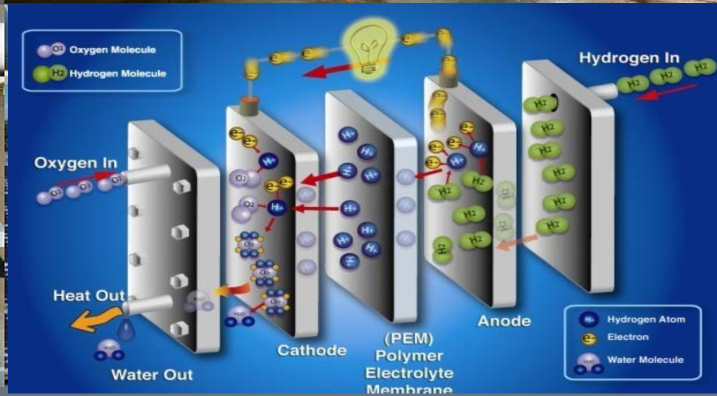
Fuel Cell Technologies Office Webinar

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy





Manufacturing Cost Analyses of Fuel Cell Systems for Non-Transportation Applications

January 24, 2017

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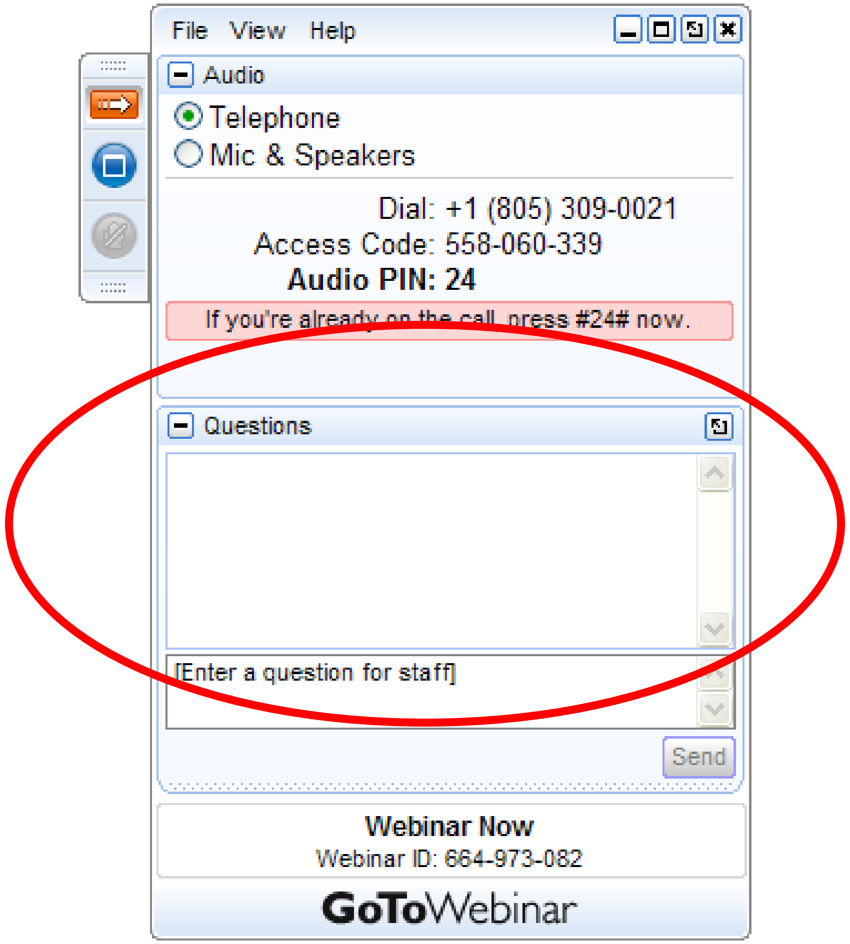
Question and Answer

- Please type your questions into the question box



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Manufacturing Cost Analyses of Fuel Cell Systems for Non-Transportation Applications

1/24/2017

Outline

- Background
- Approach
- MHE Systems
  - Design
  - Costs
  - Sensitivity and Life Cycle Cost
- Primary Power & Combined Heat and Power (CHP) Systems
  - Design
  - Costs
  - Sensitivity and Life Cycle Cost
- Summary/Conclusions

Acknowledgements

Funding and support of this work by the U.S. Department of Energy, Fuel Cell Technologies Office is gratefully acknowledged

Collaborators

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

- Plug Power
- Hydrogenics
- Nexceris
- Ballard
- API Heat Transfer
- Innovatek
- Panasonic
- US Hybrid
- NREL
- Dry Coolers
- Johnson Matthey/Catacel
- Advanced Power Associates
- Zahn Electronics
- Strategic Analysis
- Cain Industries
- Watt Fuel Cell
- Vicor Power
- SMA-America
- Ideal Power
- Proctor and Gamble
- Outback Power Technologies
- Tranter
- dPoint Technologies
- Honda

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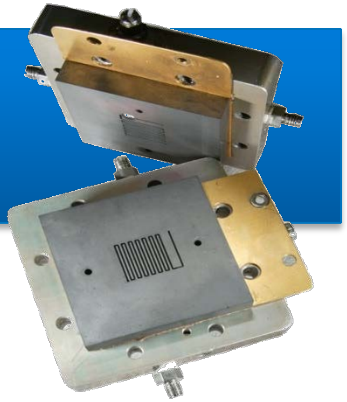
Background



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 (MHE)
- Fuel Cell Types Considered - 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

This year

- Updated Primary Power (including CHP) and MHE reports

Approach – Manufacturing Cost Analysis Methodology

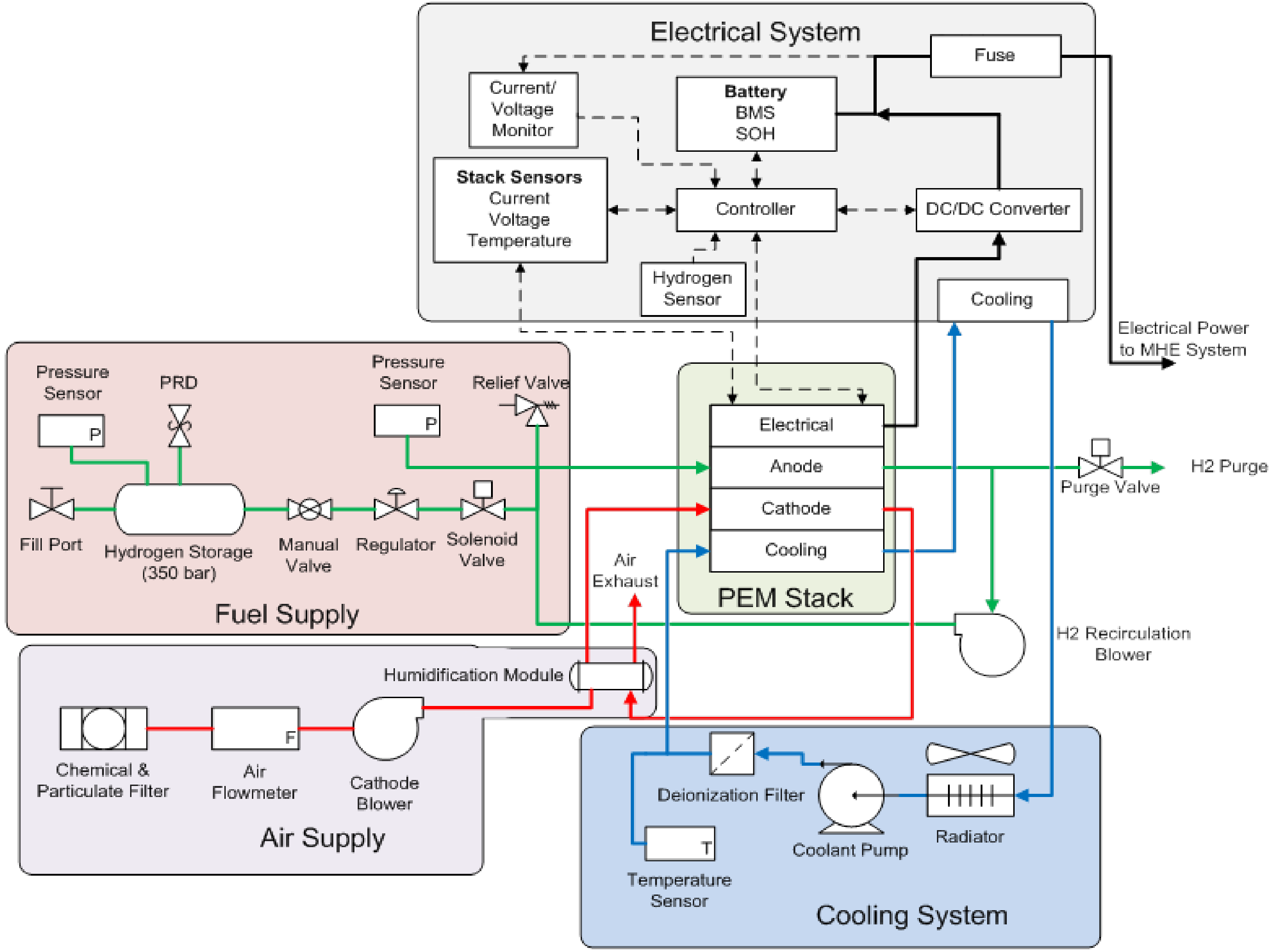
Market Assessment
- Characterization of potential markets
- Identification of operational and performance requirements
- Evaluation of fuel cell technologies relative to requirements
- Selection of specific systems for cost modeling

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

Representative MHE System



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Nominal Design Basis

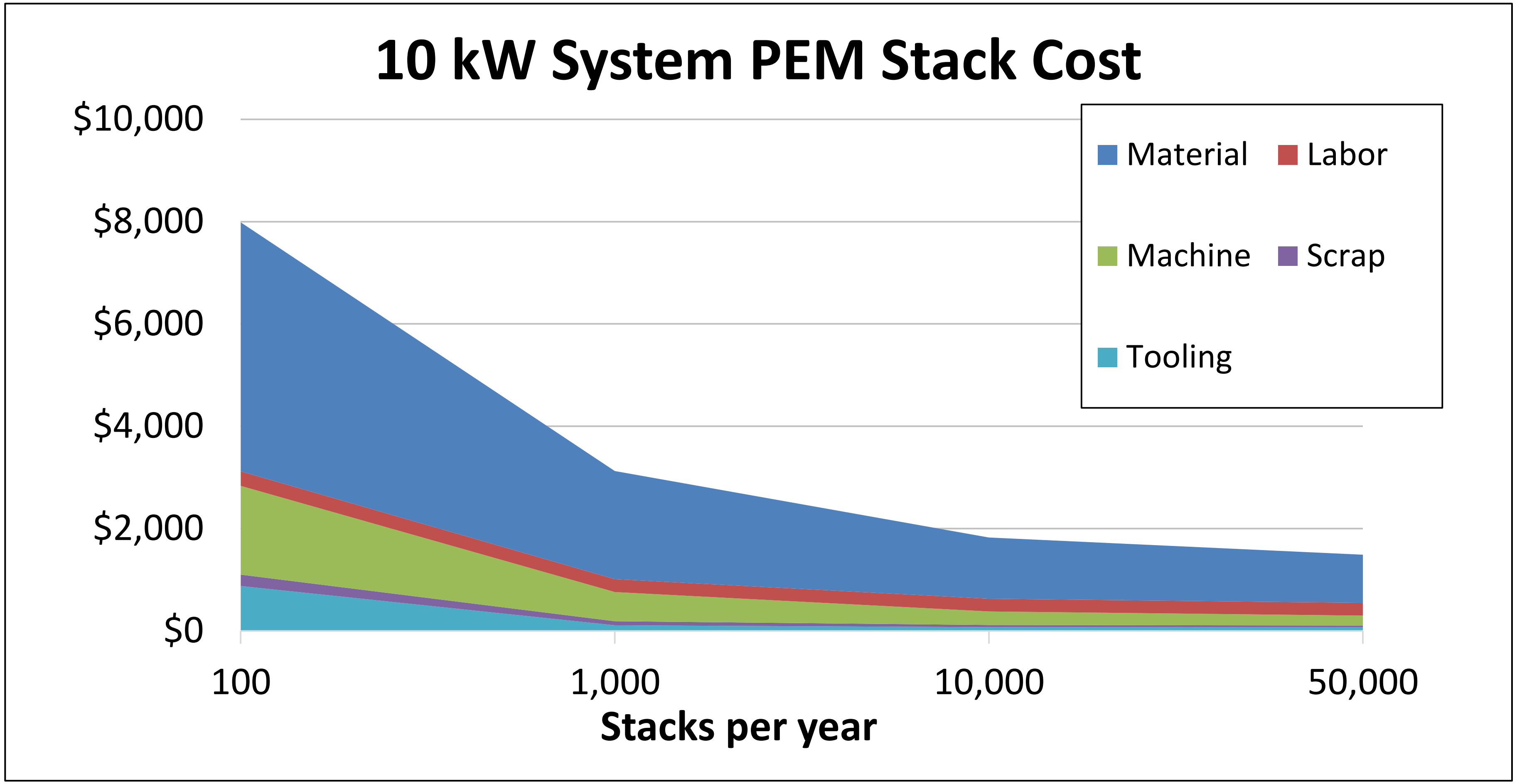
Parameter	1 kW System	5 kW System	10 kW System	25 kW System
Power Density (W/cm^2)	0.68			
Current Density (A/cm^2)	0.8			
Cell Voltage (VDC)	0.68			
Active Area Per Cell (cm^2)	200			400
Net Power (kW)	1	5	10	25
Gross Power (kW)	1.5	5.75	11.5	28.75
Number of Cells (#)	14	53	106	132
Full Load Stack Voltage (VDC)	9	36	72	90
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 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, die cut			
Stack Assembly	Hand assembled, tie rods			
Bipolar Plates	Graphite composite, compression molded			
End Plates	Die cast and machined cast aluminum			

MHE Stack Manufacturing Cost – 10 kW System

Stack Components	10 kW			
	100	1,000	10,000	50,000
MEA	$4,990	$2,052	$1,106	$828
Anode / Cooling Gasket	$172	$75	$62	$57
Cathode Gasket	$144	$34	$29	$26
Anode Bipolar Plate	$528	$307	$194	$184
Cathode Bipolar Plate	$509	$288	$175	$165
End plates	$114	$60	$55	$29
Assembly hardware	$54	$51	$48	$45
Assembly labor	$69	$55	$53	$53
Test and conditioning	$1,405	$204	$105	$102
Total	**$7,986**	**$3,126**	**$1,827**	**$1,490**
Cost per kW_{net}	**$799**	**$313**	**$183**	**$149**

The catalyst, membrane and gas diffusion layer (GDL) all contribute to make the membrane electrode assembly (MEA) the largest contributor to stack cost – cost decreases to < $150/kW at high volume

