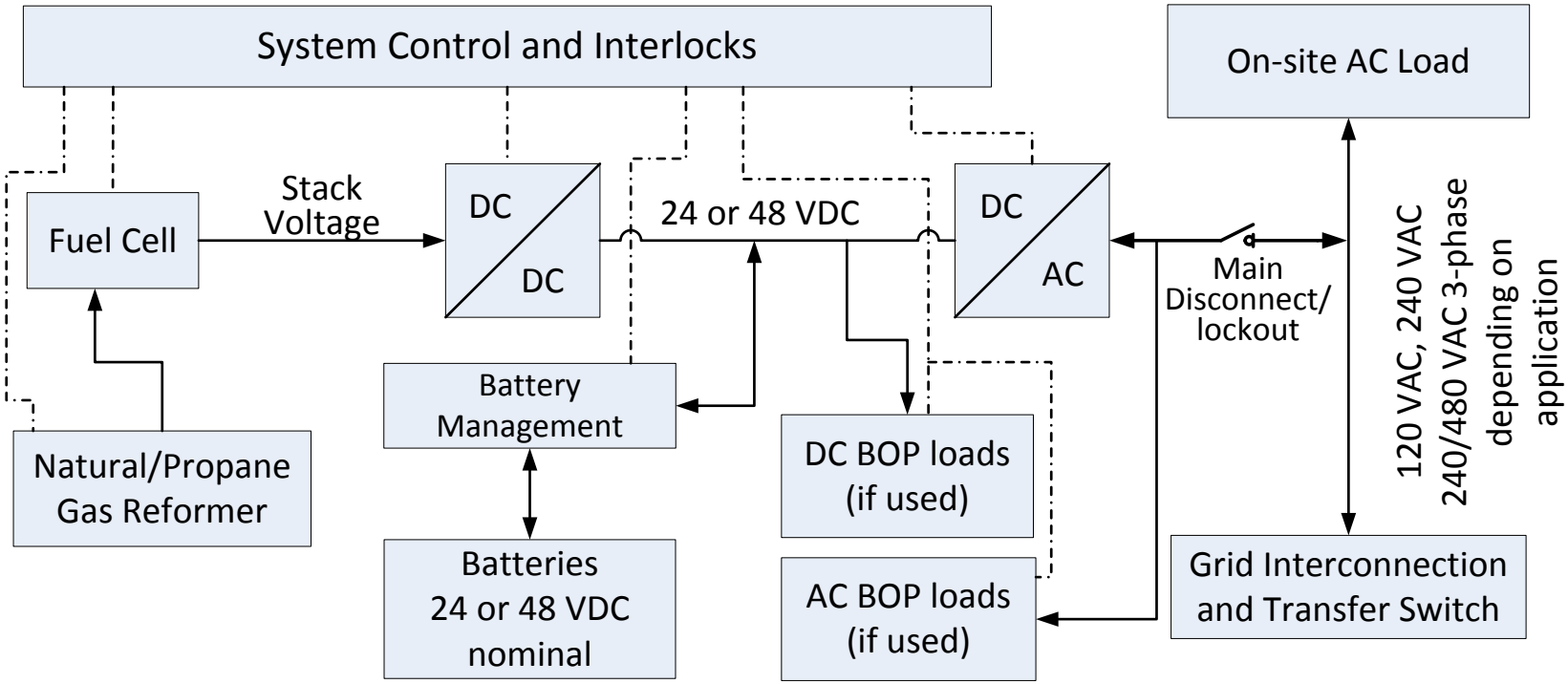


Progress & Accomplishments – Representative SOFC CHP system



SOFC
mCHP System

Progress & Accomplishments – Electrical System Schematic



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 VAC 3-phase optional
Net Power Output	1, 5, 10, 25 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	1 kW	5 kW	10 kW	25 kW
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)	200		400	
Net Power (kW)	1	5	10	25
Gross Power (kW)	1.2	6	12	30
Number of Cells (#)	22	110	110	276
Full Load Stack Voltage (VDC)	15	75	75	188
Membrane Base Material	PFSA, 0.2mm thick, PTFE reinforced			
Catalyst Loading	0.4 mg Pt/cm2 (total) Cathode is 2:1 relative to Anode			
Catalyst Application	Catalyst ink prepared, 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, infection molded			
Stack Assembly	Hand assembled, tie rods			
Bipolar Plates	Graphite composite, compression molded			
End Plates	Die cast and machined A356 aluminum			

Progress & Accomplishments –SOFC Fuel Cell Design Parameters

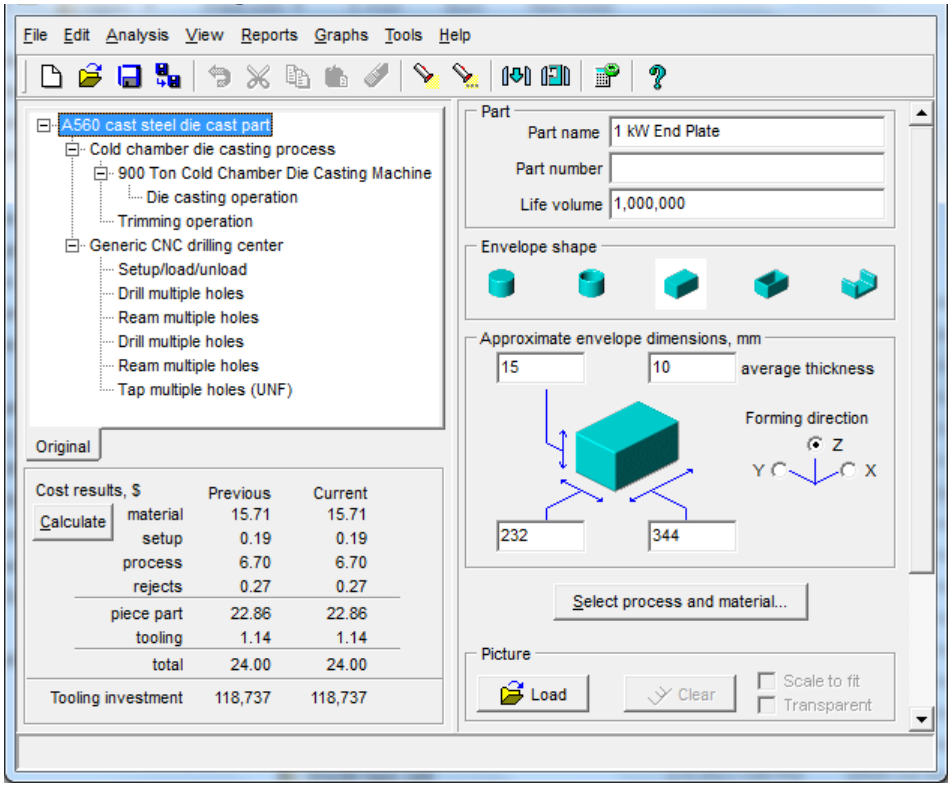
Parameter	1 kW	5 kW	10 kW	25kW
Cell Power Density (W/cm^2)	0.32			
Cell Current Density (A/cm^2)	0.4			
Cell Voltage (VDC)	0.7			
Active Area Per Cell (cm^2)	200	200	400	400
Rated Net Power (kW, continuous)	1	5	10	25
Rated Gross Power (kW, continuous)	1.2	6	12	30
Number of Cells (#)	21	107	107	268
Open Circuit Voltage (VDC)	24	118	118	295
Full Load Stack Voltage (VDC)	15	75	75	188
Cell Design	Planar, Anode supported			
Anode Material	Ni-8YSZ, 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			
Electrolyte Material	8YSZ, 8 µm thick			
Electrolyte Application	Screen print, kiln fire			

Progress & Accomplishments –SOFC Fuel Cell Design Parameters

Parameter	
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
End Plates	Die Cast and Machined A560 Steel

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 –Manufacturing Processes Evaluated

PEM

Process	Method Evaluated	Alternatives not Evaluated
Catalyst deposition	Slot die coating	Tape casting Nanostructure Thin Film Screen printing Spray coating
	Single head slot die with decal transfer	Dual head slot die Multi-pass slot die
Bipolar plate	Compression molding	Die stamping and coating (metal plates)
MEA forming	Ruler blade die cutting	Laser cutting
Gasket/seal forming	Injection molding	Laser cutting Die cutting

SOFC

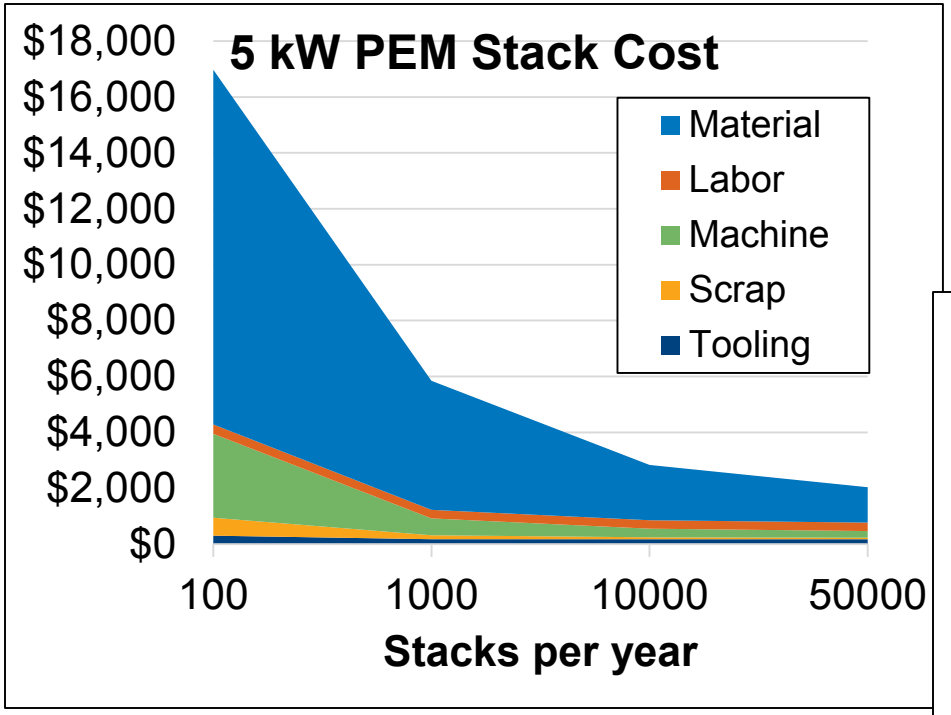
Process	Method Evaluated	Alternatives not Evaluated
Ceramic deposition	Screen printing	Plasma spray coating
	Tape casting	
Interconnect	Sheet metal stamping, laser etching	Laser cutting, water jet cutting, chemical etching
	Spray deposition coating	CVD/PVD
Sealing	Bead deposition	Screen printing, tape casting
Picture frame	Sheet metal stamping	Laser cutting, water jet cutting.
End plate	Die casting + final machining	Stamping, welding
	Machine from block (not chosen)	

