A Total Cost of Ownership Model for Design and Manufacturing Optimization of Fuel Cells in Stationary and Emerging Market Applications

Department of Energy Annual Merit Review for Fuel Cell Research

Washington, D.C.
June 19, 2014

Max Wei (Co-P.I.)

Thomas McKone (P.I.)

Lawrence Berkeley National Laboratory

Project ID #
FC098

Overview AMR 2014

Timeline

- Project start date: Oct 2011
- Project end date: Sept 2016
- Percent complete: 60%

Budget

- Total project funding
  - DOE share: $1.9M
  - Contractor share: n.a.
- FY13 DOE Funding: $600k
- Planned Funding for FY14: $374k

DOE Cost Targets

Characteristic	2015 Target	2020 Target
10kW CHP System	$1900/kW	$1700/kW
100kW CHP System	$2300/kW	$1000/kW

Barriers Addressed

- Fuel-cell cost: expansion of cost envelope to total cost of ownership including full life cycle costs and externalities (*MYPP 3.4.5B*)
- Lack of High-Volume Membrane Electrode Assembly Processes (*MYPP 3.5.5A*)
- Lack of High-Speed Bipolar Plate Manufacturing Processes (*MYPP 3.5.5B*)

Partners

- University of California Berkeley
  - Department of Mechanical Engineering Laboratory for Manufacturing and Sustainability
  - Transportation Sustainability Research Center
- Ballard Power Systems
- Other Industry Advisors (Altergy Systems)
- Strategic Analysis

Acknowledgment

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

Thanks also to:

Micky Oros, Altergy Power Systems
Bob Sandbank, Eurotech
Mark Miller, Coating Tech Services,
Geoff Melicharek and Nicole Fenton, ConQuip
Charleen Chang, Richest Group (Shanghai, China)
Emory De Castro, Advent Technologies
Douglas Wheeler, DJW Technology, LLC
Don Gervasio, University of Arizona
Tequila Harris, Georgia Tech University
Owen Hopkins from Entegris
Gerald DeCuollo from Treadstone
Brent Cunningham

Relevance & Goals

Total-cost-of-ownership (TCO) modeling tool for design and manufacturing of fuel cells in stationary and materials-handling systems in emerging markets

Expanded framework to include life-cycle analysis (LCA) and possible ancillary financial benefits, including:

- carbon credits, health/environmental externalities, end-of-life recycling, reduced costs for building operation

Identify system designs that meet lowest manufacturing cost and TCO goals as a function of application requirements, power capacity, and production volume

Provide capability for sensitivity analysis to key cost assumptions

BARRIERS

- High capital and installation costs with a failure to address reductions in externalized costs and renewable energy value
- Potential policy and incentive programs may not value fuel cell (FC) total benefits.

Overview: Chemistries and Applications

- **Fuel cell types to be considered:**
  - Conventional, low-temp (~80°C) PEM fuel cell (LTPEM)
  - High-temp (~180°C) PEM fuel cell (HTPEM)
  - Solid oxide fuel cell (SOFC)
- **Application Space:**

APPLICATION	SIZE [KW]	PRODUCTION VOLUME (UNITS/YEAR)			
		100	1000	10,000	50,000
STATIONARY POWER / COMBINED HEAT AND POWER (C)	1	C,B	C,B	C,B	C,B
	10	C,B	CB	C,B	C,B
	50	C,B	C,B	C,B	C,B
BACKUP POWER (B)	100	C	C	C	C
	250	C	C	C	C

Milestones / AOP FY2014

Quarter	Task Description/ Due Date	Go/No-Go Description and Due Date
Q1 10/1/2013 -- 12/31/2013	Detailed design plans and bill-of materials and balance-of-plant inventory for HT-PEM systems in co-generation and stationary power applications (12/31/13)	Done
Q2 1/1/2014 -- 3/31/2014	Direct cost model for HT-PEM systems for co-generation and stationary power applications completed (3/31/2014)	Done
Q3 4/1/2014 -- 6/30/2014	*Literature/patent summary and functional specifications completed for SOFC systems in co-generation and stationary power (6/30/14)*	*In Progress*
Q4 7/1/2014 -- 9/30/2014	*Total cost of ownership model satisfactorily completed for HT- PEM systems in CHP and stationary power applications along with a report describing this work (9/30/14)*	*Go / No Go Review meeting in September 2014.*

TCO Model Structure and Key Outputs

Assumptions:

Application/ Size
Mfg Volume/Yr
Location (mfg, op)
Prices
Policies
Fuel input
Outages/Lifetimes