MHE Stack Cost – Volume Trends



Material cost is the highest contributor at all production levels

MHE BOP Costs

BOP Components	10 kW			
	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Fuel Storage	$2,808	$2,595	$2,416	$2,242
H2 Recirculation	$1,012	$608	$572	$538
Air Supply	$1,734	$1,374	$955	$811
Cooling System	$612	$578	$541	$510
Electronics	$4,380	$3,093	$2,431	$1,915
Energy Storage	$2,500	$1,800	$1,250	$1,038
Instrumentation and Controls	$666	$590	$560	$536
Assembly Components	$429	$390	$351	$316
Additional Work Estimate	$700	$600	$500	$400
BOP Total	**$14,841**	**$11,628**	**$9,576**	**$8,306**

Price of power management and energy storage benefits significantly from increased production volume – but overall BOP costs remain significant

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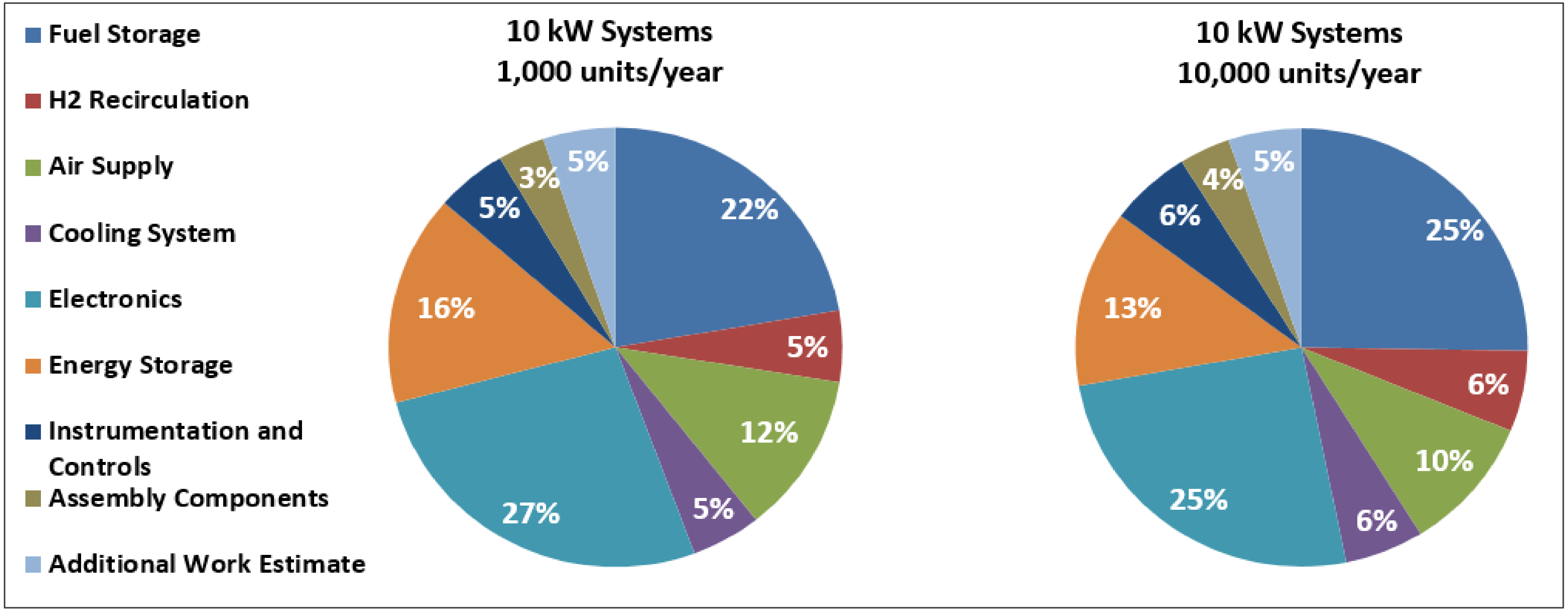
MHE BOP Costs



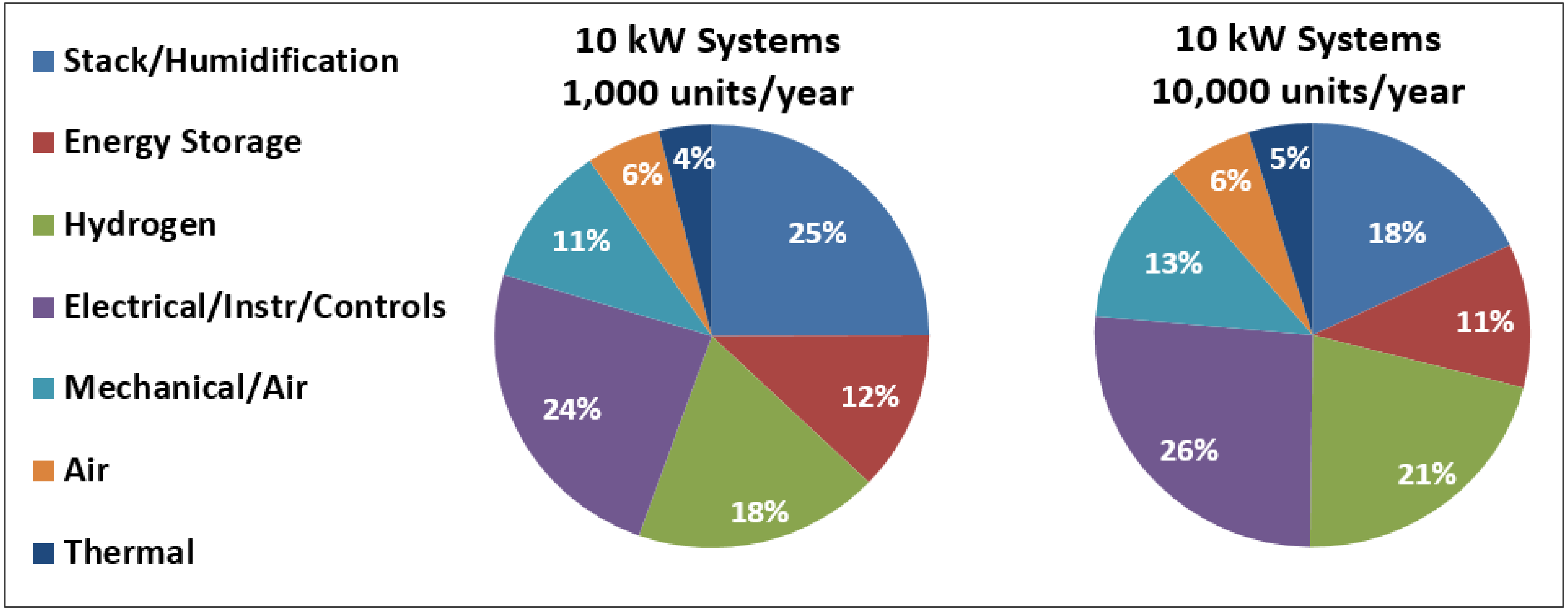
Fuel storage and electronics/energy storage are the largest contributors to BOP costs

10 kW MHE System Cost Summary

Description	100 Units	1000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$7,986	$3,126	$1,827	$1,490
Stack manufacturing capital cost	$567	$71	$39	$38
BOP	$14,841	$11,628	$9,576	$8,305
System assembly, test, and conditioning	$1,431	$259	$185	$184
Total system cost, pre-markup	$24,825	$15,084	$11,626	$10,018
System cost per net KW, pre-markup	$2,482	$1,508	$1,163	$1,002
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$37,237	$22,626	$17,439	$15,028
System cost per net KW, with markup	$3,724	$2,263	$1,744	$1,503

BOP dominates system cost for all capacities and volumes examined contributing at least 60% and up to 90% of system cost

10 kW MHE System Cost Summary



System costs at 1000 units/year have been validated to be consistent with current market status

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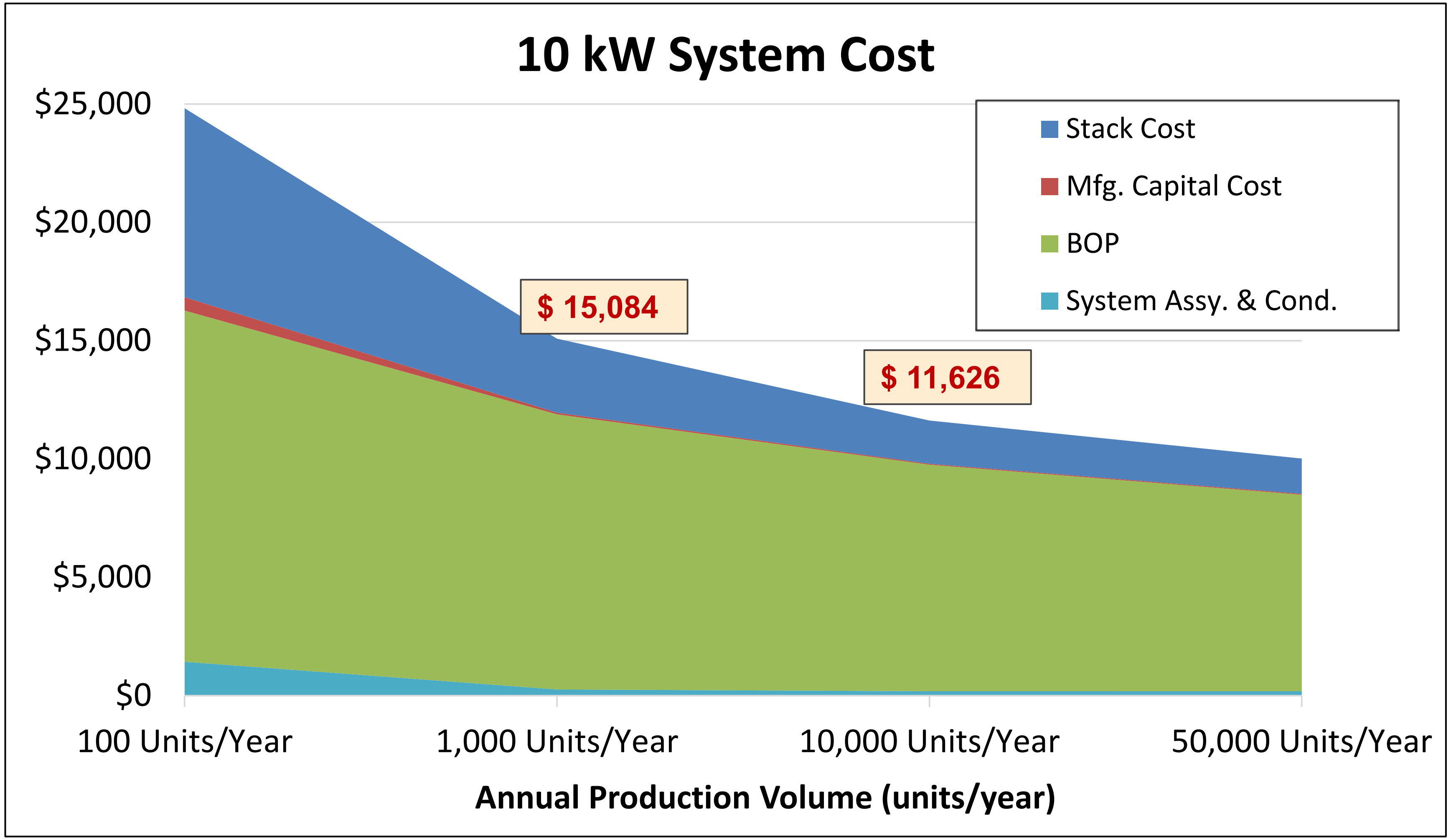
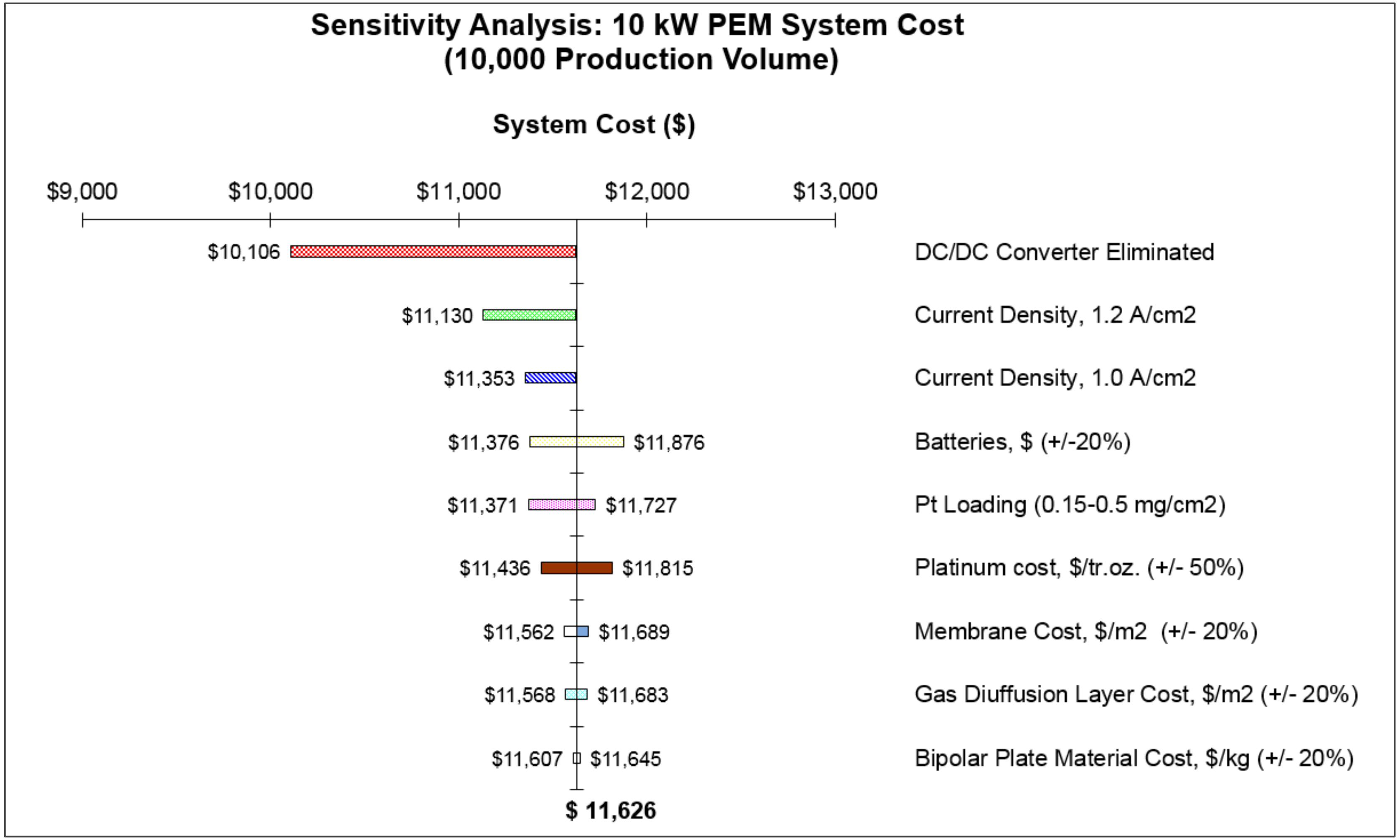
10 kW MHE System Cost - Volume Trends