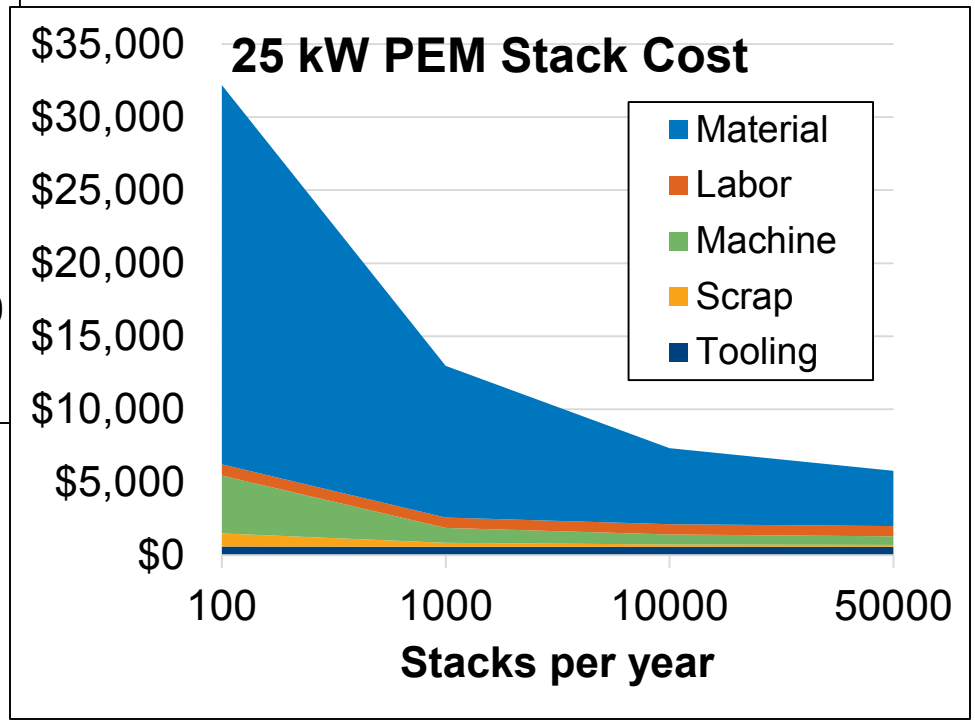
Progress & Accomplishments – PEM Stack Manufacturing Cost (5&25kW)

Stack Components	5 kW				25 kW			
	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	$12,756	$4,518	$1,877	$1,147	$26,050	$10,404	$5,163	$3,705
Bipolar plates	$821	$587	$438	$419	$2,280	$1,414	$1,261	$1,214
Seals	$175	$170	$165	$158	$431	$419	$407	$393
End plates	$57	$43	$41	$20	$65	$50	$47	$42
Assembly hardware	$74	$74	$74	$74	$74	$74	$74	$74
Assembly labor	$80	$64	$63	$63	$194	$155	$151	$151
Test and conditioning	$3,013	$390	$177	$156	$3,107	$452	$226	$200
Total Cost	**$16,978**	**$5,846**	**$2,835**	**$2,038**	**$32,200**	**$12,967**	**$7,329**	**$5,779**
Cost per kW_{net}	**$3,396**	**$1,169**	**$567**	**$408**	**$1,288**	**$519**	**$293**	**$231**

All costs include manufacturing scrap

PEM Fuel Cell Stack Volume Trends

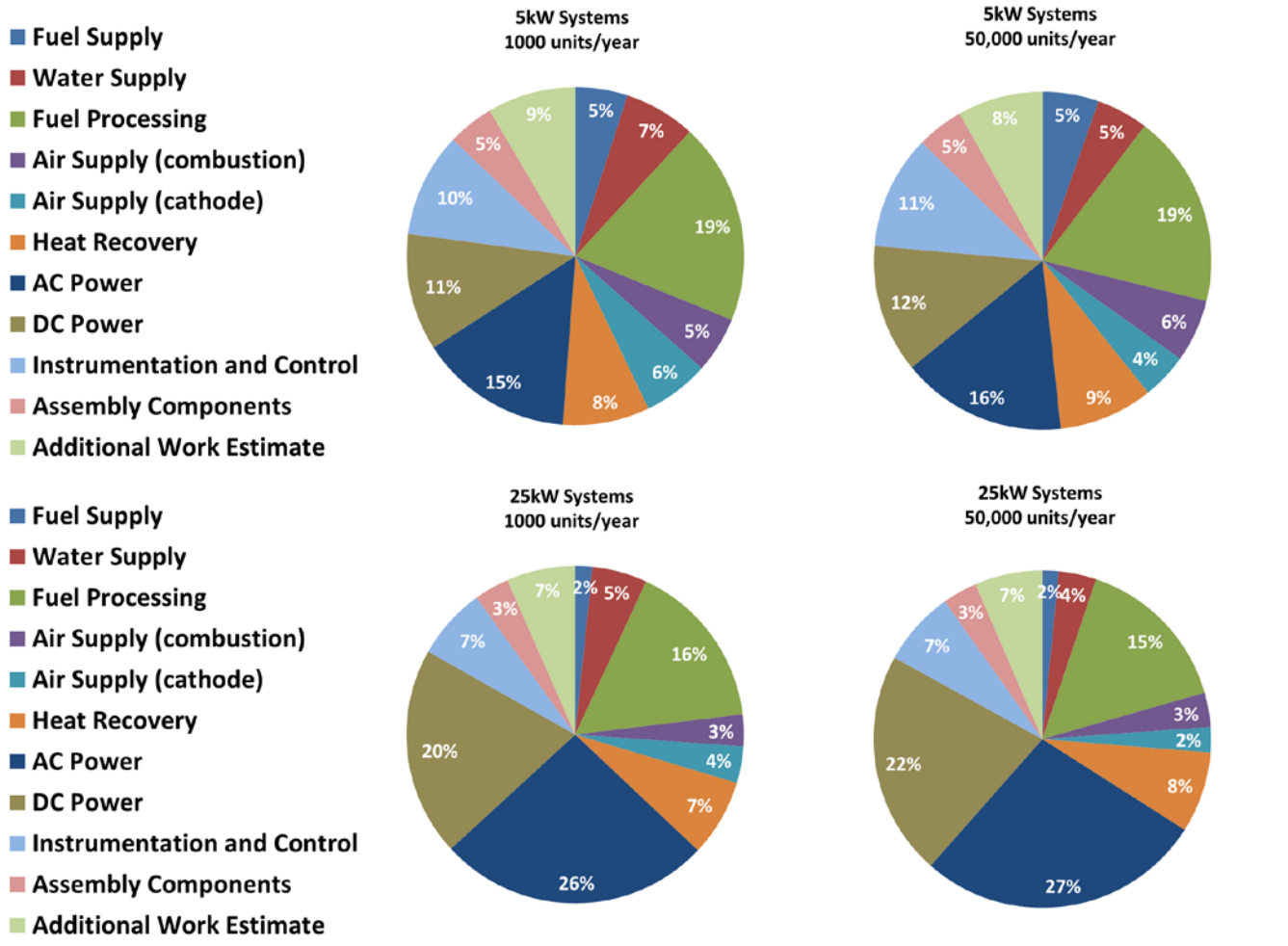




Progress & Accomplishments – CHP PEM BoP Manufacturing Cost

BoP Components	5 kW				25 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	$1,620	$766	$687	$658	$1,782	$646	$553	$508
Water Supply	$1,226	$1,050	$784	$604	$2,267	$2,083	$1,495	$1,164
Fuel Processing	$3,975	$2,962	$2,432	$2,262	$8,713	$6,386	$5,399	$4,989
Air Supply (Combustion)	$893	$824	$762	$733	$1,311	$1,198	$1,106	$1,069
Air Supply (Cathode)	$1,234	$972	$640	$539	$1,749	$1,384	$921	$781
Heat Recovery	$1,592	$1,276	$1,153	$1,103	$3,706	$2,924	$2,637	$2,515
AC Power	$2,438	$2,253	$2,083	$1,935	$11,150	$10,321	$9,555	$8,899
DC Power	$2,123	$1,721	$1,560	$1,500	$10,638	$7,900	$7,283	$6,970
Instrumentation and Control	$1,700	$1,531	$1,390	$1,335	$3,012	$2,719	$2,459	$2,330
Assembly Components	$746	$678	$610	$548	$1,455	$1,323	$1,190	$1,072
Additional Work Estimate	$1,600	$1,300	$1,100	$1,000	$3,200	$2,600	$2,200	$2,100
BOP Total	**$19,146**	**$15,335**	**$13,202**	**$12,216**	**$48,983**	**$39,485**	**$34,799**	**$32,396**

Progress & Accomplishments – CHP PEM BoP Manufacturing Cost



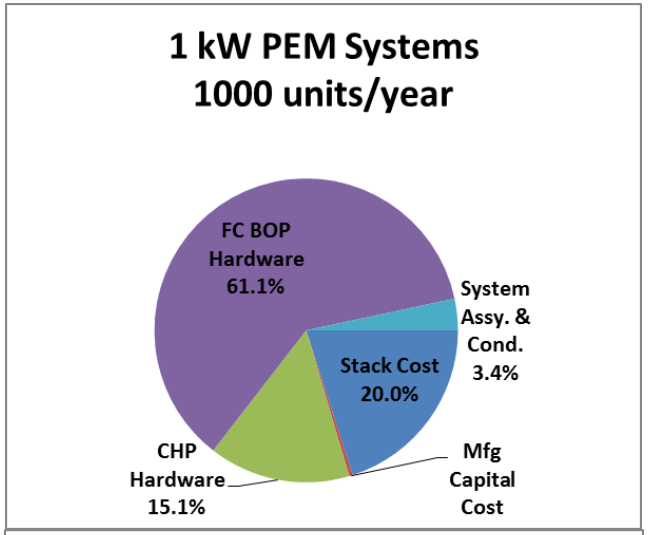
Progress & Accomplishments – 5 kW CHP PEM Fuel Cell System Cost Summary

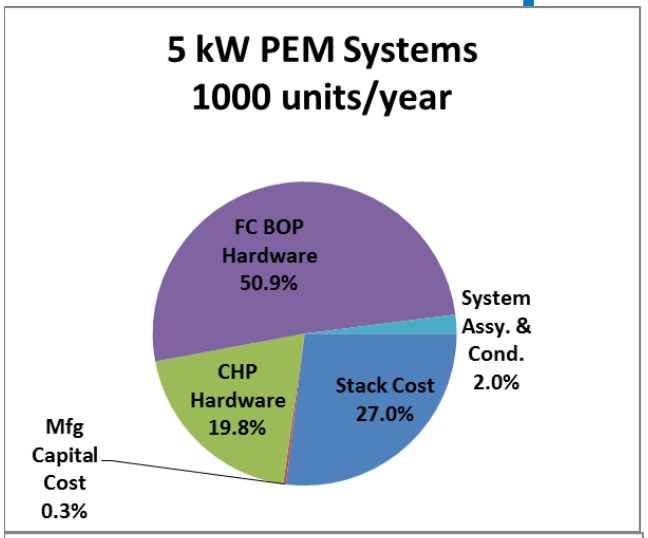
BoP Components	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Total stack manufacturing cost, with scrap	$16,978	$5,847	$2,835	$2,039
Stack manufacturing capital cost	$481	$62	$24	$24
CHP Hardware	$4,915	$4,293	$3,934	$3,719
FC BOP Hardware	$14,231	$11,042	$9,268	$8,497
System assembly, test, and conditioning	$2,737	$433	$274	$252
Total system cost, pre-markup	**$39,343**	**$21,677**	**$16,335**	**$14,531**
System cost per KW_{net}, pre-markup	**$7,869**	**$4,335**	**$3,267**	**$2,906**
Sales Markup	50.00%	50.00%	50.00%	50.00%
Total system cost, with markup	**$59,014**	**$32,515**	**$24,503**	**$21,796**
System cost per KW_{net}, with markup	**$11,803**	**$6,503**	**$4,901**	**$4,359**