Total Cost of Ownership (TCO) Model

Manufacturing Cost Model

Direct mfg costs
Indirect mfg costs

Lifecycle Cost Model

Capital/installation
Fuel and operations
Maintenance
Stack replacements
End of life

LBNL DER-CAM Model (CHP)

Life Cycle Impact Assessment Models
Monetized health and GHG impacts

LBNL Impact Models/ Info

Key Outputs:

1) System manufacturing costs and "factory gate" prices
2) TCO Metrics: Levelized costs ($/kWh), Total costs/yr
3) TCO including broader social costs

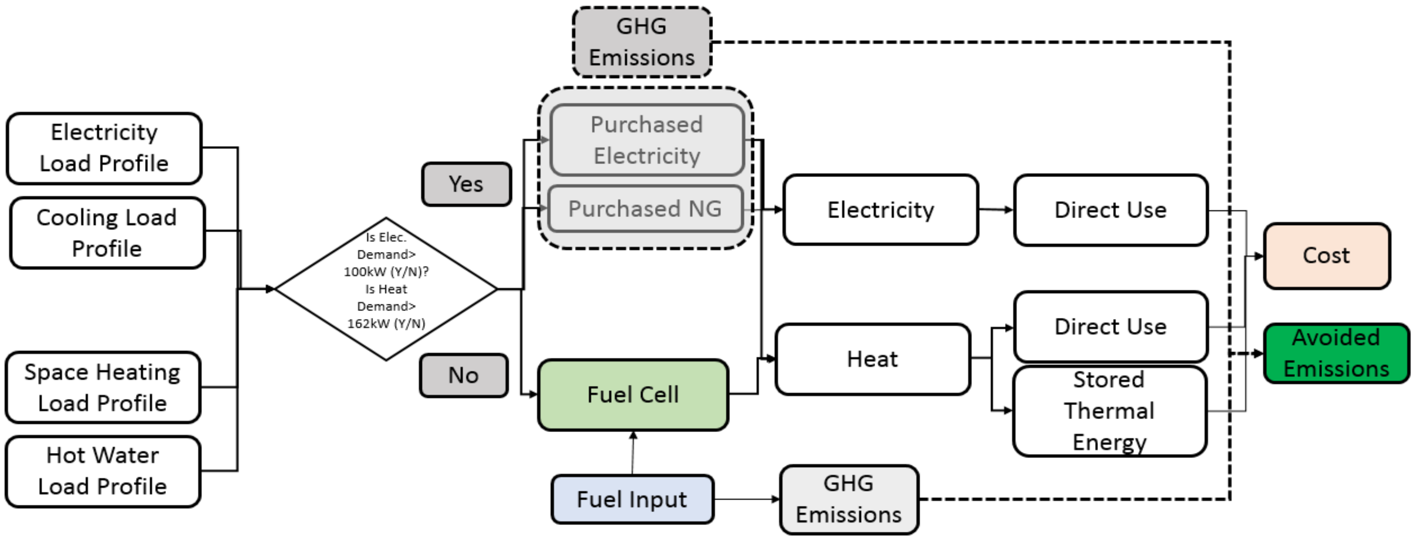
1 - Costing Approach

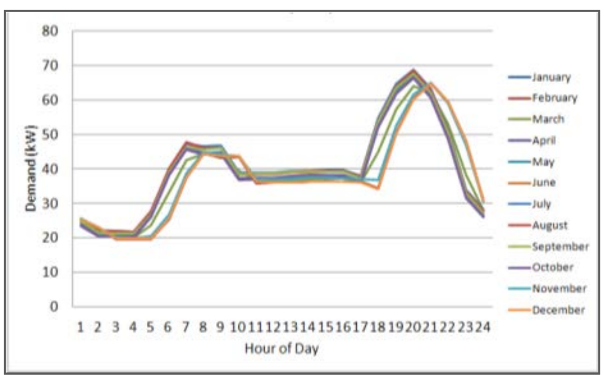
- **Direct Manufacturing Costs**
  - Capital costs
  - Labor costs
  - Materials costs
  - Consumables
  - Scrap/yield losses
  - Factory costs
- **Global Assumptions**
  - Discount rate, inflation rate
  - Tool lifetimes
  - Costs of energy, etc.
- **Other Costs:**
  - R&D costs, G&A, sales, marketing
  - Product warranty costs