Stack costs reduce sharper than BOP costs with increased production volumes

10 kW MHE Cost Sensitivity Analysis



Elimination of the DC/DC converter reduces the cost by 13%, while a Pt cost can vary greatly with only minor effect

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10kW System Lifecycle Cost Analysis

Input Data	Fuel Cell	Battery
Cost of forklift	$25,000	$25,000
Cost of power system	$17,439	$14,600
Cost of additional required power system infrastructure	$0	$2,500
Power system replacement time, hours	10,000	10,000
Power system replacement cost	$3,075	$14,600
Operational days per year	363	363
Shifts per day	2-3	2-3
Power factor, hours per 8 hour shift	1.6	1.6
Shifts per lifecycle	7,260-10,890	7,260-10,890
Power system replacement events per lifetime	2-3	2-3
Time refuel/recharge-battery change per day	2-3	2-3
Labor time for refuel/recharge – per event, minutes	3.3	13.5
Labor cost per day for refuel/recharge-battery change	$2.20-$3.30	$9.00-$13.50
Fuel usage per hour at full power, kg	0.64	
Electricity use per recharge, kW-hr		40
Daily consumables cost	$13.71-$20.56	$7.68-$11.52
Consumable (hydrogen/electricity) cost	$6.70/kg	$0.12/kW-hr

Baseline assumptions based on 10,000 units per year production volume – assumes two battery systems per forklift

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10kW System Lifecycle Cost Analysis

Life Cycle Assessment Output with 1,000 units manufacturing volume				
Fleet size	75	75	300	300
Shifts	2	3	2	3
NPV of Savings, $M	$7.08	$10.72	$28.31	$42.89
ROI, %	25.90	38.60	25.90	38.60
Payback Period, years	3.86	2.59	3.86	2.59
ΔEAC, $M	$0.83	$1.26	$3.32	$5.03

Life Cycle Assessment Output with 10,000 units manufacturing volume				
Fleet size	75	75	300	300
Shifts	2	3	2	3
NPV of Savings, $M	$7.13	$10.80	$28.52	$43.21
ROI, %	29.24	43.58	29.24	43.58
Payback Period, years	3.42	2.29	3.42	2.29
ΔEAC, $M	$0.84	$1.27	$3.34	$5.07

Value proposition improves for 3 shifts a day and higher production volumes

MHE Lifecycle Cost Sensitivity Analysis

Variable	Low	Nominal	High
Fleet size	50	75	300
Operational days per year	260	312	363
Shifts worked per day	2	3	3
Pedal time fraction	0.15	0.20	0.25
Hours to battery system	7,500	10,000	12,500
Hours to replace fuel stack system	5,000	10,000	15,000
Labor rate (hourly)	$15.00	$25.00	$35.00
Inflation	1.45%	1.91%	2.38%
Discount Rate	7%	8%	9%
Loan Interest	2%	3%	4%
Loan repayment time, years	5	10	15
Electricity cost, $/kW-hr	$0.10	$0.12	$0.17
Hydrogen cost, $/kg	$5.00	$6.70	$9.00

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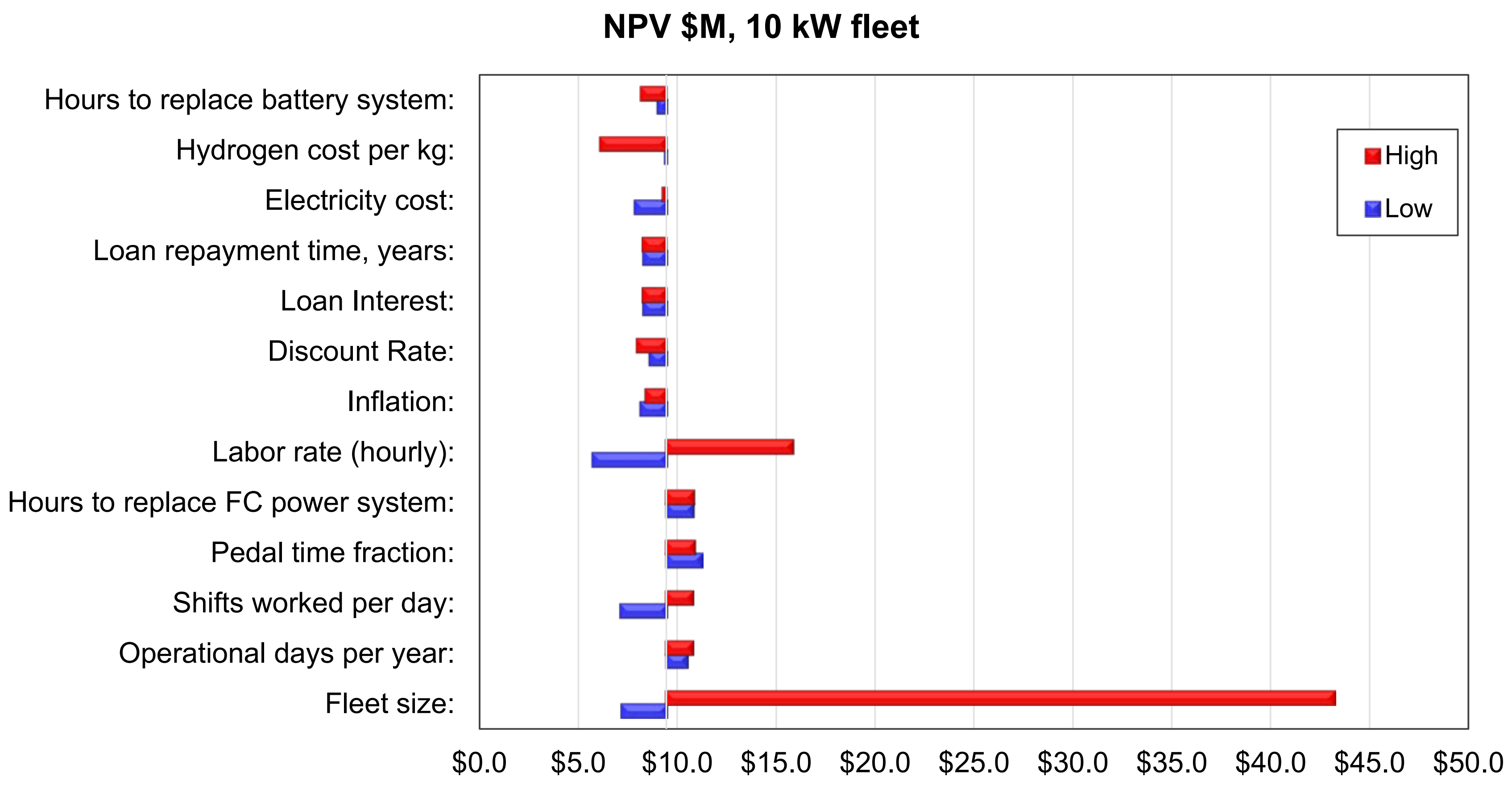
10kW System Sensitivity Analysis Results



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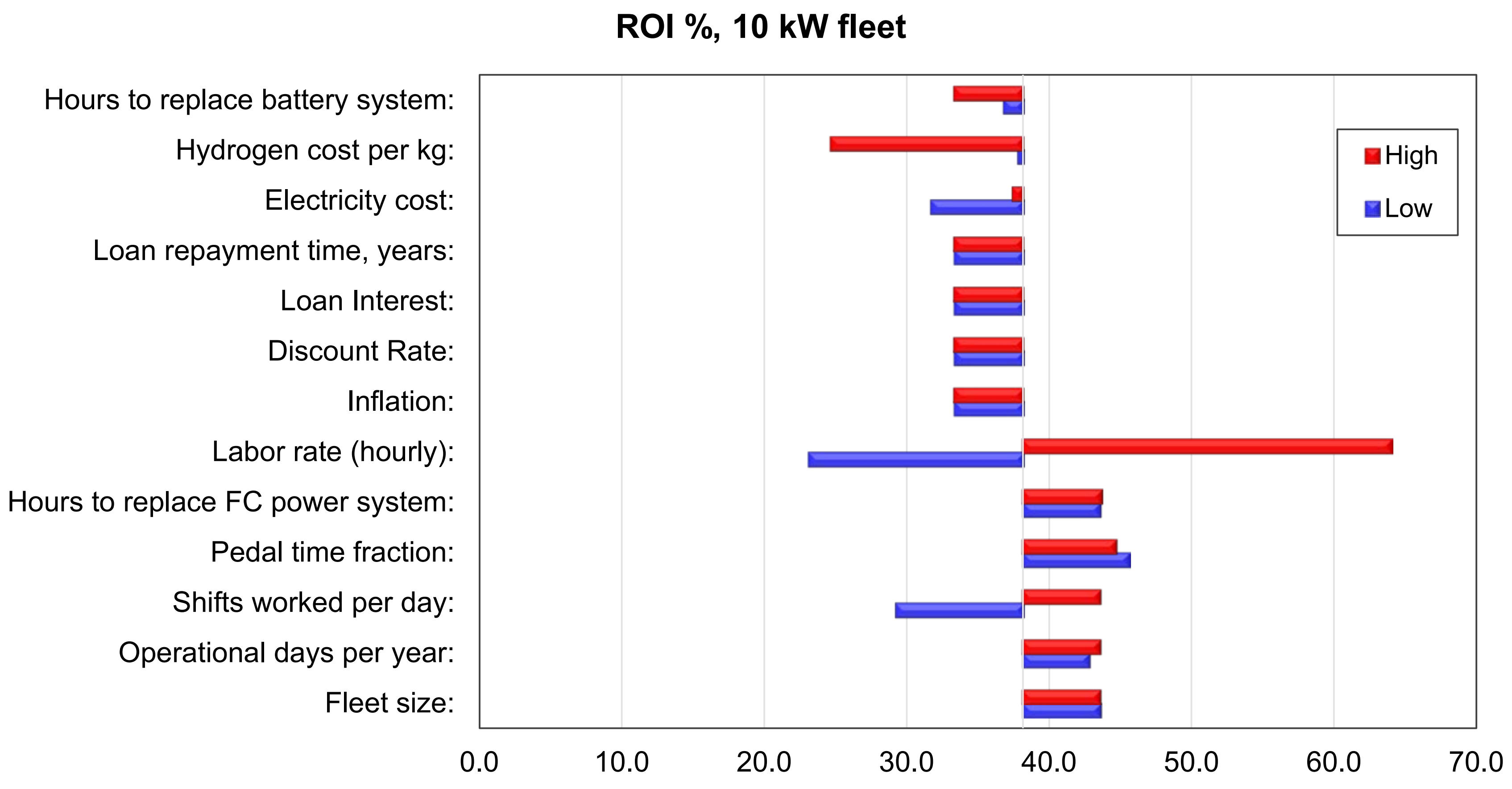
10kW System Lifecycle Cost Analysis