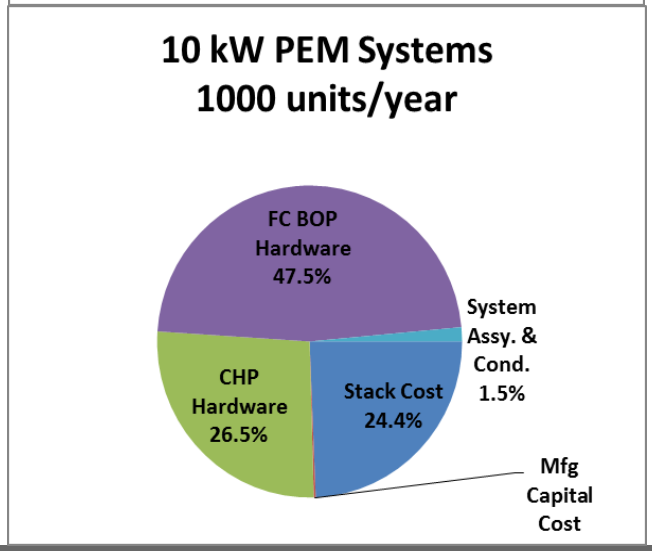
Progress & Accomplishments – 25 kW CHP PEM Fuel Cell System Cost Summary

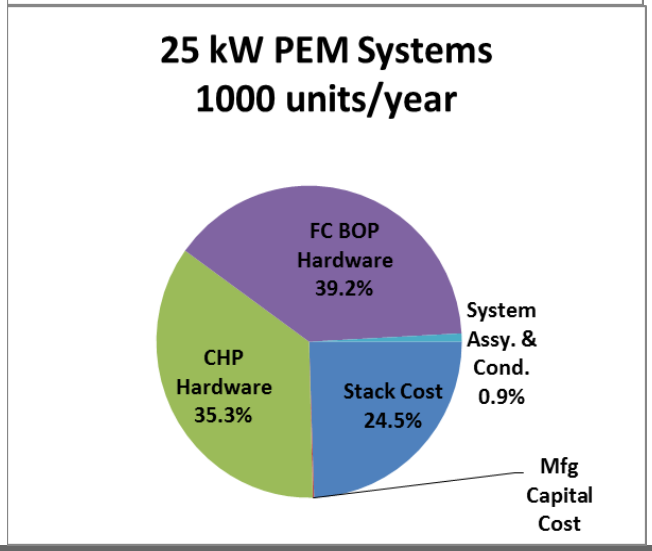
BoP Components	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Total stack manufacturing cost, with scrap	$32,200	$12,967	$7,329	$5,779
Stack manufacturing capital cost	$481	$76	$54	$48
CHP Hardware	$22,325	$18,705	$17,279	$16,298
FC BOP Hardware	$26,658	$20,780	$17,520	$16,097
System assembly, test, and conditioning	$2,777	$452	$283	$257
Total system cost, pre-markup	**$84,442**	**$52,980**	**$42,465**	**$38,480**
System cost per KW_{net}, pre-markup	**$3,378**	**$2,119**	**$1,699**	**$1,539**
Sales Markup	50.00%	50.00%	50.00%	50.00%
Total system cost, with markup	**$126,663**	**$79,471**	**$63,697**	**$57,721**
System cost per KW_{net}, with markup	**$5,067**	**$3,179**	**$2,548**	**$2,309**

Progress & Accomplishments – CHP PEM Fuel Cell System Cost Comparison

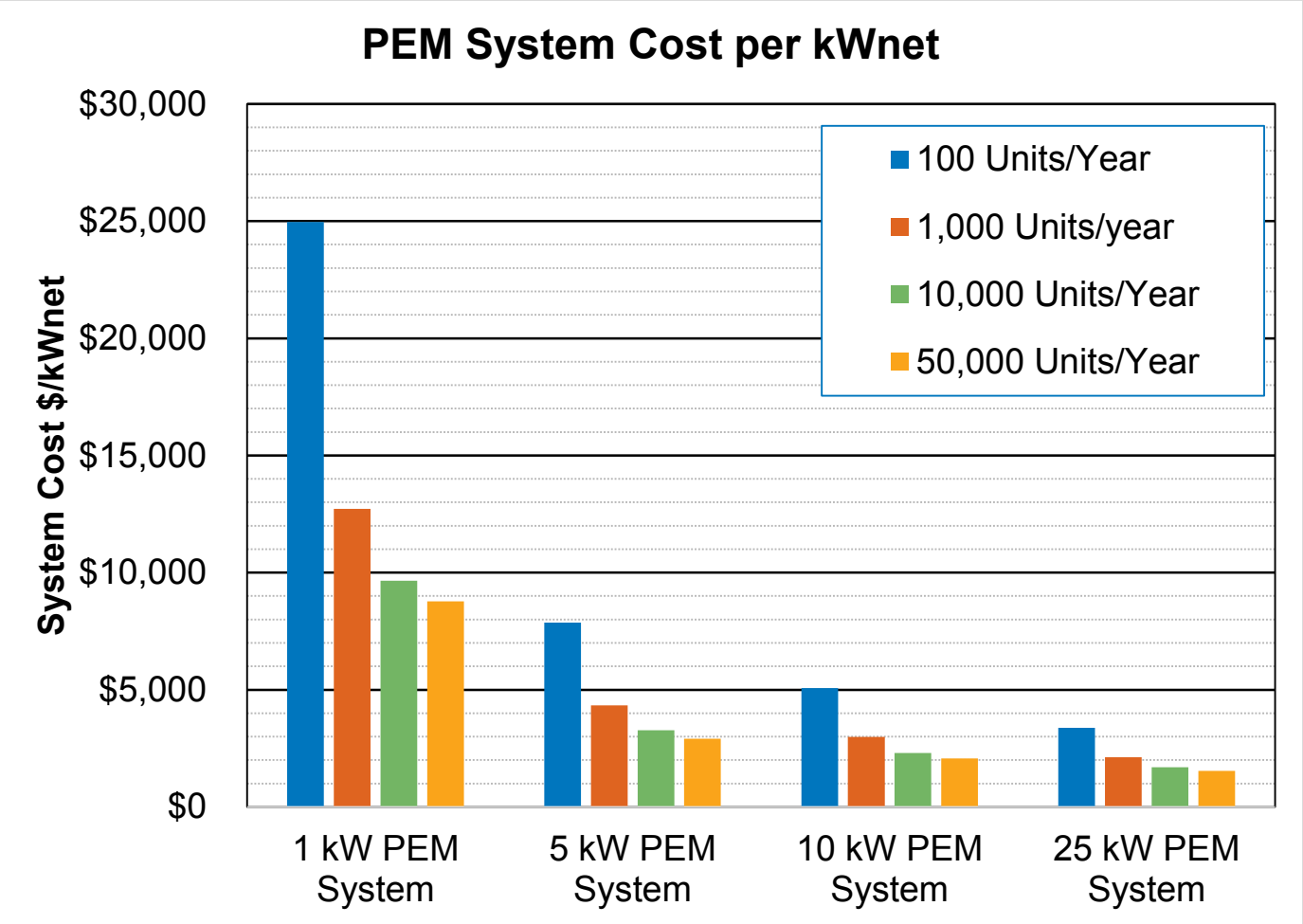








Progress & Accomplishments – CHP PEM Fuel Cell System Cost Comparison

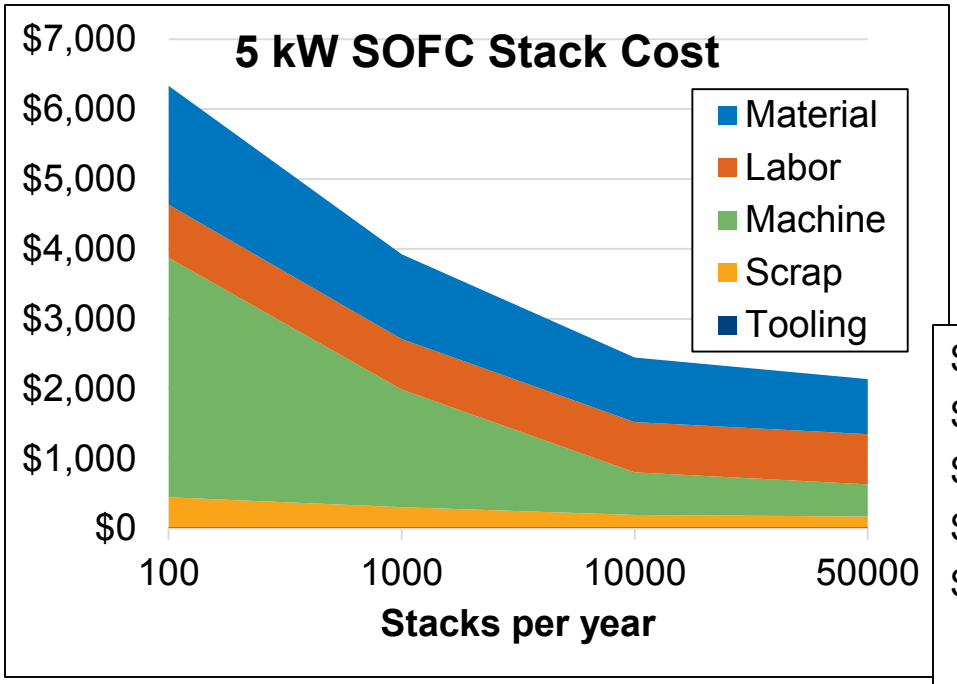


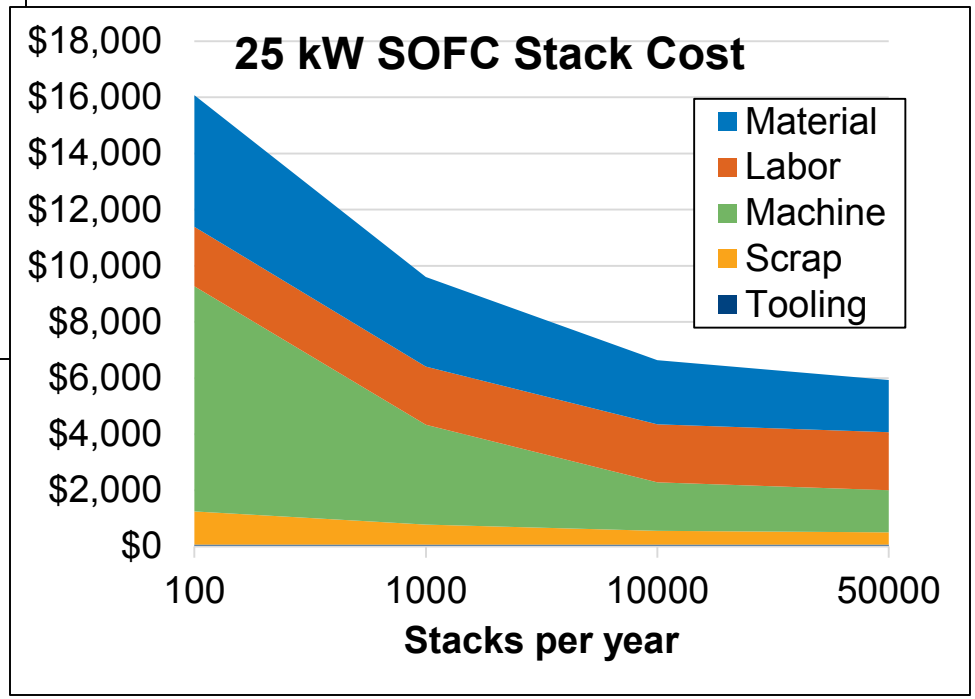
Progress & Accomplishments – SOFC Stack Manufacturing Cost (5&25kW)