Source: Altergy Systems

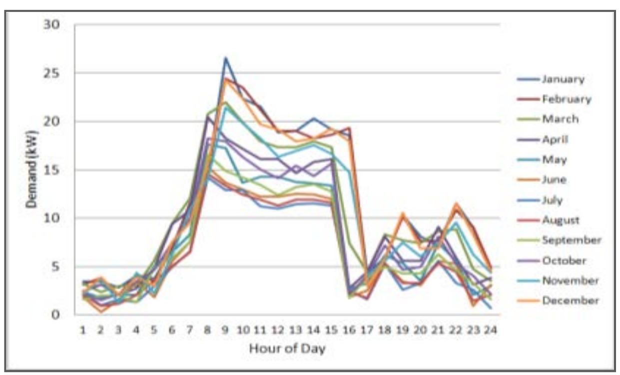
2 - Fuel Cell System Life Cycle Cost (Use Phase) Modeling

Combined Heat & Power Fuel Cell System (100kW example)



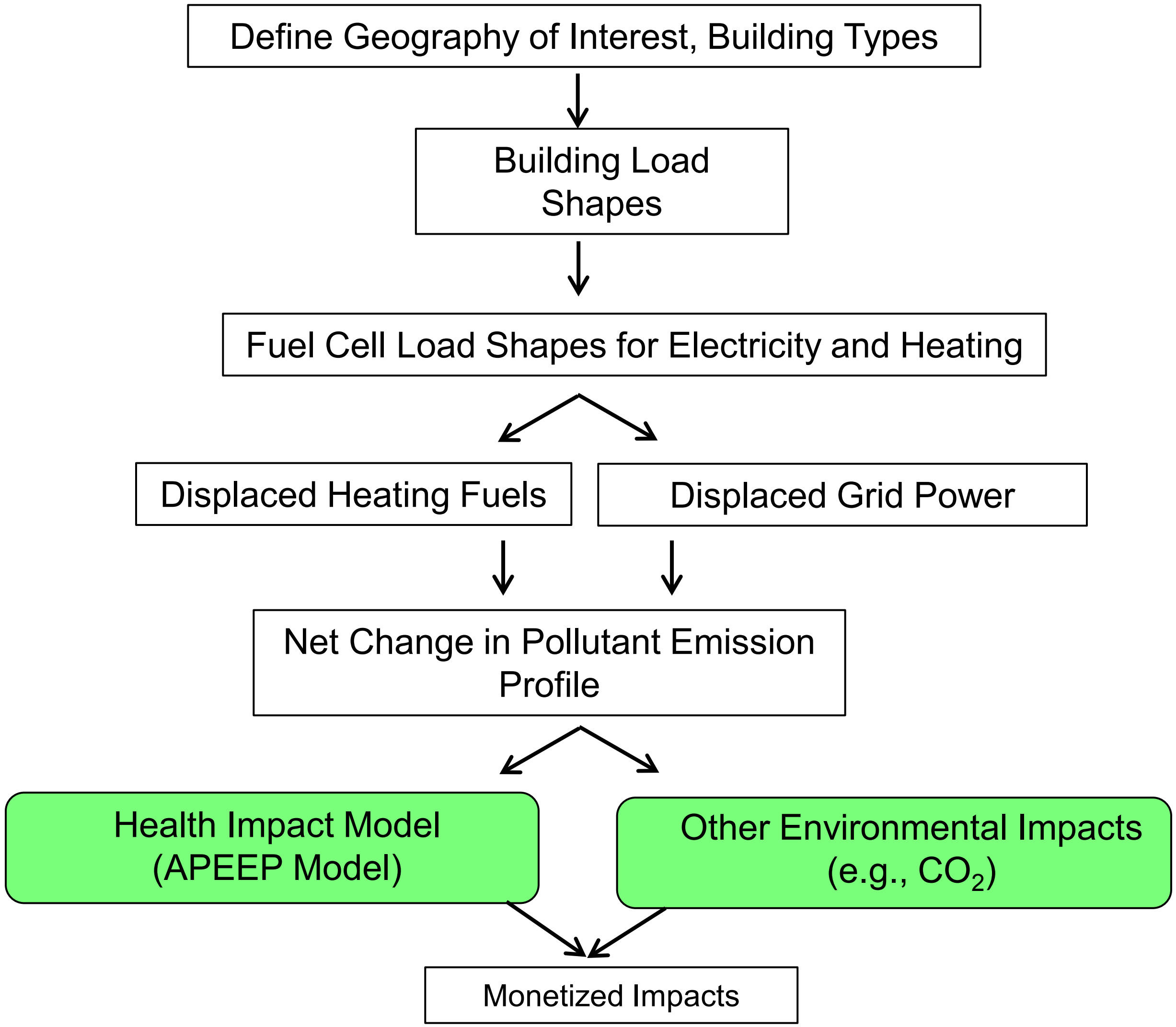


Daily electricity load profiles for small hotel in AZ



Daily hot water load profiles for small hotel in AZ

3 - Life-Cycle Impact Assessment for Environmental and Health Externalities – Fuel Cell CHP Systems