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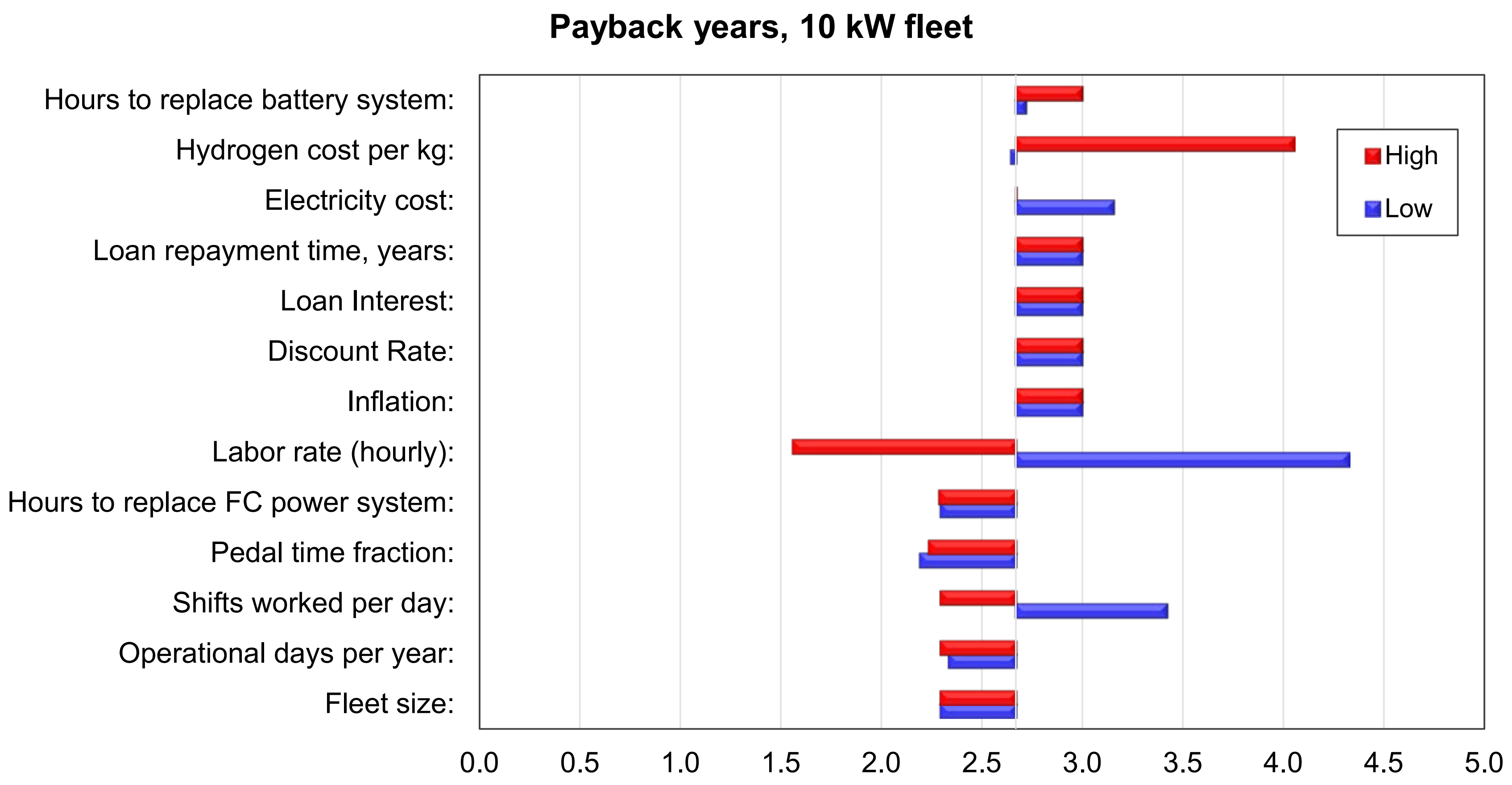
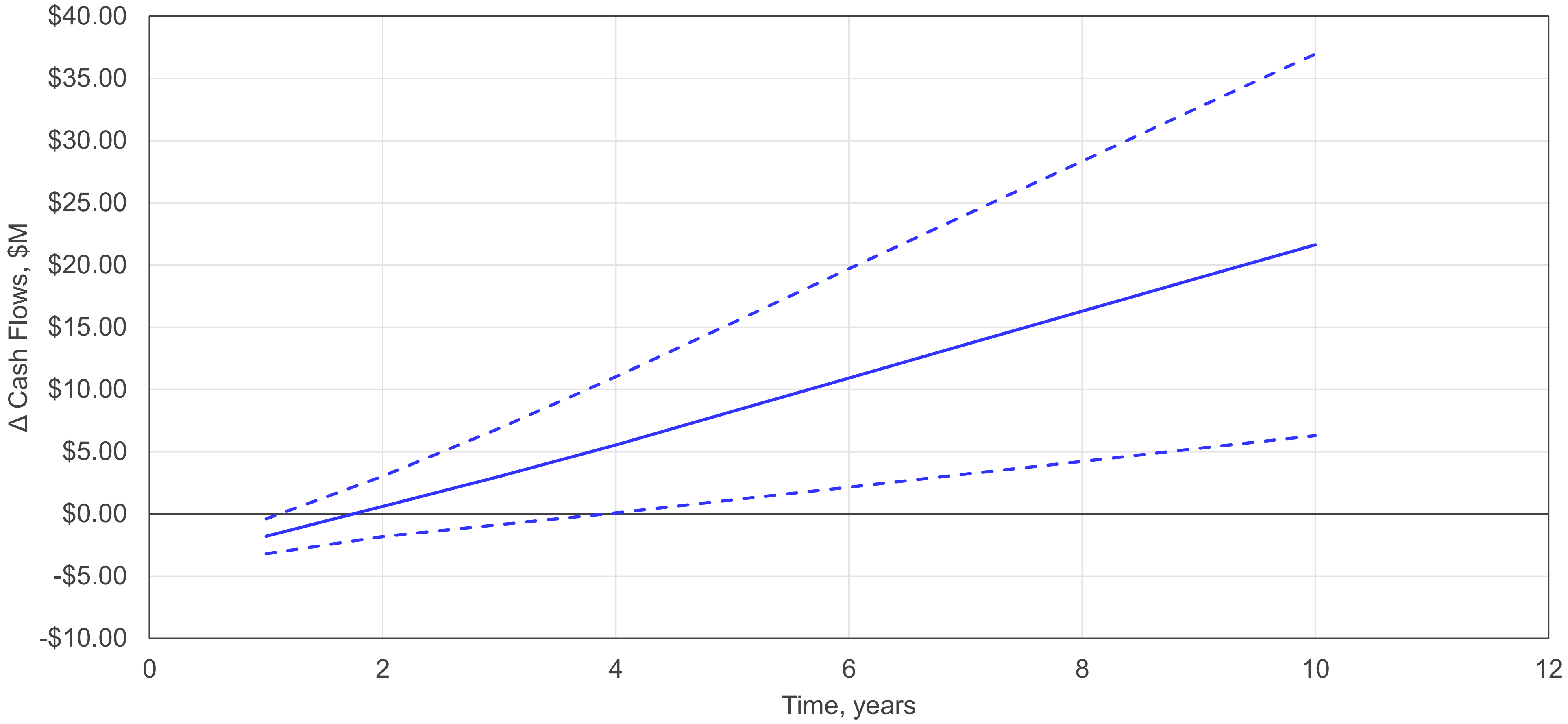
10kW System Lifecycle Cost Analysis



10kW System Cash Flow Diagram



Expected change in cash flow diagram, based on selecting fuel cells over battery power, with error-bounds as determined by the mean cash flow with a single standard deviation as generated through 10,000 Monte Carlo iterations assuming a manufacturing volume of 10,000 units.

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MHE Market Highlights

- To date – MHE has been the **biggest success story** for the fuel cell industry
- Robust collaboration (true-partnership) between **stakeholders** and **manufacturers** facilitated **customized** MHE programs and helped lead to the market's success
- **Greenfield/Brownfield** projects are both viable with an even stronger value proposition for Greenfield projects
- Success of pilot studies helped lead to **higher production**, **standard system/stack design** and **supply chain leverage** for cost reduction (**as much as 70% over the past 5 years in one case**)
- Success of forklift application has motivated manufacturers to pursue new markets such as **auto-guided vehicles** (**AGV) and cargo/industrial trucks**

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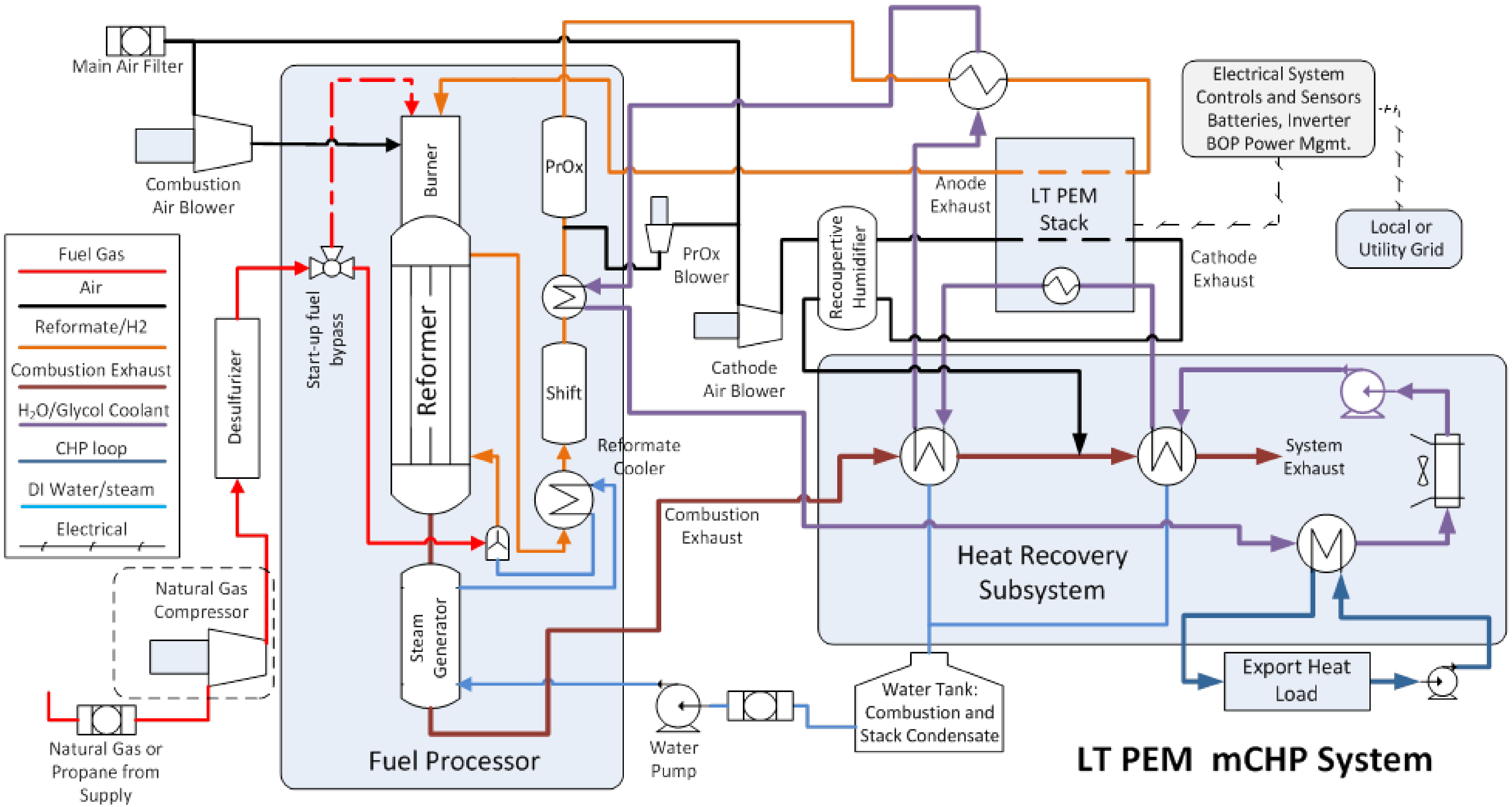
Representative LTPEM CHP system



Complex system due to need for fuel processing with H_2 cleanup – requiring multiple heat exchangers

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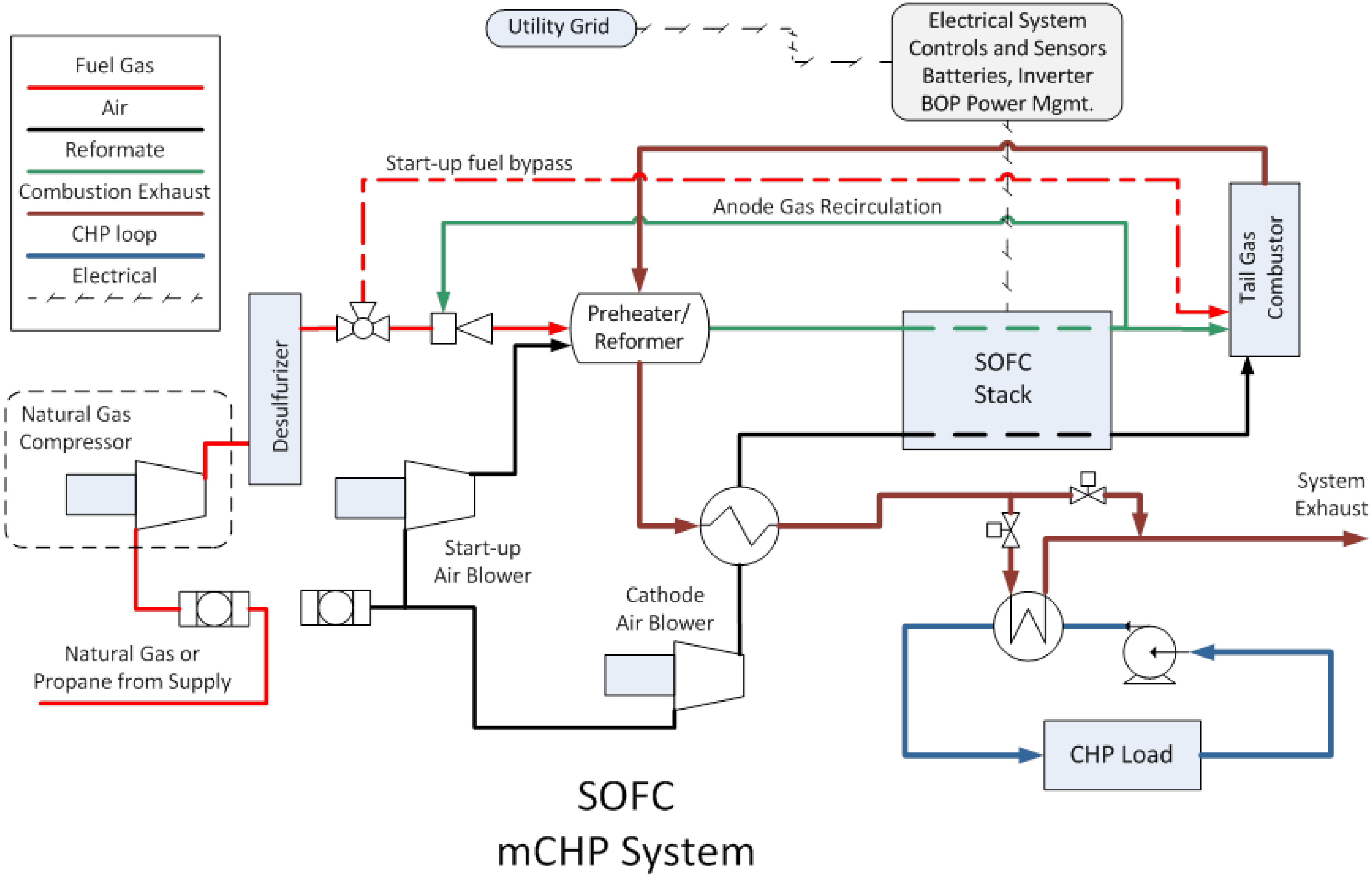
Representative SOFC CHP system



SOFC system is less complex than the PEM system due to simpler fuel processor and less needed heat exchangers

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Primary Power/CHP Nominal Design Basis

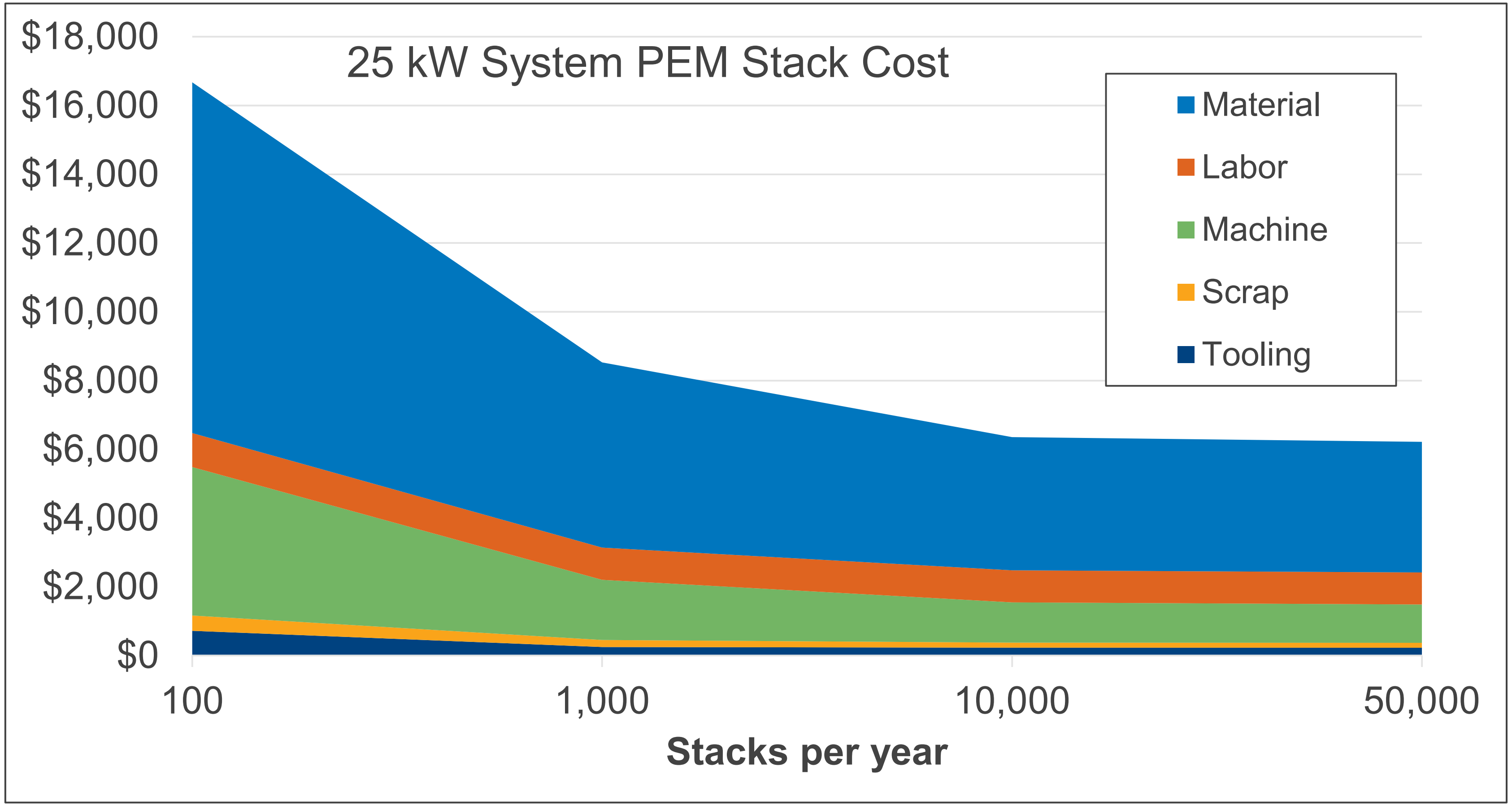
Metric/Feature	Objective
Input, Fuel	Utility Natural Gas or Propane
	(>30 psig preferred)
Input, Air	Ambient air (-20° to 50°C)
Input, Other	N/A
Output	120/240 VAC
	480 VAC 3-phase optional
Net Power Output	1, 5, 10, 25, 100, 250 kW
System Efficiency (electrical)	
LTPEM	30%
SOFC	40%
System Efficiency 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