Stack Components	5 kW				25 kW			
	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)
Ceramic Cells	$1,728	$1,555	$923	$788	$5,825	$4,359	$2,913	$2,648
Interconnects	$1,348	$905	$428	$347	$5,150	$2,362	$1,566	$1,294
Picture Frames	$27	$17	$14	$12	$63	$44	$35	$29
Glass Ceramic Sealing	$200	$196	$162	$141	$623	$617	$466	$444
End plates	$537	$496	$380	$348	$1,026	$939	$771	$718
Assembly hardware	$222	$222	$222	$222	$222	$222	$222	$222
Assembly labor	$43	$35	$34	$34	$106	$85	$82	$82
Stack Brazing	$38	$30	$26	$20	$121	$96	$55	$42
Test and conditioning	$2,190	$466	$257	$226	$2,940	$876	$527	$452
Total Cost	**$6,333**	**$3,923**	**$2,446**	**$2,137**	**$16,075**	**$9,600**	**$6,637**	**$5,930**
Cost per kW_{net}	**$1,267**	**$785**	**$489**	**$427**	**$643**	**$384**	**$265**	**$237**

All costs include manufacturing scrap

SOFC Fuel Cell Stack Volume Trends

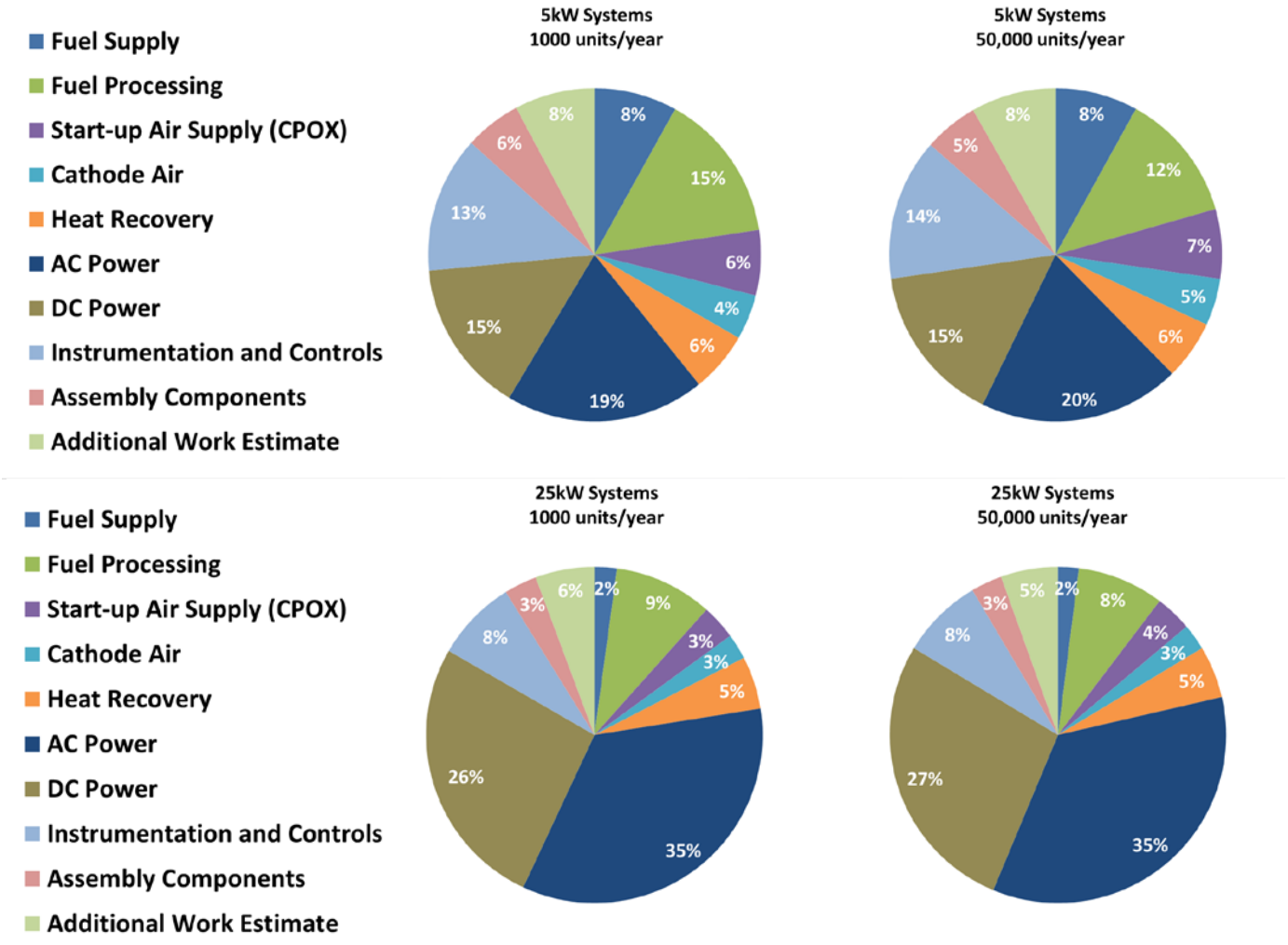




Progress & Accomplishments – CHP SOFC BoP Manufacturing Cost

BoP Components	5 kW				25 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	$1,795	$930	$822	$778	$1,782	$646	$553	$508
Fuel Processing	$2,162	$1,680	$1,283	$1,216	$3,904	$2,830	$2,224	$2,123
Start-up Air Supply (CPOX)	$791	$732	$679	$655	$1,094	$1,004	$931	$899
Cathode Air	$562	$506	$455	$442	$816	$735	$661	$641
Heat Recovery	$956	$677	$605	$557	$2,047	$1,517	$1,357	$1,276
AC Power	$2,438	$2,238	$2,043	$1,899	$11,150	$10,321	$9,555	$8,898
DC Power	$2,123	$1,721	$1,560	$1,500	$10,638	$7,900	$7,283	$6,970
Instrumentation and Control	$1,700	$1,530	$1,389	$1,335	$2,993	$2,346	$2,123	$2,006
Assembly Components	$697	$634	$568	$512	$1,037	$942	$848	$764
Additional Work Estimate	$1,200	$900	$800	$800	$2,100	$1,700	$1,500	$1,400
BOP Total	**$14,424**	**$11,548**	**$10,204**	**$9,694**	**$37,560**	**$29,941**	**$27,036**	**$25,485**

Progress & Accomplishments – CHP SOFC BoP Manufacturing Cost



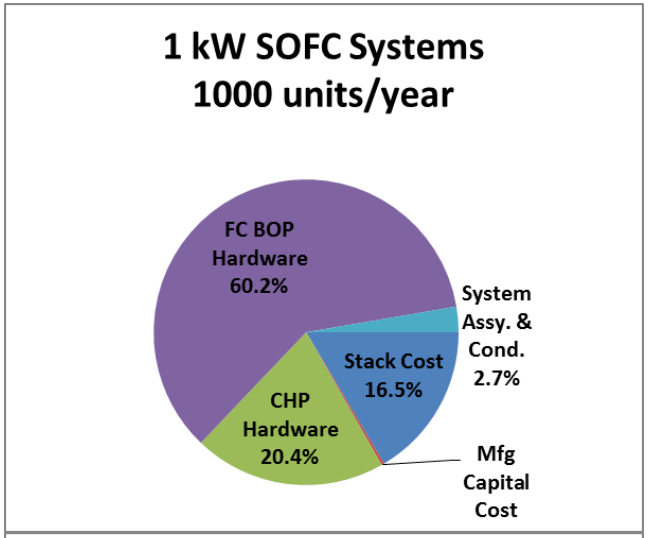
Progress & Accomplishments – 5 kW CHP SOFC Fuel Cell System Cost Summary

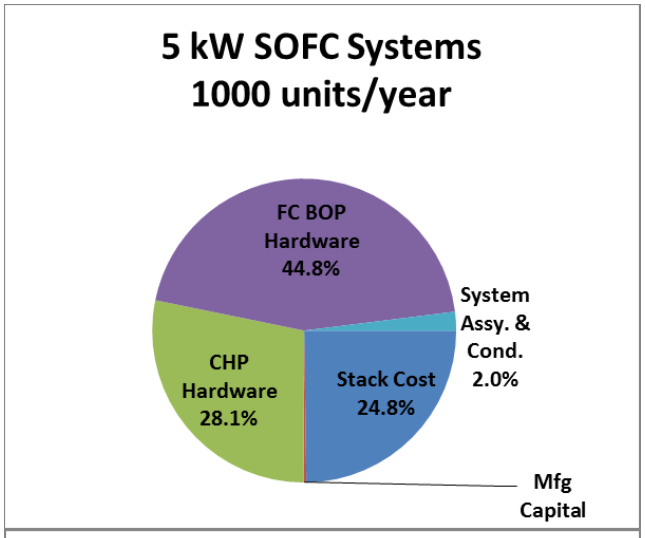
BoP Components	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Total stack manufacturing cost, with scrap	$6,333	$3,923	$2,446	$2,137
Stack manufacturing capital cost	$295	$47	$65	$56
CHP Hardware	$5,112	$4,456	$4,054	$3,838
FC BOP Hardware	$9,311	$7,093	$6,150	$5,856
System assembly, test, and conditioning	$1,946	$316	$178	$162
Total system cost, pre-markup	**$22,998**	**$15,834**	**$12,893**	**$12,050**
System cost per KW_{net}, pre-markup	**$4,600**	**$3,167**	**$2,579**	**$2,410**
Sales Markup	50.00%	50.00%	50.00%	50.00%
Total system cost, with markup	**$34,497**	**$23,751**	**$19,339**	**$18,075**
System cost per KW_{net}, with markup	**$6,899**	**$4,750**	**$3,868**	**$3,615**

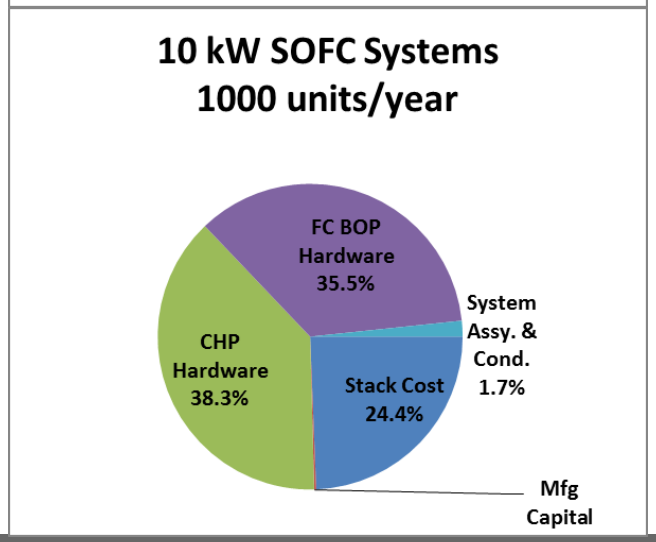
Progress & Accomplishments – 25 kW CHP SOFC Fuel Cell System Cost Summary

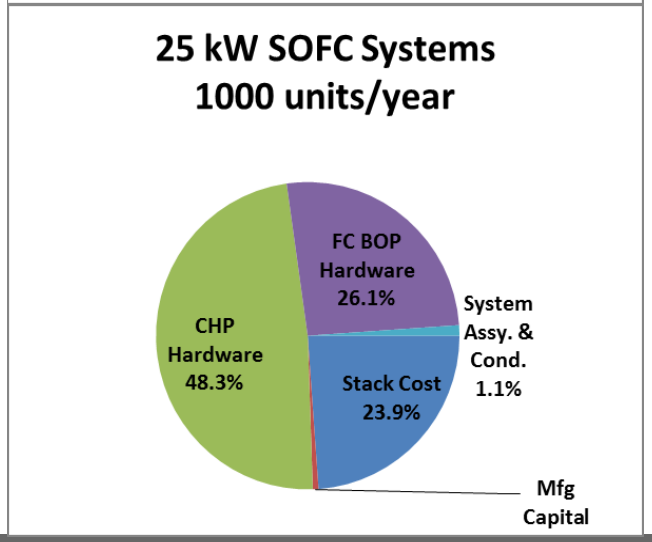
BoP Components	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Total stack manufacturing cost, with scrap	$16,075	$9,600	$6,637	$5,930
Stack manufacturing capital cost	$295	$245	$177	$164
CHP Hardware	$23,134	$19,433	$17,939	$16,939
FC BOP Hardware	$14,426	$10,508	$9,097	$8,546
System assembly, test, and conditioning	$2,211	$442	$238	$198
Total system cost, pre-markup	**$56,142**	**$40,228**	**$34,087**	**$31,778**
System cost per KW_{net}, pre-markup	**$2,246**	**$1,609**	**$1,363**	**$1,271**
Sales Markup	50.00%	50.00%	50.00%	50.00%
Total system cost, with markup	**$84,214**	**$60,342**	**$51,131**	**$47,666**
System cost per KW_{net}, with markup	**$3,369**	**$2,414**	**$2,045**	**$1,907**