PEM Stack Manufacturing Cost – 25 kW System

Stack Components	25 kW System			
	100	1,000	10,000	50,000
MEA	$10,288	$5,266	$3,624	$3,515
Anode / Cooling Gasket	$508	$304	$240	$238
Cathode Gasket	$179	$81	$65	$65
Anode Bipolar Plate	$1,986	$1,229	$1,065	$1,064
Cathode Bipolar Plate	$1,905	$1,148	$983	$983
End plates	$111	$58	$53	$35
Assembly hardware	$94	$88	$82	$78
Assembly labor	$158	$126	$123	$123
Test and conditioning	$1,445	$227	$120	$116
Total	**$16,674**	**$8,527**	**$6,354**	**$6,217**
Cost per kW_{net}	**$667**	**$341**	**$254**	**$249**

The catalyst, membrane and gas diffusion layer (GDL) all contribute to make the membrane electrode assembly (MEA) the largest contributor to stack cost

PEM Fuel Cell Stack Volume Trend



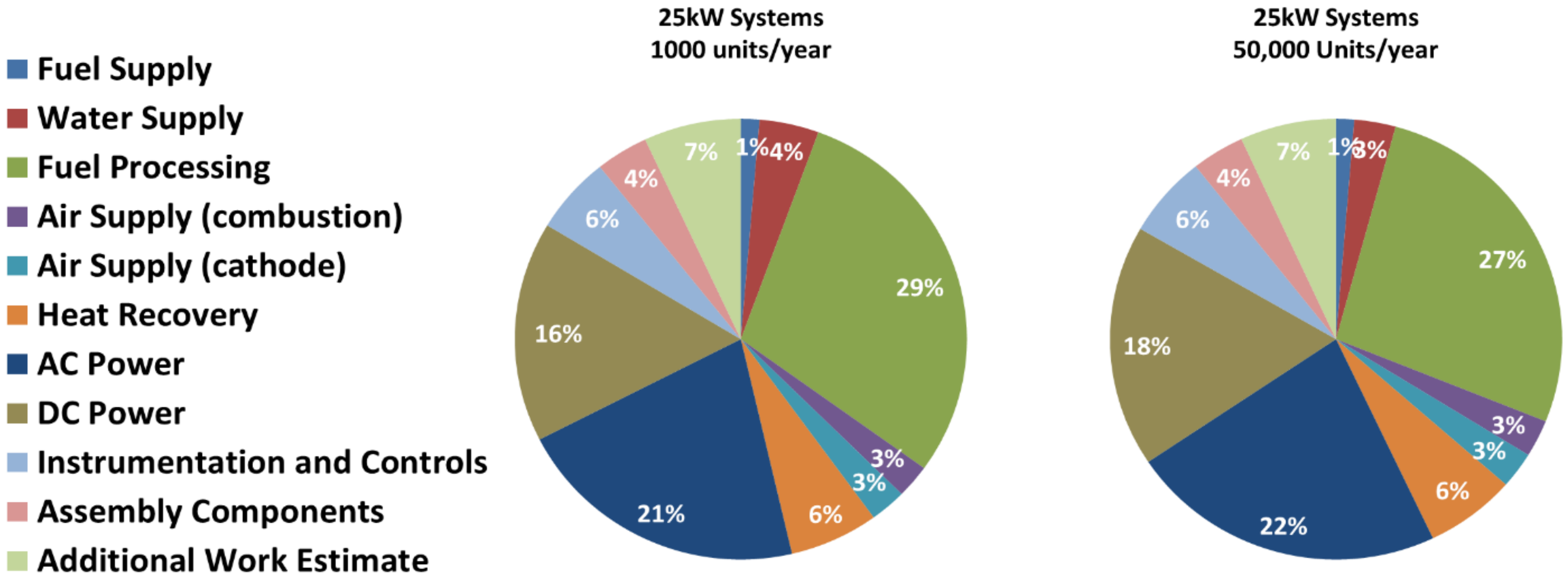
Material cost is the highest contributor at all production levels

CHP PEM BOP Cost

BoP Components	25 kW			
	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Fuel Supply	$1,782	$646	$553	$508
Water Supply	$2,267	$2,083	$1,495	$1,164
Fuel Processing	$19,140	$14,355	$11,813	$10,537
Air Supply (Combustion)	$1,311	$1,198	$1,106	$1,069
Air Supply (Cathode)	$1,550	$1,270	$1,098	$1,045
Heat Recovery	$4,198	$3,109	$2,715	$2,545
AC Power	$11,150	$10,321	$9,555	$8,899
DC Power	$10,638	$7,900	$7,283	$6,970
Instrumentation and Control	$3,068	$2,762	$2,495	$2,357
Assembly Components	$2,019	$1,836	$1,652	$1,485
Additional Work Estimate	$4,300	$3,400	$2,900	$2,700
BOP Total	**$61,423**	**$48,879**	**$42,665**	**$39,279**

BOP has several significant contributors, particularly for the PEM systems – most notably, the fuel processing and AC & DC Power

CHP PEM BoP Manufacturing Cost



BOP has several significant contributors, particularly for the PEM systems – most notably, the fuel processing and AC & DC Power – a hybrid 3-port DC/AC inverter has potential to lower cost of power equipment

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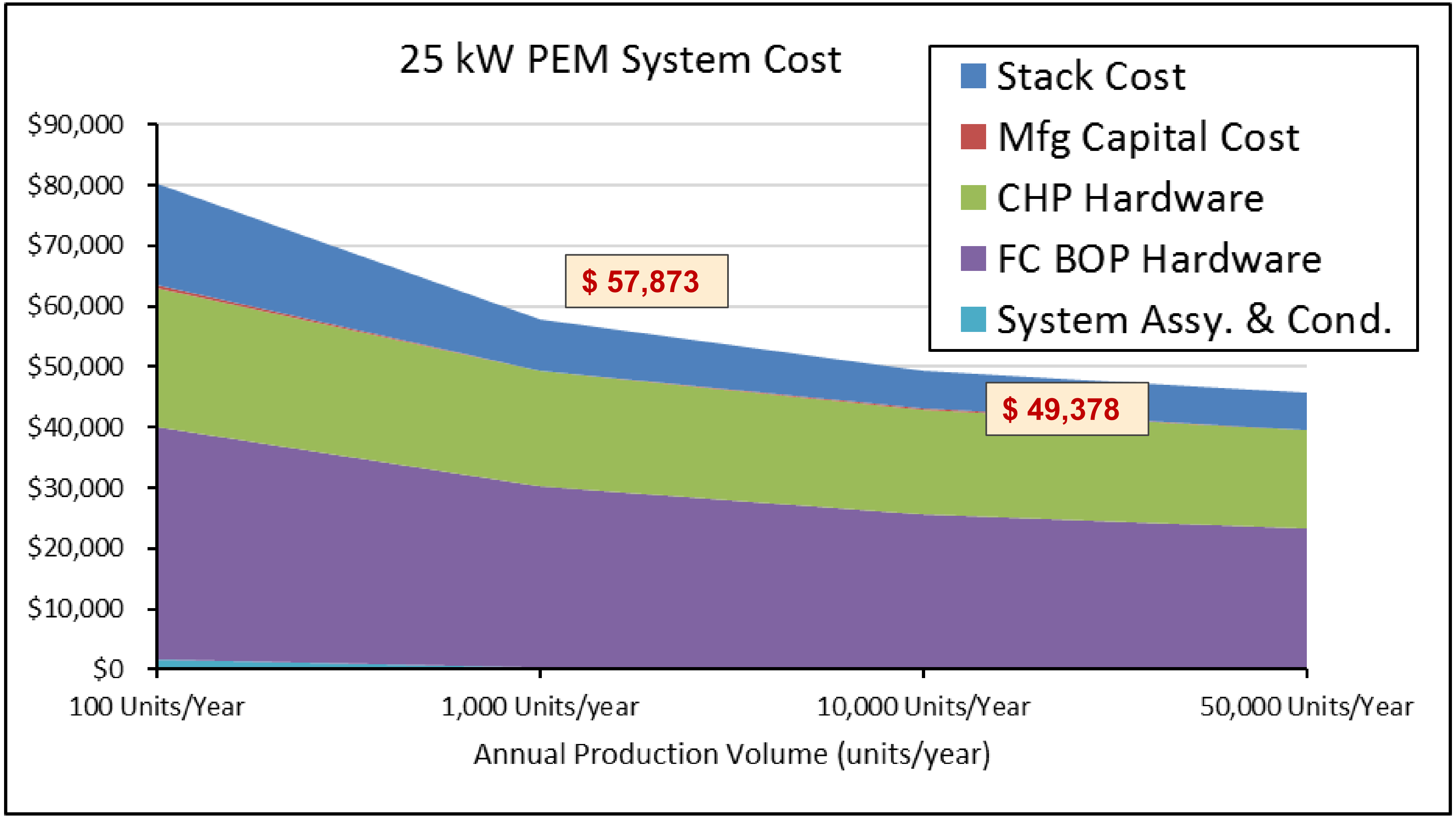
25 kW CHP PEM Fuel Cell System Cost Summary

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$16,674	$8,527	$6,354	$6,217
Stack manufacturing capital cost	$567	$101	$65	$64
CHP Hardware	$22,817	$18,890	$17,356	$16,329
FC BOP Hardware	$38,606	$29,990	$25,309	$22,950
System assembly, test, and conditioning	$1,558	$365	$293	$293
Total system cost, pre-markup	$80,221	$57,873	$49,378	$45,852
System cost per net KW, pre-markup	$3,209	$2,315	$1,975	$1,834
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$120,332	$86,809	$74,067	$68,779
System cost per net KW, with markup	$4,813	$3,472	$2,963	$2,751

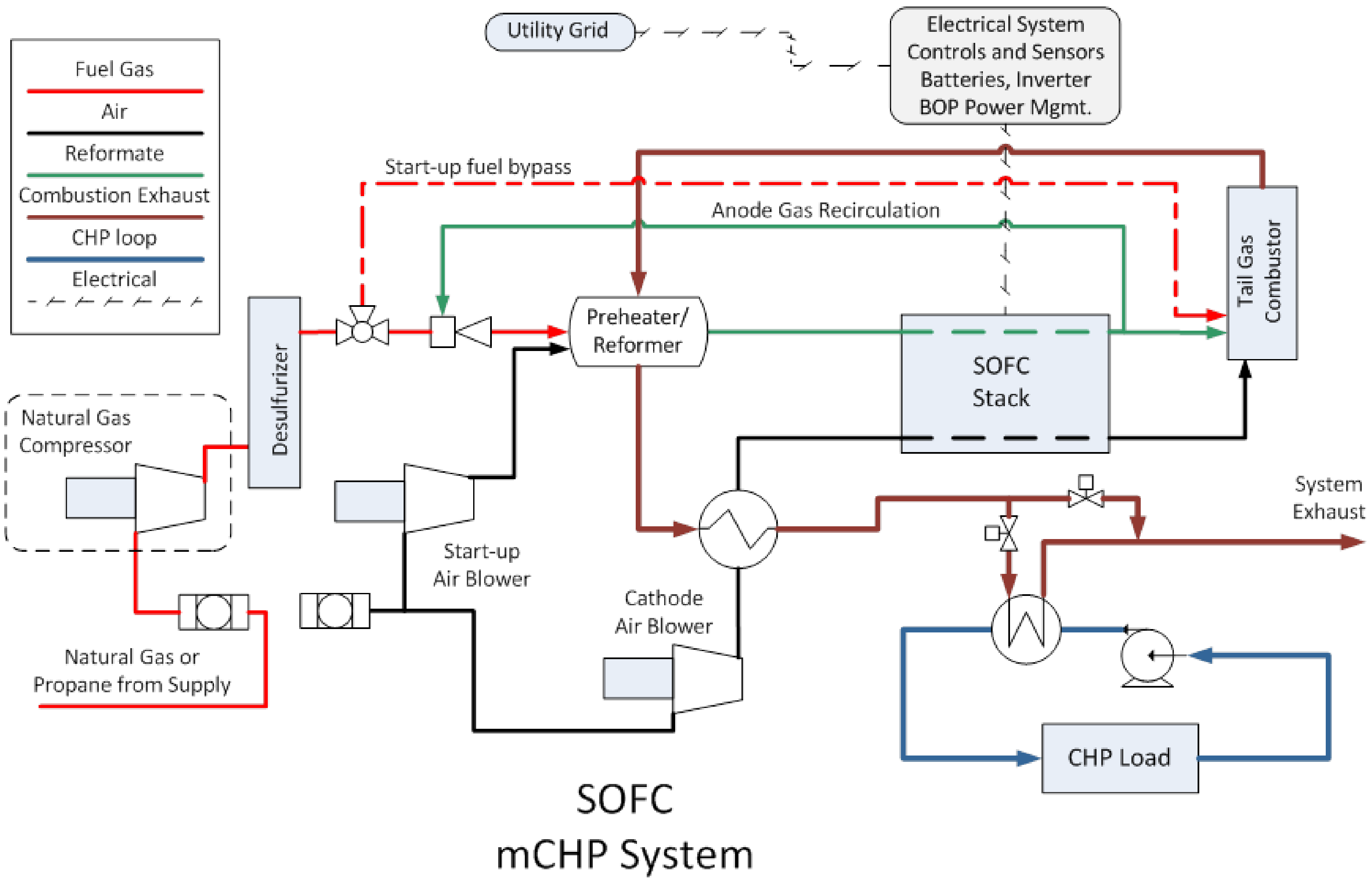
BOP dominates system cost for all capacities and volumes examined

25 kW PEM System Cost - Volume Trend



BOP contribution to cost is even more substantial as production volume increases

Representative SOFC CHP system



SOFC system is less complex than the PEM system due to simpler fuel processor and less needed heat exchangers

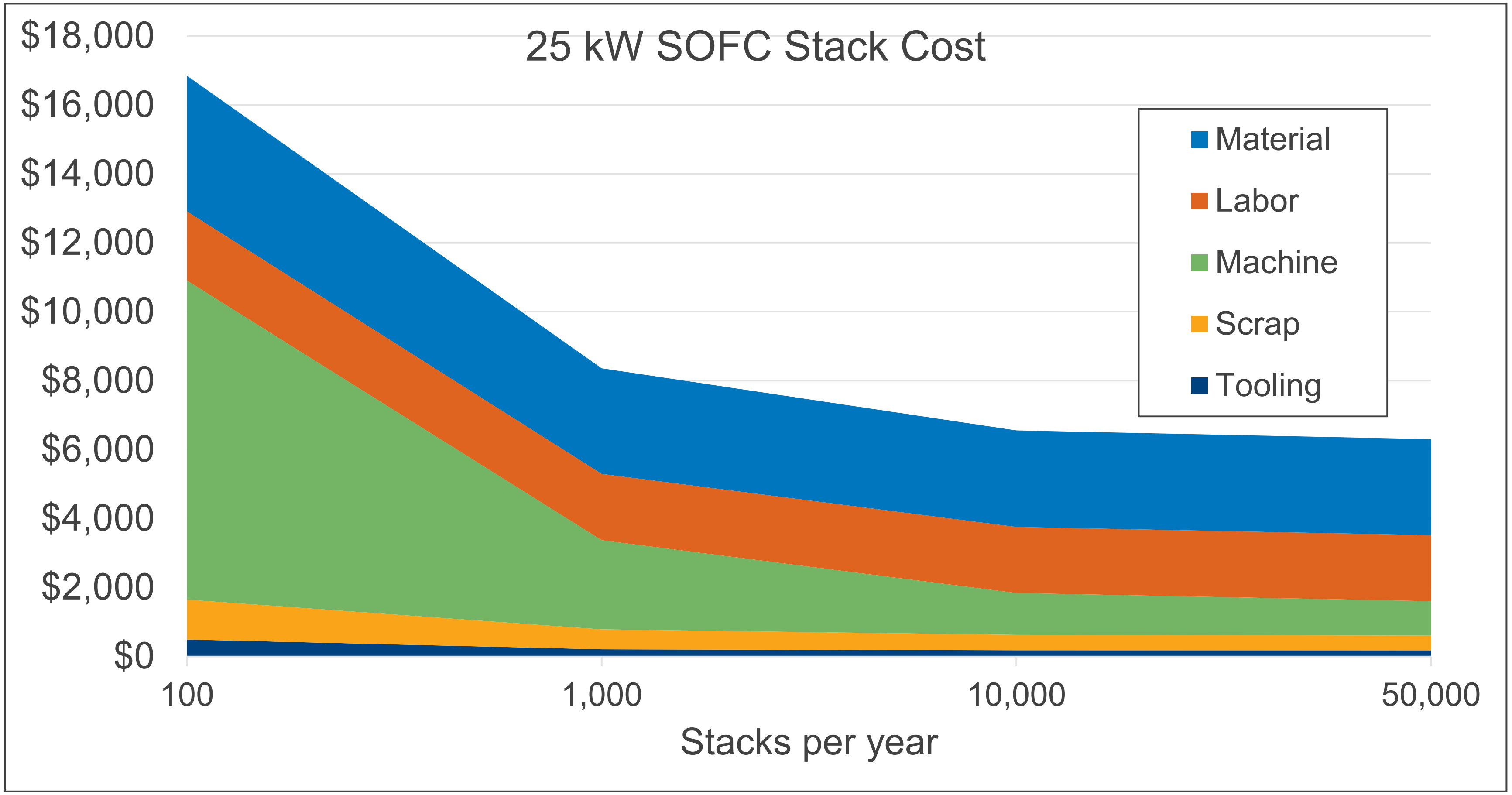
SOFC Stack Manufacturing Cost – 25kW System

Stack Components	25 kW System			
	100 Units ($/each)	1,000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Ceramic Cells	$4,828	$3,395	$2,766	$2,650
Interconnects	$1,109	$870	$495	$444
Anode Frame	$434	$370	$363	$357
Anode Mesh	$365	$275	$191	$189
Cathode Frame	$180	$121	$115	$111
Cathode Mesh	$380	$286	$199	$196
Picture Frame	$212	$135	$128	$123
Laser Weld	$1,444	$168	$112	$112
Glass Ceramic Sealing	$3,890	$655	$401	$373
End Plates	$822	$720	$644	$643
Assembly Hardware	$229	$214	$200	$191
Assembly Labor	$266	$212	$207	$206
Stack Brazing	$98	$81	$67	$50
Test and Conditioning	$2,589	$856	$668	$656
Total Cost	**$16,848**	**$8,358**	**$6,555**	**$6,302**
Cost per kW_{net}	**$674**	**$334**	**$262**	**$252**

Machine utilization leads to significant cost reductions for processing steps such as laser weld and sealing while ceramic cells stay remain high due to machine time (kiln firing process and screen printing)

All costs include manufacturing scrap

SOFC Fuel Cell Stack Volume Trend



Costs more evenly spread for SOFC Stacks between material, labor and machine costs –with machine cost dominating at low volume

CHP SOFC BoP Cost

BoP Components	25 kW			
	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Fuel Supply	$1,782	$646	$553	$508
Fuel Processing	$3,686	$2,531	$1,933	$1,847
Start-up Air Supply (CPOX)	$1,094	$1,004	$931	$899
Cathode Air	$816	$735	$661	$641
Heat Recovery	$2,376	$1,881	$1,618	$1,532
AC Power	$11,150	$10,321	$9,555	$8,898
DC Power	$10,638	$7,900	$7,283	$6,970
Instrumentation and Control	$2,993	$2,346	$2,123	$2,006
Assembly Components	$1,047	$951	$854	$770
Additional Work Estimate	$2,100	$1,700	$1,500	$1,400
BOP Total	**$37,682**	**$30,014**	**$27,011**	**$25,471**

BOP has several significant contributors– most notably, AC & DC Power – fuel processing is less significant than for PEM systems

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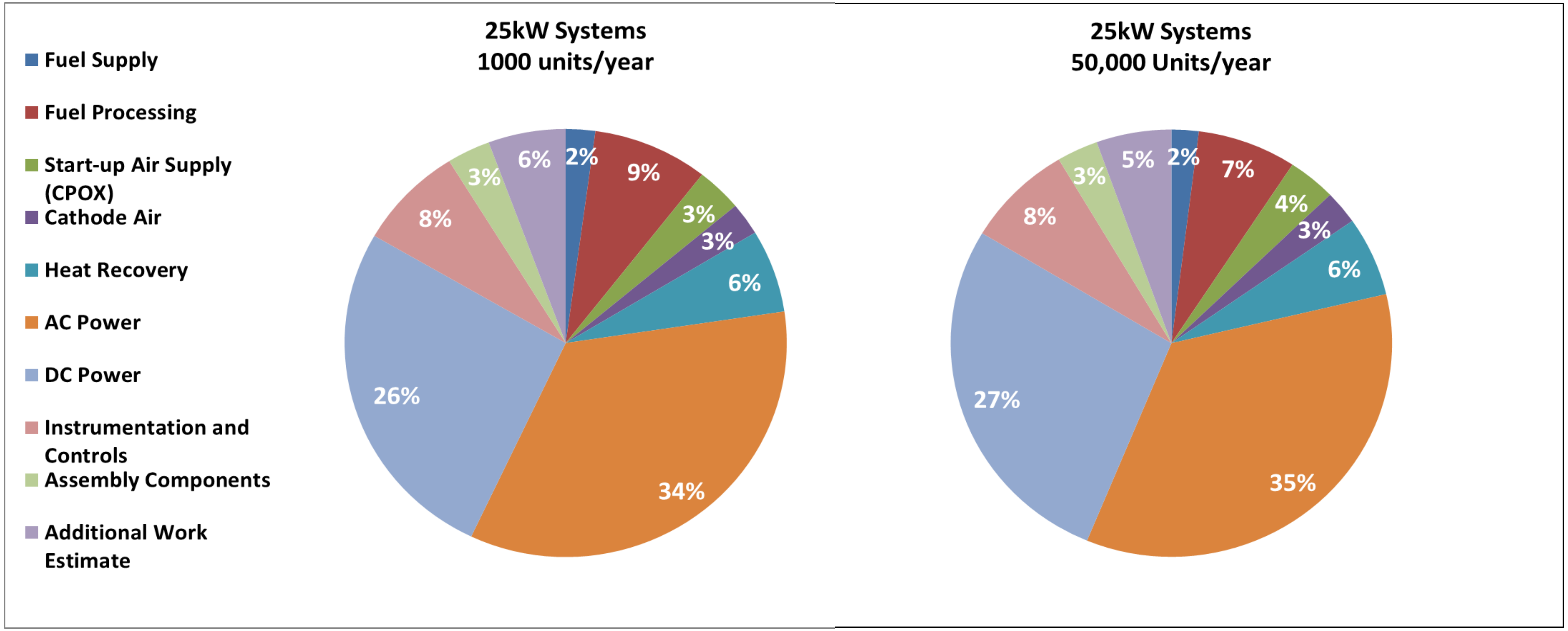
CHP SOFC BOP Manufacturing Cost



AC & DC Power contribute even more significantly than for the PEM system – a hybrid 3-port DC/AC inverter has potential to lower cost of power equipment

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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	$16,848	$8,358	$6,555	$6,302
Stack manufacturing capital cost	$748	$209	$135	$126
CHP Hardware	$23,134	$19,433	$17,939	$16,939
FC BOP Hardware	$14,548	$10,581	$9,073	$8,532
System assembly, test, and conditioning	$1,428	$399	$330	$330
Total system cost, pre-markup	$56,706	$38,980	$34,032	$32,229
System cost per KW_{net}, pre-markup	$2,268	$1,559	$1,361	$1,289
Sales Markup	50%	50%	50%	50%
Total system price, with markup	$85,059	$58,470	$51,048	$48,344
System price per KW_{net}, with markup	$3,402	$2,339	$2,042	$1,934

BOP dominates system cost for all capacities and volumes examined

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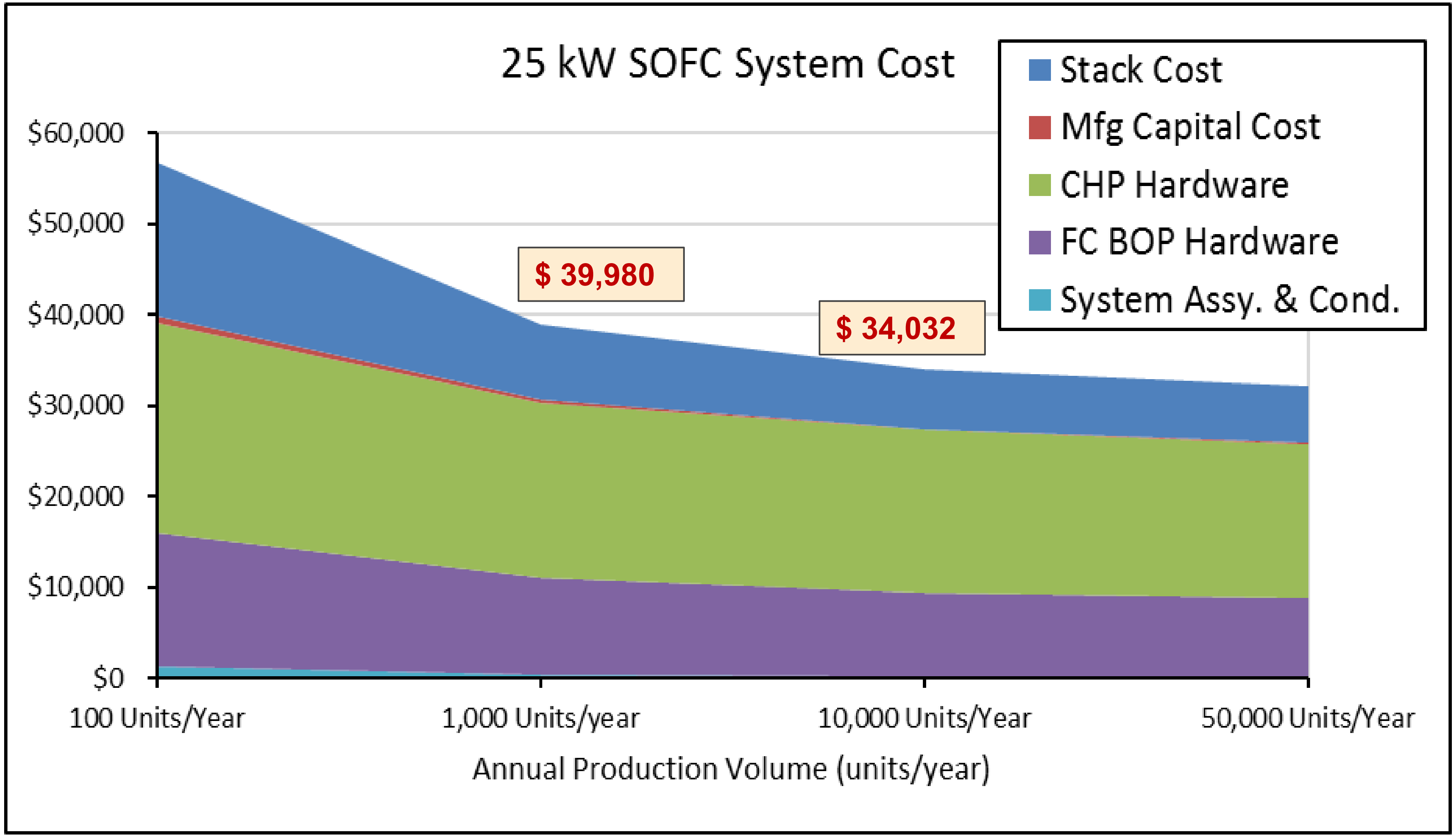
25 kW SOFC CHP System Cost - Volume Trend