Progress & Accomplishments – CHP SOFC Fuel Cell System Cost Comparison

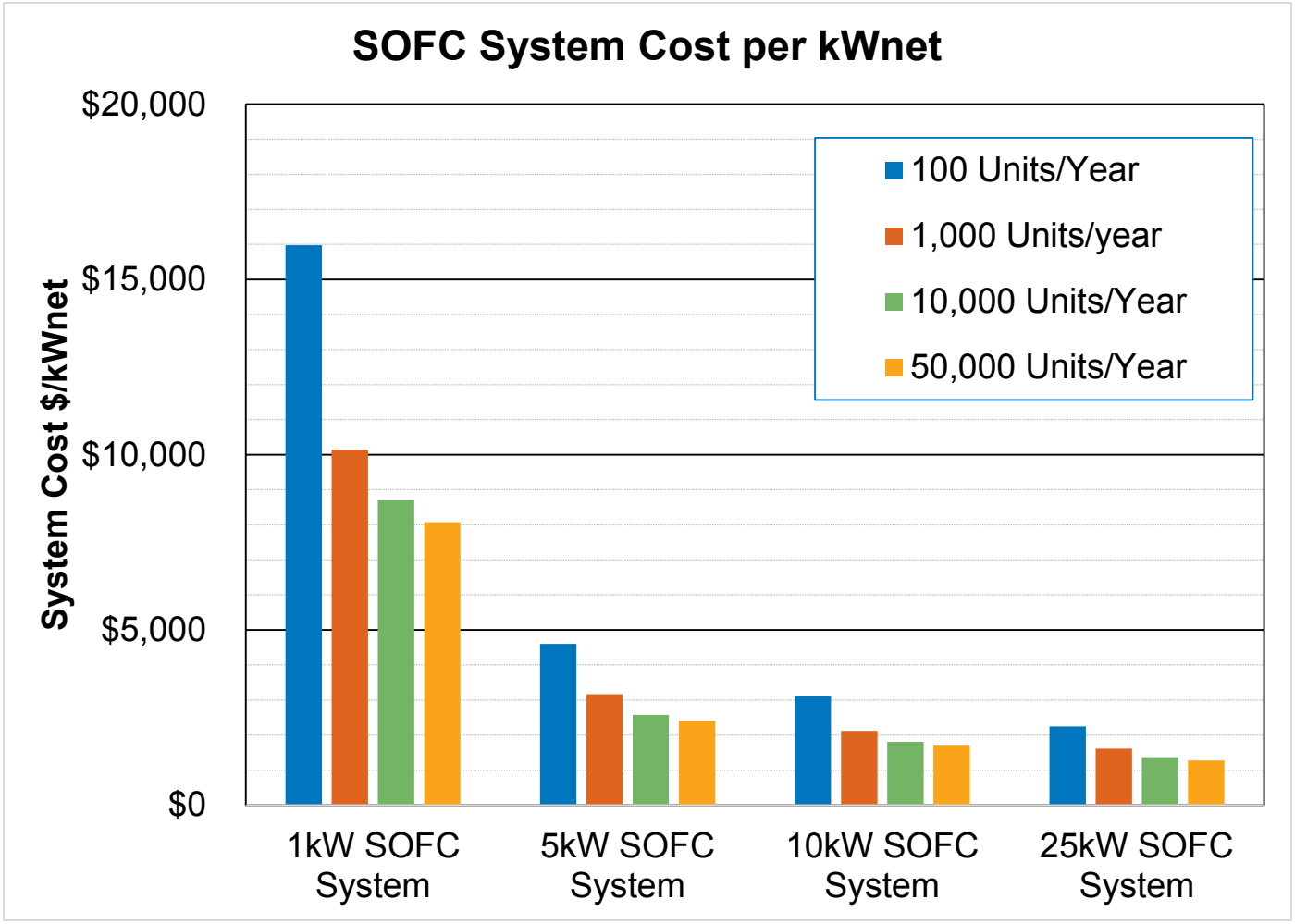




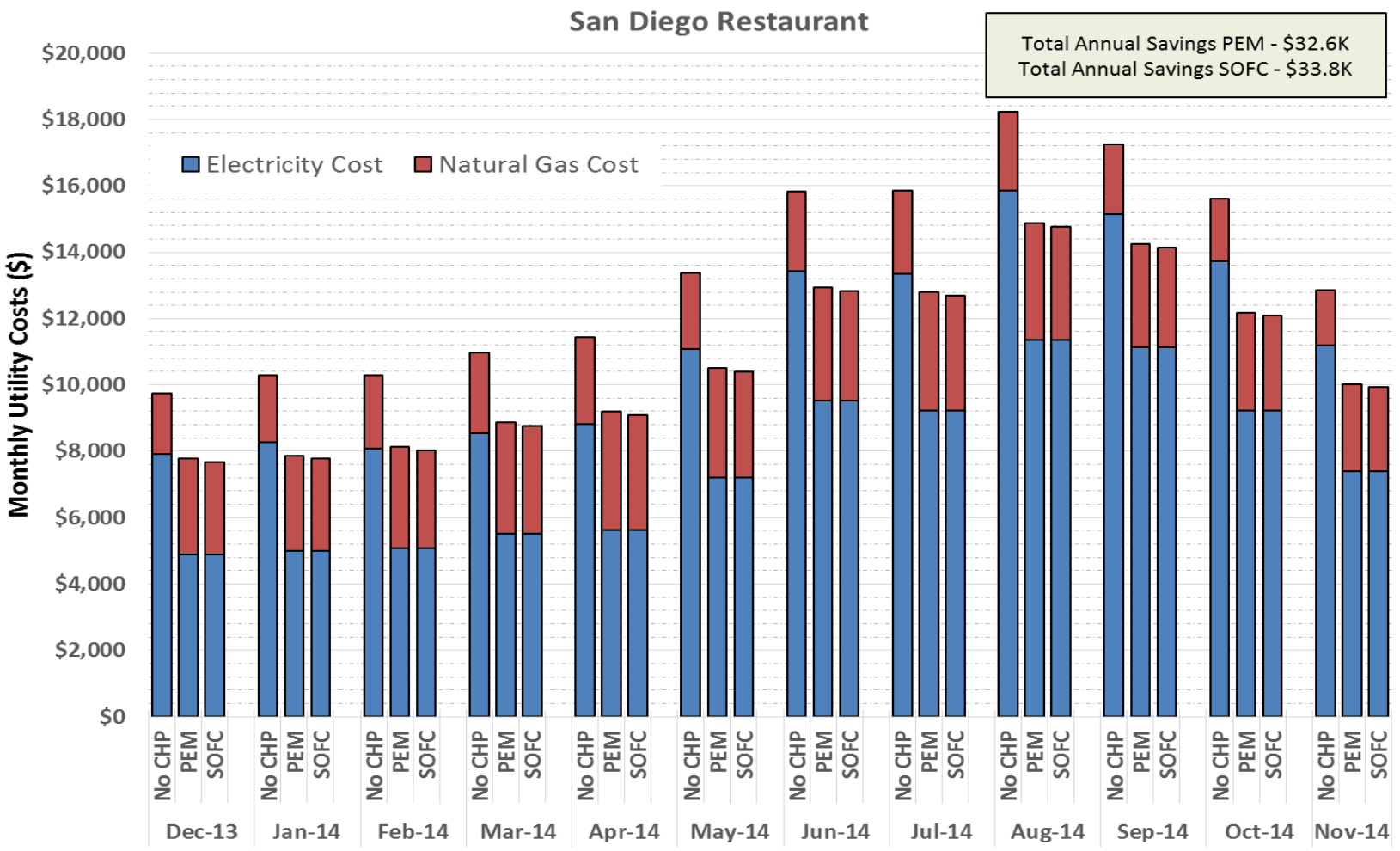




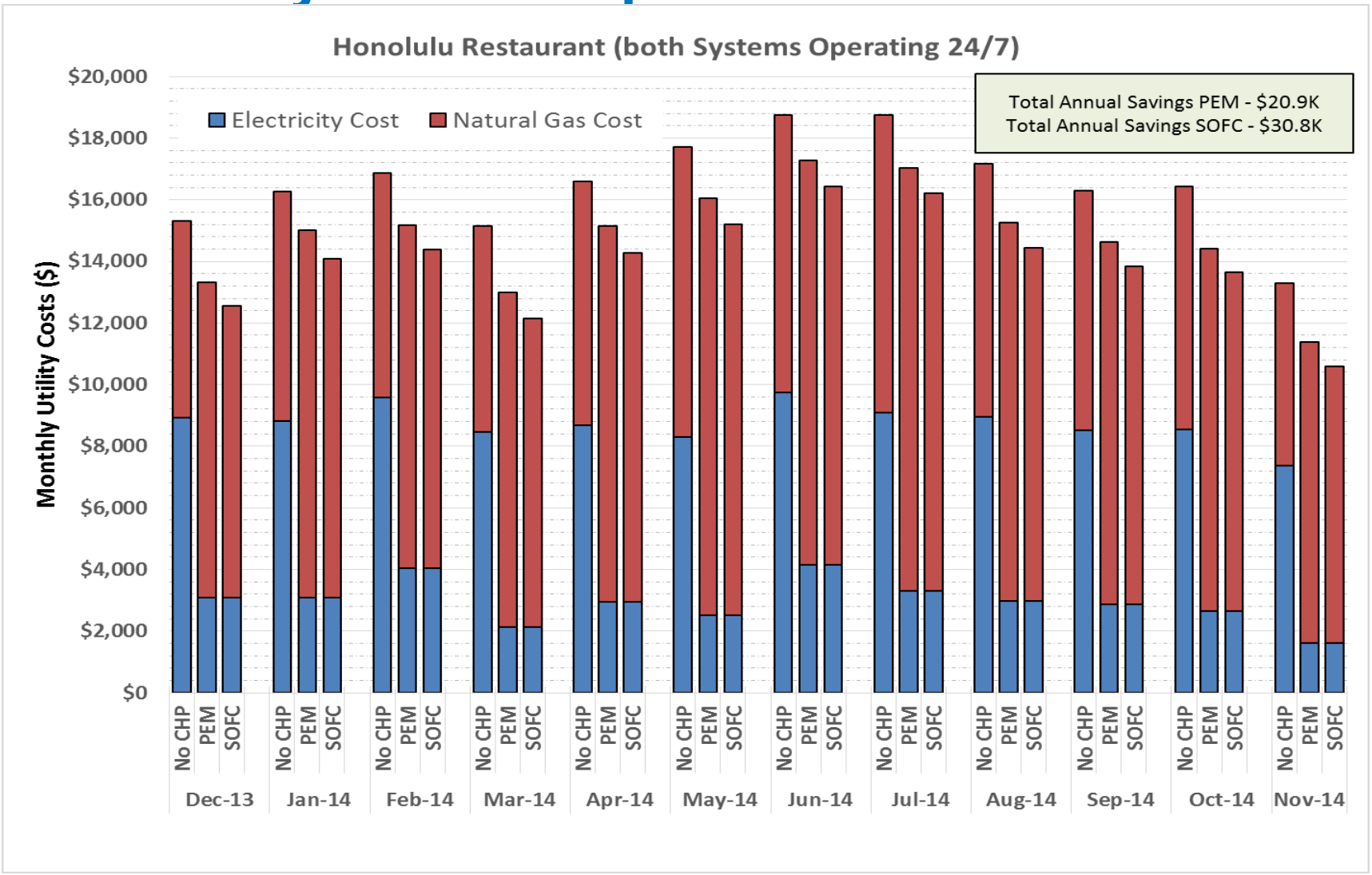
Progress & Accomplishments – CHP SOFC Fuel Cell System Cost Comparison



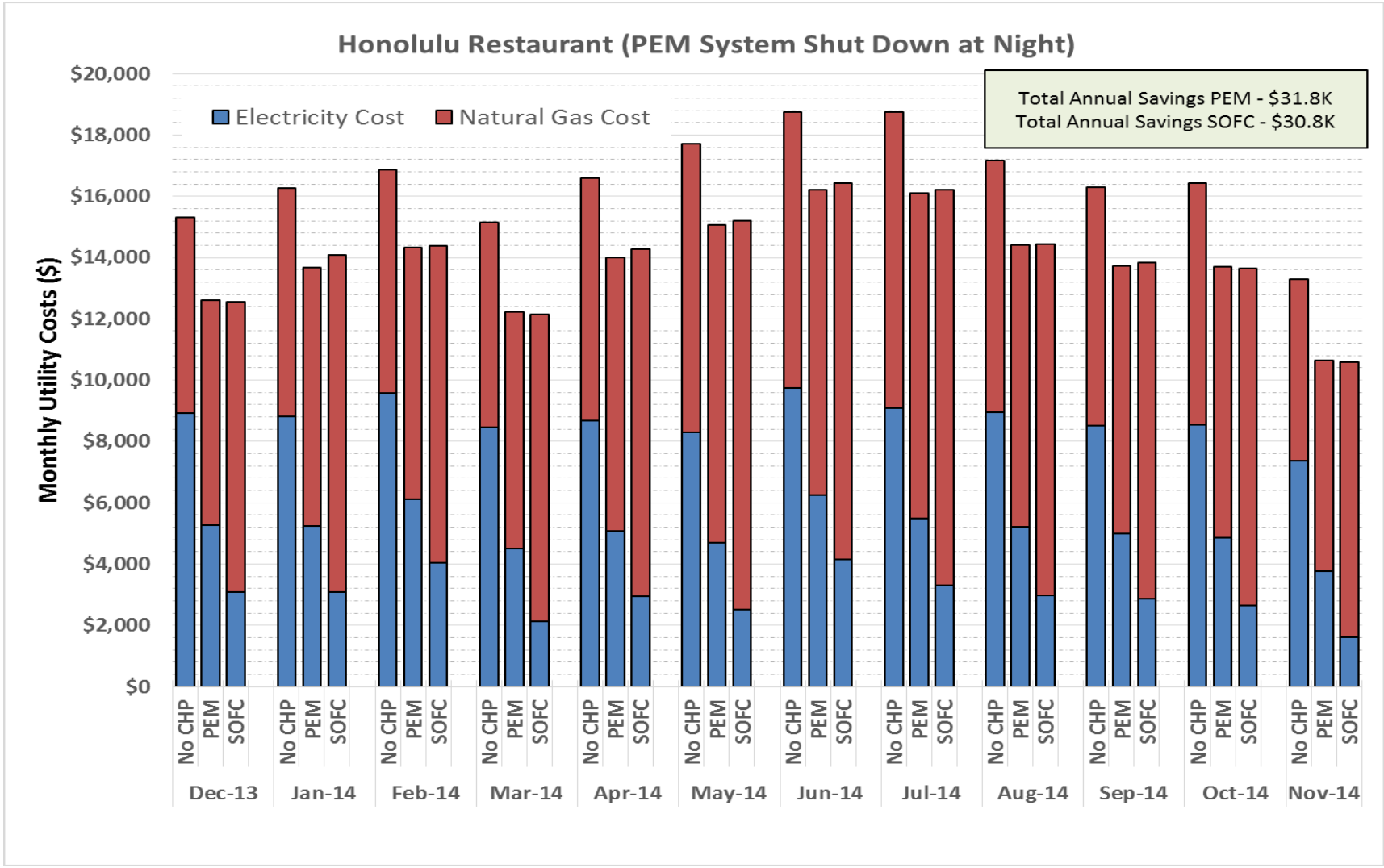
Progress & Accomplishments – Life Cycle Cost Analysis Assumptions



Progress & Accomplishments – Life Cycle Cost Analysis Assumptions



Progress & Accomplishments – Life Cycle Cost Analysis Assumptions



Progress & Accomplishments – Life Cycle Cost Analysis Assumptions

PEM – 1,000 units/year	Fuel Cell	Utilities Only
Cost of System	$79,471	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$22,812	N/A
Annual Consumables	$1,252	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$91,185	$135,427
Annual Gas Utility Cost	$37,958	$26,290
Annual Total	$153,957	$161,717
Annual Savings	$7,760	

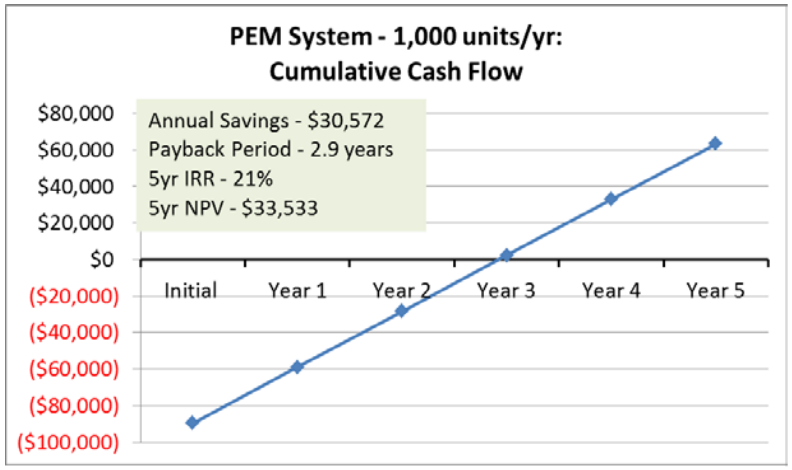
SOFC – 1,000 units/year	Fuel Cell	Utilities Only
Cost of System	$60,342	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$17,935	N/A
Annual Consumables	$521	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$91,185	$135,427
Annual Gas Utility Cost	$36,763	$26,290
Annual Total	$147,154	$161,717
Annual Savings	$14,563	

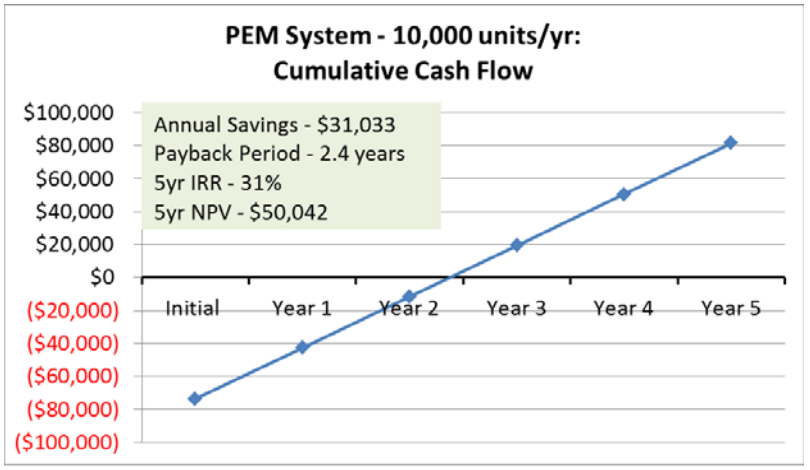
PEM – 10,000 units/year	Fuel Cell	Utilities Only
Cost of System	$63,697	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$18,790	N/A
Annual Consumables	$791	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$91,185	$135,427
Annual Gas Utility Cost	$37,958	$26,290
Annual Total	$149,474	$161,717
Annual Savings	$12,243	