BOP contribution to cost is even more substantial as production volume increases

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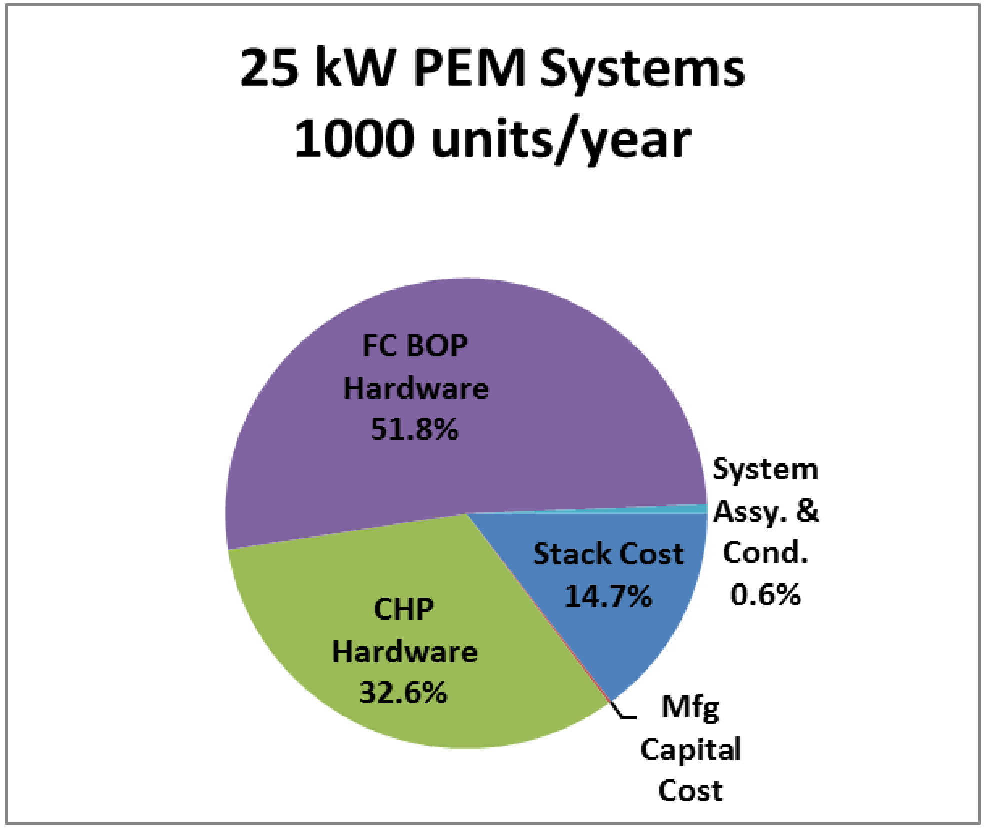
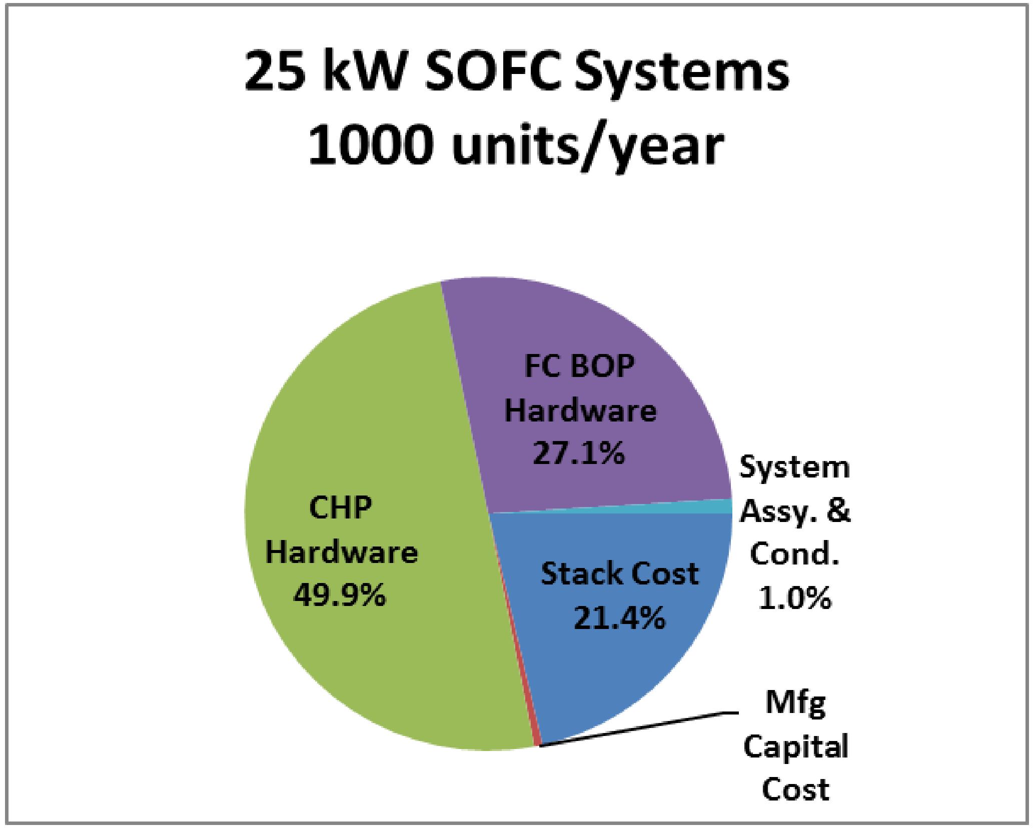
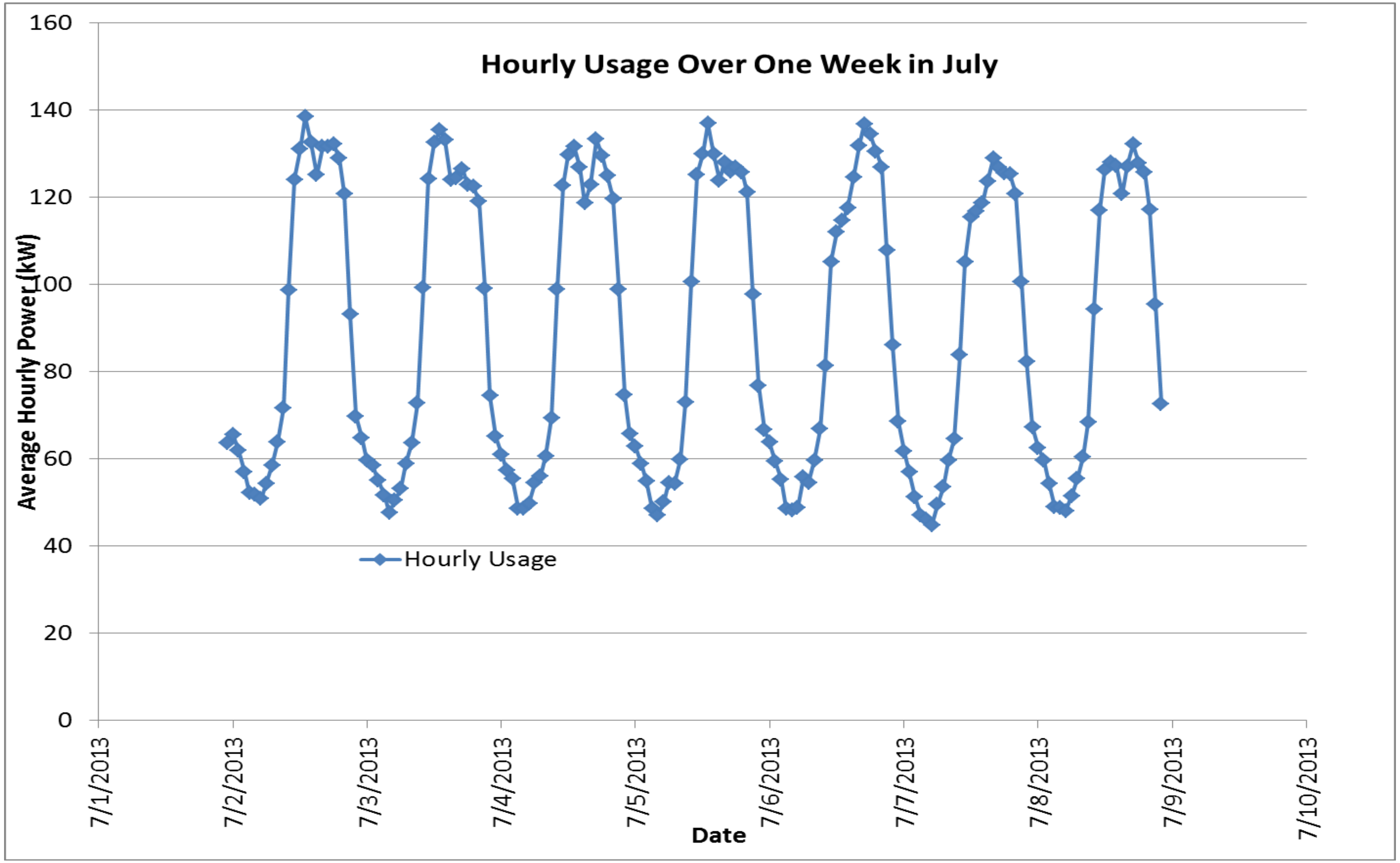
CHP Fuel Cell System Cost Comparison



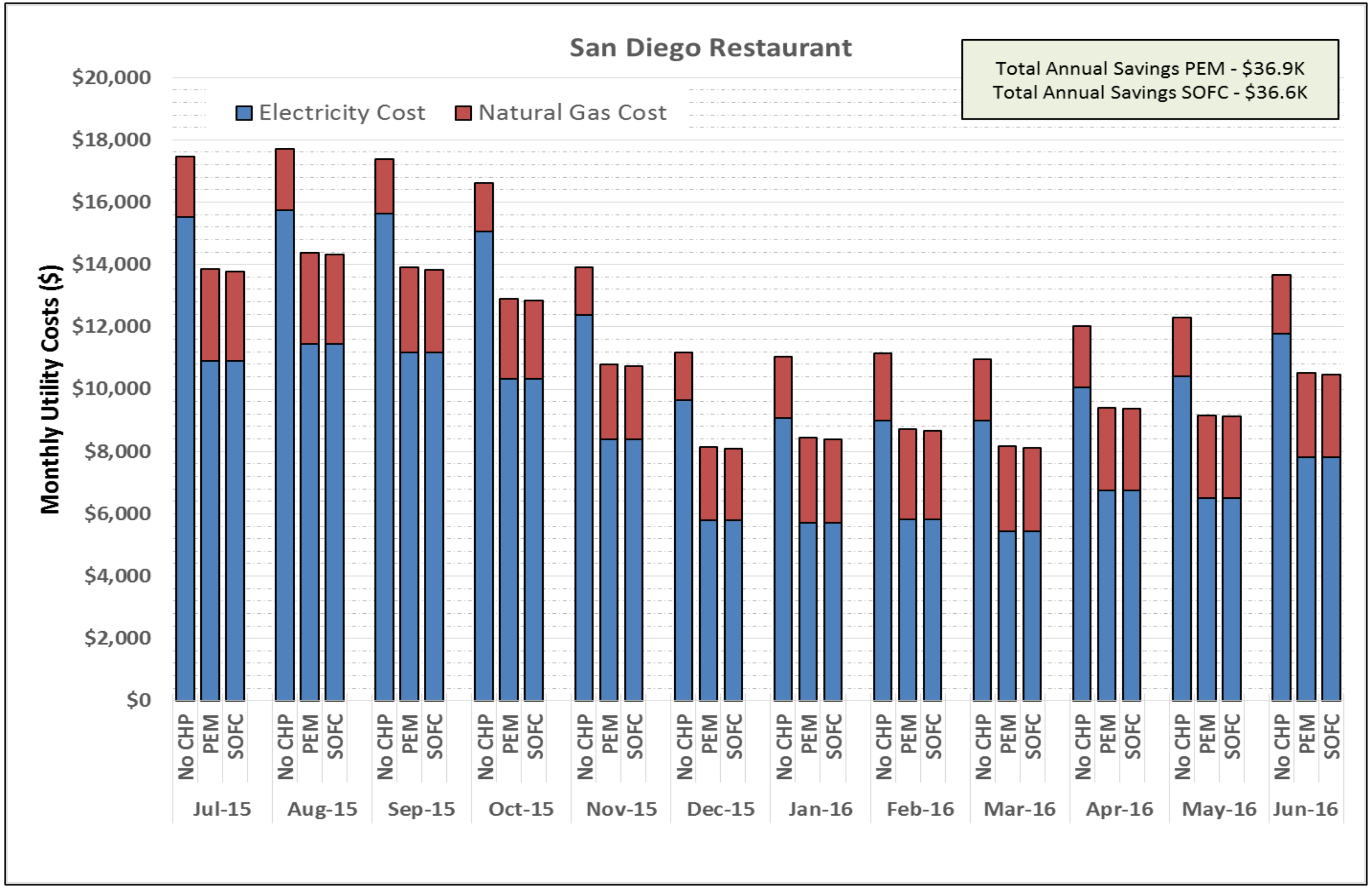


For both technologies, BOP (including CHP hardware) dominates – more significant for the PEM systems

Life Cycle Cost Analysis Assumptions – Restaurant in Southern California



Life Cycle Cost Analysis – 25kW System



Significant annual savings on utilities for San Diego restaurant due to high electricity costs