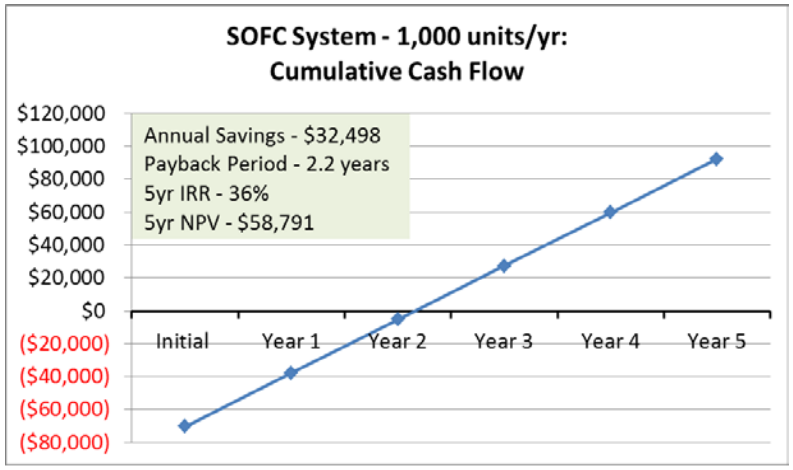
SOFC – 10,000 units/year	Fuel Cell	Utilities Only
Cost of System	$51,131	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$15,586	N/A
Annual Consumables	$460	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$91,185	$135,427
Annual Gas Utility Cost	$36,763	$26,290
Annual Total	$144,744	$161,717
Annual Savings	$16,973	

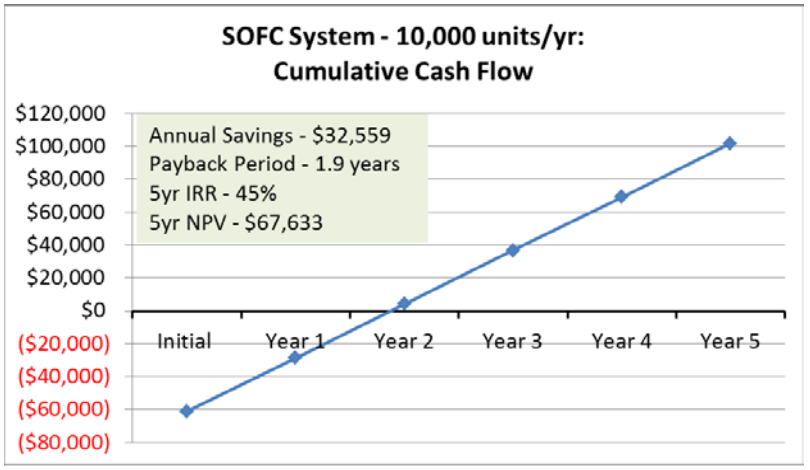
*Annual cost comparison when using CHP system in San Diego Restaurant with a Production Volume of 1,000 or 10,000 Units per Year

Progress & Accomplishments – Life Cycle Cost Analysis Assumptions









*Cumulative cash flows for PEM and SOFC systems with production volumes of 1,000 and 10,000 units/year in the San Diego store

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Progress & Accomplishments – Results Summary

- Electronics and power conversion dominate system cost, particularly as you increase in system size
- An attractive value proposition exists under specific utility rate conditions
- 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

- FY14 Reviewer comment: "Battelle should expand cooperation to include InnovaTek. DOE should facilitate the collaboration."
  - Innovatek did collaborate this year and provided system design review and feedback.
- FY14 Reviewer comment: "The team should delete HT PEM and add collaboration with InnovaTek for 5 kW SOFC cost analysis."
  - We agree that the applicability of HTPEM is in question and it did not make the cut for this year's CHP and Primary Power analysis.
- FY14 Reviewer comment: "The team should make sure end users are involved."
  - For this year's life cycle cost analysis a potential end user was utilized and actual utilities data was used for the analysis.

Collaborations

The following companies provided support for the CHP and Primary Power effort

- Johnson Matthey/Catacel
  - System Design Review/Feedback
  - Fuel Processing technology review/feedback
- NexTech Materials
  - System Design Review/Feedback
  - SOFC technology assessment
- Innovatek
  - System Design Review/Feedback
- Ballard
  - System Design Review/Feedback
- Panasonic
  - System Design Review/feedback
  - BOP design comments

Proposed Future Work

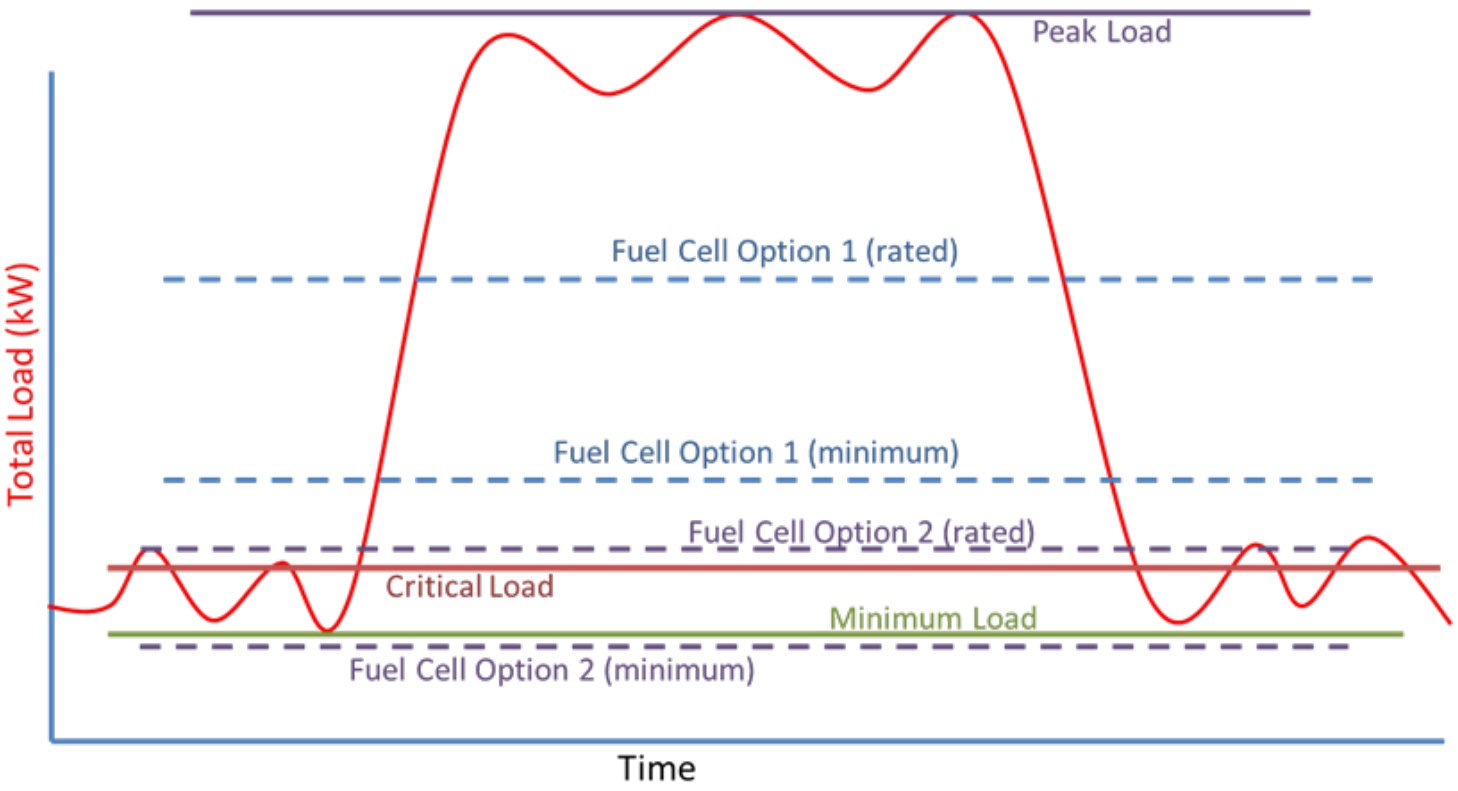
Budget Period 4	Budget Period 5
• Large Scale Primary Power and CHP Applications (PEMFC, High Temp PEMFC, SOFC) 100 kW, 250 kW •Backup Power (PEMFC)	• Revisit all applications in previous 4 budget periods

Summary

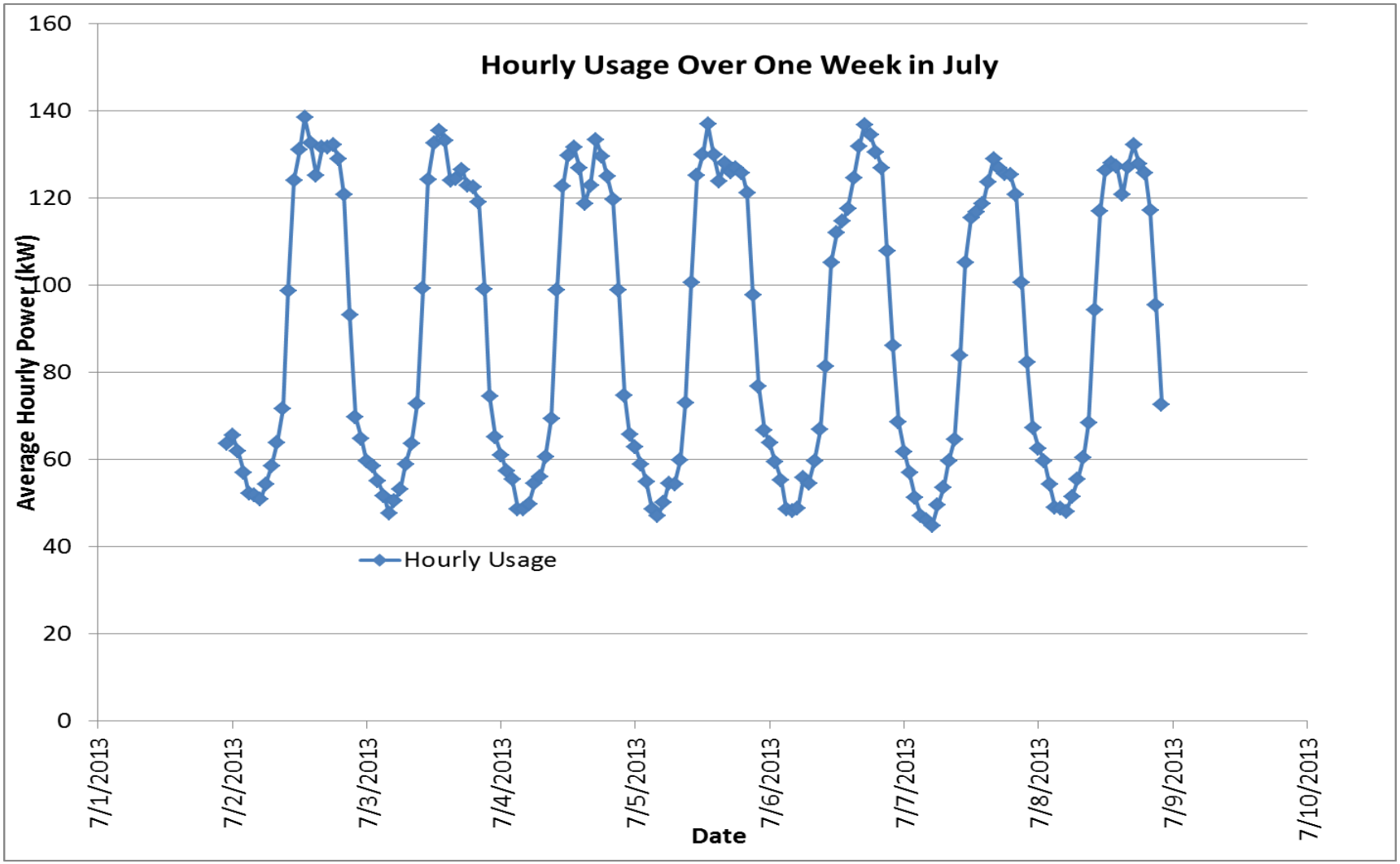
- **Relevance:** Help answer questions on opportunities for cost reduction to penetrate non-automotive applications
- **Approach:** Perform cost modeling including DFMA® analysis of a generic fuel cell system design developed for the application
- **Technical Accomplishments and Progress:** Completed cost analysis of 1, 5, 10 and 25 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, NexTech Materials, Ballard) for design inputs, cost inputs, design review and results review
- **Proposed Future Research:** 100 and 250 kW Primary Power and CHP Applications (PEMFC, High Temp PEMFC, SOFC) and Backup Power Applications (PEMFC)