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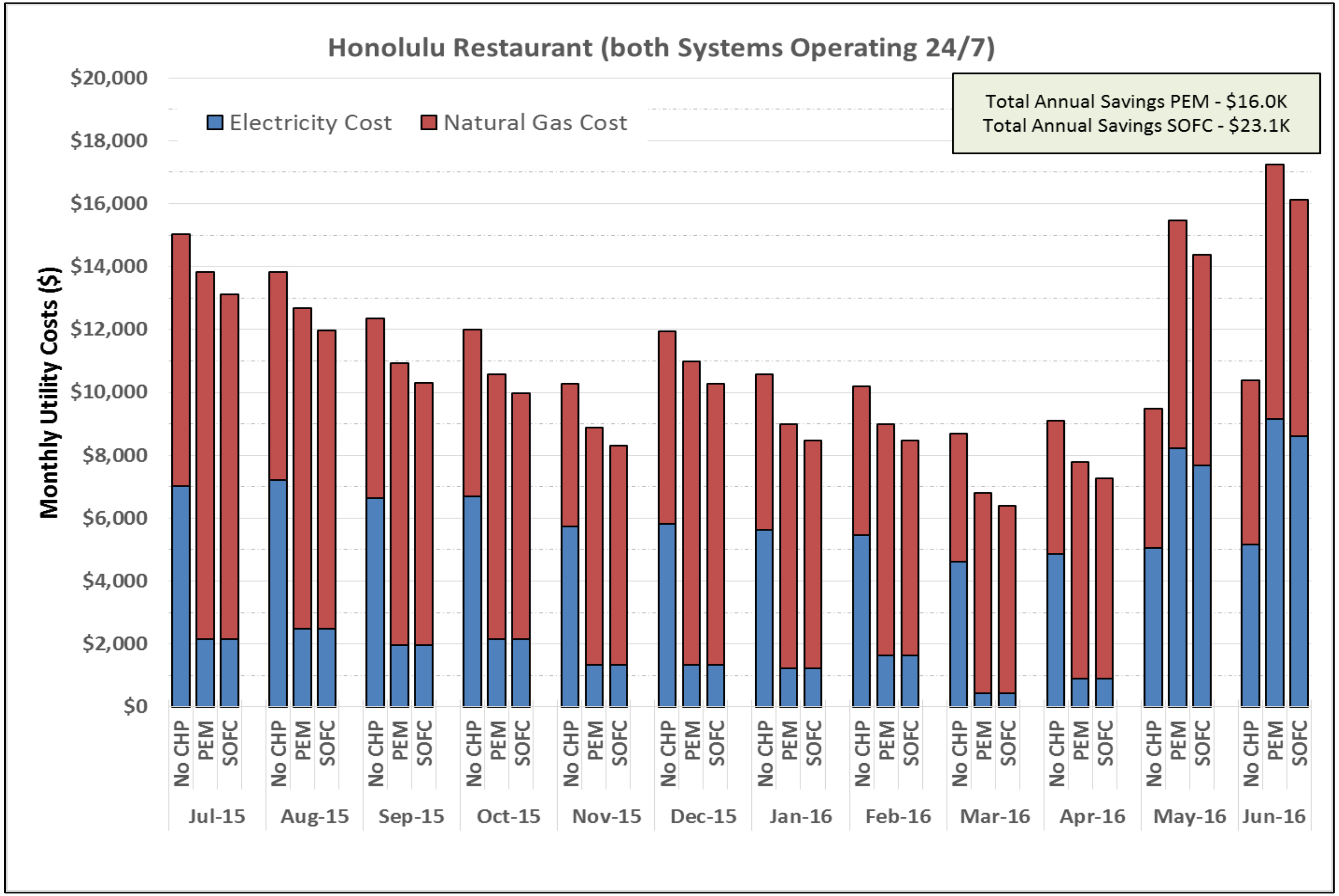
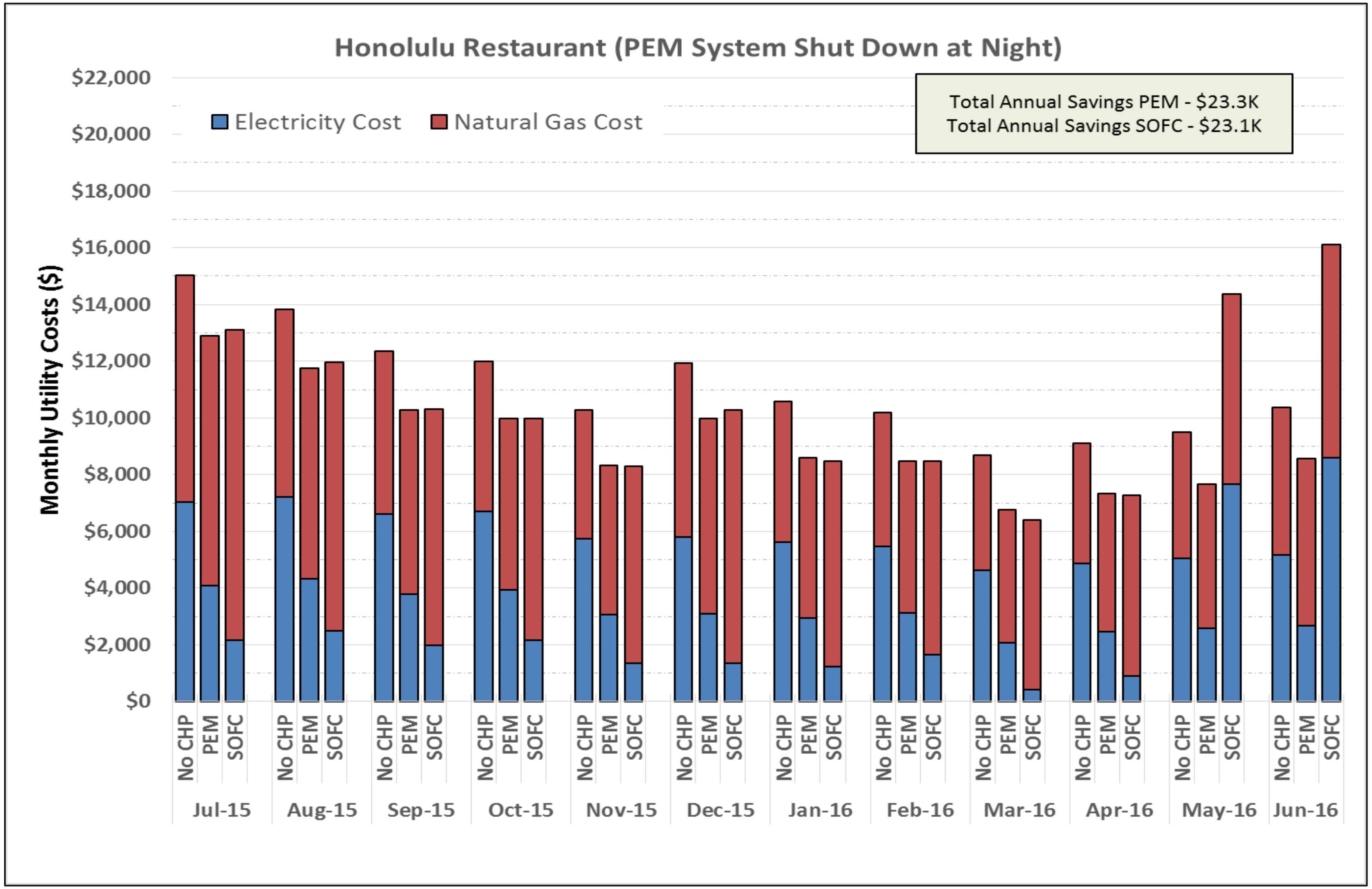
Life Cycle Cost Analysis – 25kW System



Even with high cost of natural gas in Hawaii, still significant savings resulting from CHP system is heat load is substantial

Life Cycle Cost Analysis – 25kW System



PEM systems benefit even more from shutting down when the restaurant is not open for business

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Life Cycle Cost Analysis

PEM – 1,000 units/year	Fuel Cell	Utilities Only
Cost of System	$86,809	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$24,683	N/A
Annual Consumables	$1,252	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$96,028	$143,226
Annual Gas Utility Cost	$32,373	$22,184
Annual Total	$155,087	$165,410
Annual Savings	$10,323	

SOFC – 1,000 units/year	Fuel Cell	Utilities Only
Cost of System	$58,470	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$17,457	N/A
Annual Consumables	$521	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$96,028	$135,427
Annual Gas Utility Cost	$31,663	$26,290
Annual Total	$146,420	$161,717
Annual Savings	$18,990	

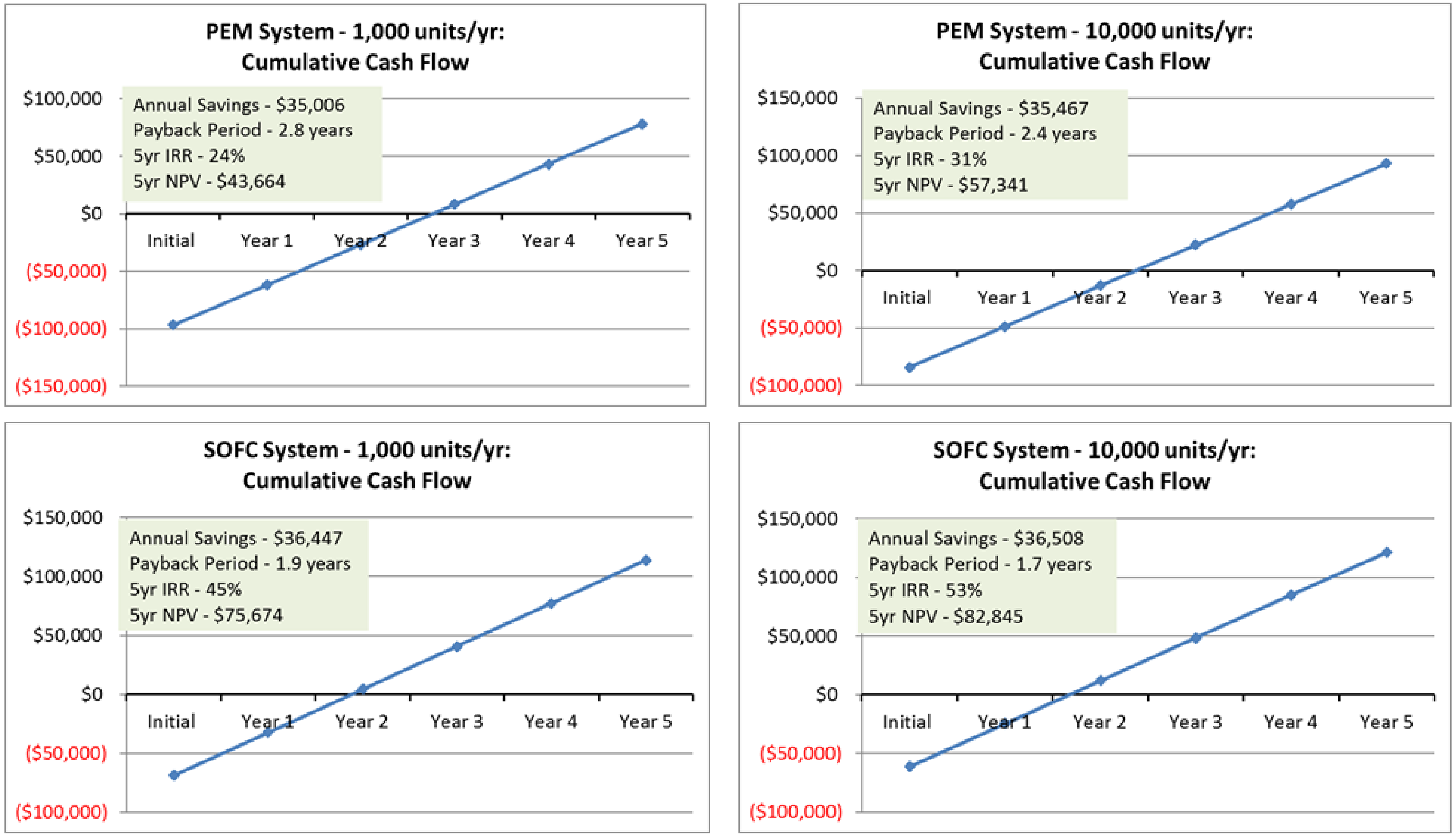
PEM – 10,000 units/year	Fuel Cell	Utilities Only
Cost of System	$74,067	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$21,434	N/A
Annual Consumables	791.15	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$96,028	$143,226
Annual Gas Utility Cost	$32,373	$22,184
Annual Total	$151,377	$165,410
Annual Savings	$14,033	

SOFC – 10,000 units/year	Fuel Cell	Utilities Only
Cost of System	$51,048	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	$96,028	$135,427
Annual Gas Utility Cost	$31,663	$26,290
Annual Total	$144,487	$161,717
Annual Savings	$20,922	

Annual savings after all costs are taken into consideration

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

Life Cycle Cost Analysis



Favorable payback period and return on investment – but does require significant production volumes

*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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Summary

- MHE market has really started to take off
- Interest in the primary power and CHP market is beginning to take shape
- Emerging markets with positive value propositions can learn from the path of the MHE market
- In the words of one end user
  - Need to undertake early efforts with a *"pilot mentality"*
  - *"Finding the right external business partner is key"*
  - *"Almost stopped pilots a couple of times, but were able to get through it by working together; reliability and value proposition is significantly better today; vendor and stakeholder were able to grow together"*
  - *"Holy grail is getting increased productivity, better sustainability and reduced greenhouse gas footprint"*

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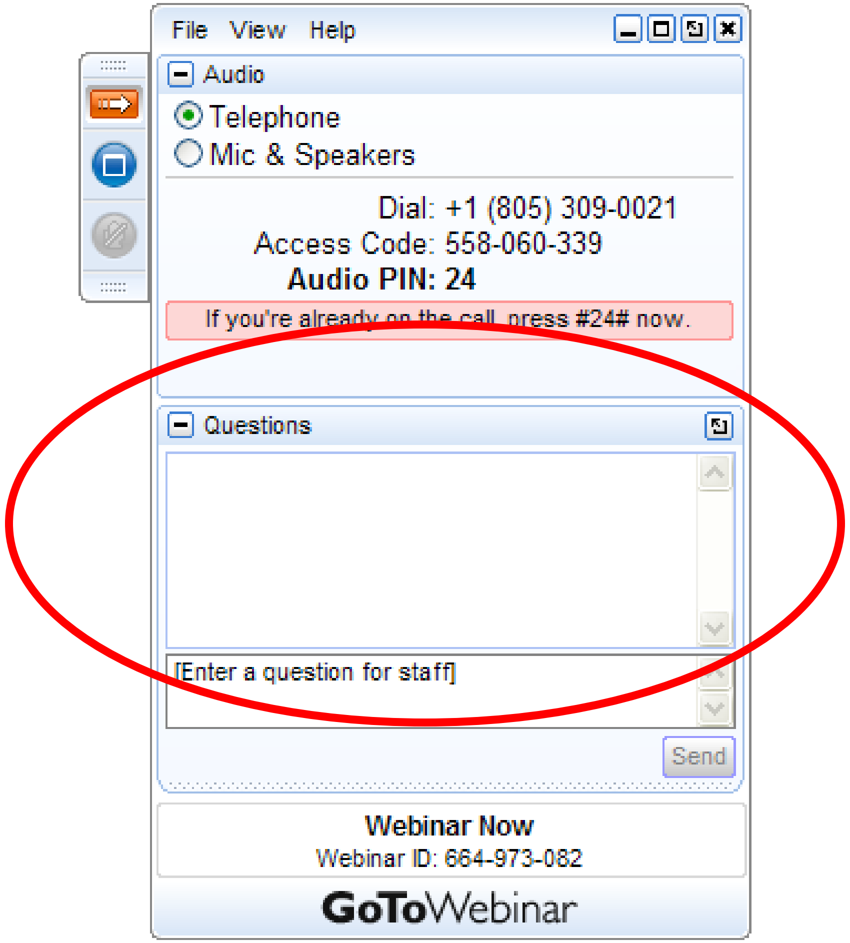
Question and Answer

- Please type your questions into the question box



Thank you

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