Technical Backup Slides

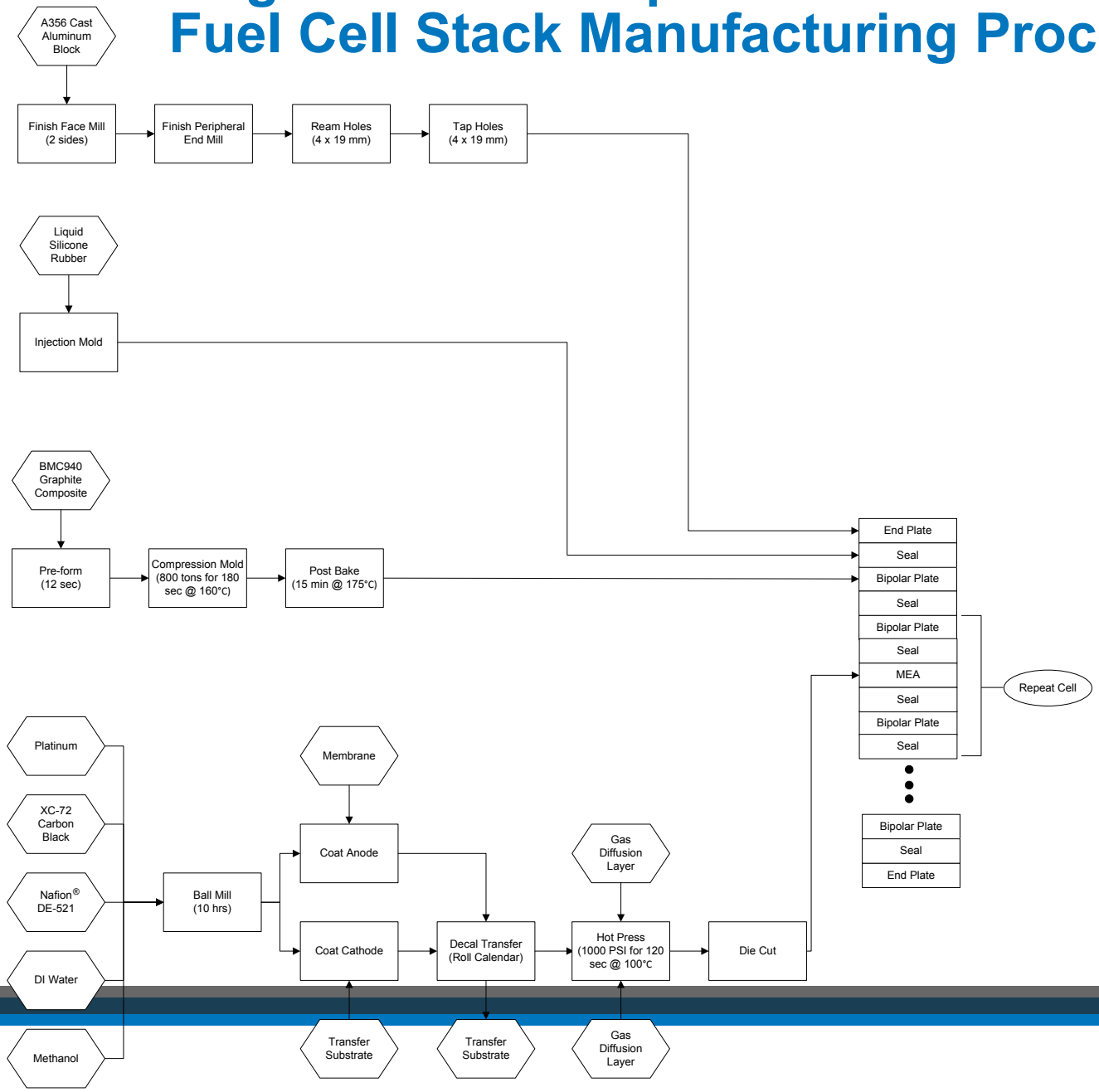
System Sizing – Notional Curve



Progress & Accomplishments – Life Cycle Cost Analysis Assumptions



Progress & Accomplishments – PEM Fuel Cell Stack Manufacturing Process Overview



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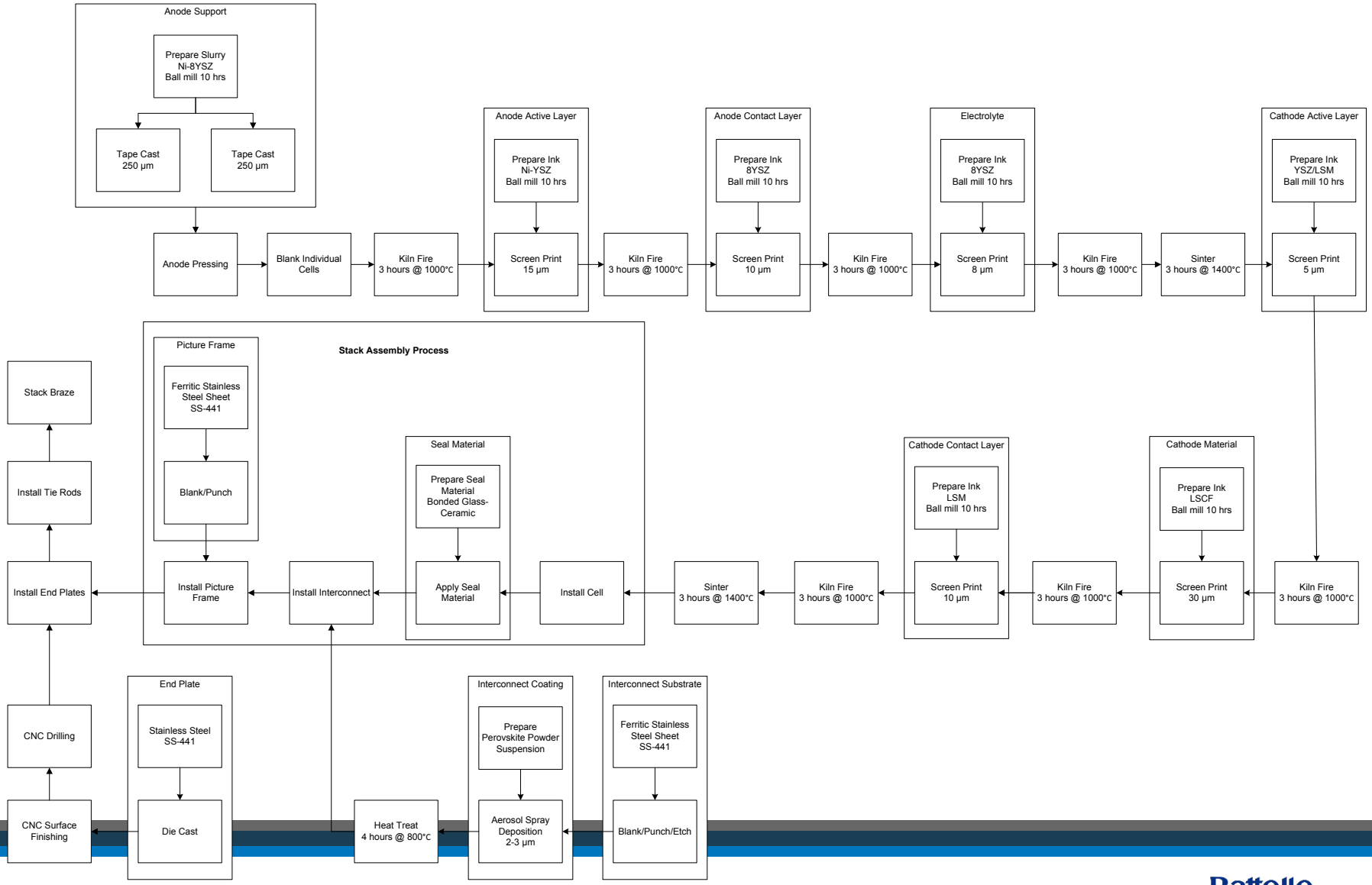
Progress & Accomplishments – SOFC
Fuel Cell Stack Manufacturing Process Overview



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Progress & Accomplishments – Capital Cost Assumptions

Capital Cost	Unit Cost (2014$)	Units	Total Cost (2014$)	Assumption/Reference
Factory Total Construction Cost	250	$/sq ft	751,723 to 1,348,055	• Includes Electrical Costs ($50/sq ft) • Total plant area based on line footprint plus 1.5x line space for working space, offices, shipping, etc. • Varies with anticipated annual production volumes of both 1 kW and 5 kW stacks
Production Line Equipment Cost	Varies by component		1,537,495 to 2,890,680	• Varies with anticipated annual production volumes of both 1 kW and 5 kW stacks
Forklifts	25,000	$/lift	50,000	• Assumes 2 forklifts with extra battery and charger
Cranes	66,000	$/crane	198,000	• Assumes 3 cranes, 5 ton capacity, 20' wide per line
Real Estate	125,000	$/acre	125,000	• Assumes 1 acre of vacant land, zoned industrial Columbus, OH
Contingency	10% Capital Cost		266,222 to 461,174	• Construction estimation assumption
Total			**2,928,440 to 5,072,909**	• Varies with anticipated annual production volumes of both 1 kW and 5 kW stacks