TECHNICAL PROGRESS: LT-PEM FC SYSTEM MANUFACTURING COST

CHP System Designs and Functional Specs

DFMA Manufacturing approaches for LT-PEM FC CHP and backup power systems

Component	Primary Approach	Reference
Membrane	Purchase Nafion®	Patent review, Industry input
CCM*	Dual Decal, slot die coating	Literature, patents, industry input
GDL*	Spray coat MPL	Literature, industry input
Bipolar Plates*	Injection molded graphite –carbon composite (and Metal Plates)	Literature, patents, industry input
Seal/Frame MEA*	Framed MEA	Patents, industry input
Stack Assembly*	Partial to fully automated	Patents, Industry input
Endplate/ Gaskets	Graphite composite/ Screen printed	Industry input, literature
Test/Burn-in	Post Assembly 3 hrs	Industry input

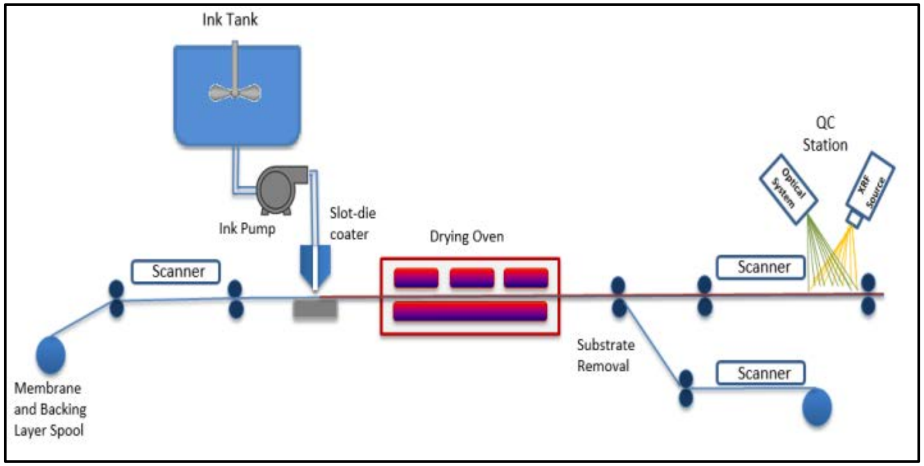
*Full DFMA Costing analysis was performed

Functional specs for 100kW CHP system operating with reformate fuel, 0.5mg/cm² Pt

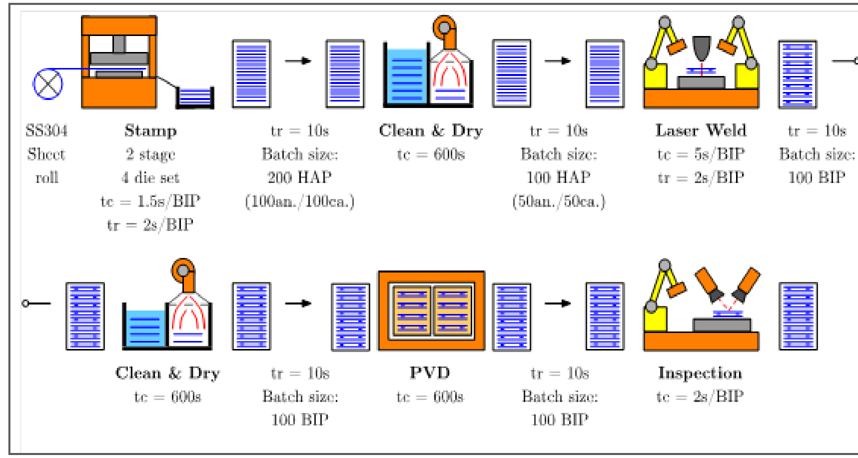
Parameter	Value	Unit
Gross system power	124	kW
Net system power	100	kW
Electrical output	480V AC	Volts AC or DC
Waste heat grade	65	Temp. °C
Fuel utilization	80-95	%
Avg. System Net Electrical efficiency	32	% LHV
Thermal efficiency	51	% LHV
Total efficiency	83	Elect.+thermal (%)
Stack power	9.5	kW
Total plate area	360	cm^2
CCM coated area	232	cm^2
Single cell active area	198	cm^2
Cell amps	111	A
Current density	0.56	A/cm^2
Reference voltage	0.7	V
Power density	0.392	W/cm^2
Single cell power	78	W
Cells per stack	122	Cells
Stacks per system	13	Stacks

Manufacturing Cost Model – CCM, Metal Plates

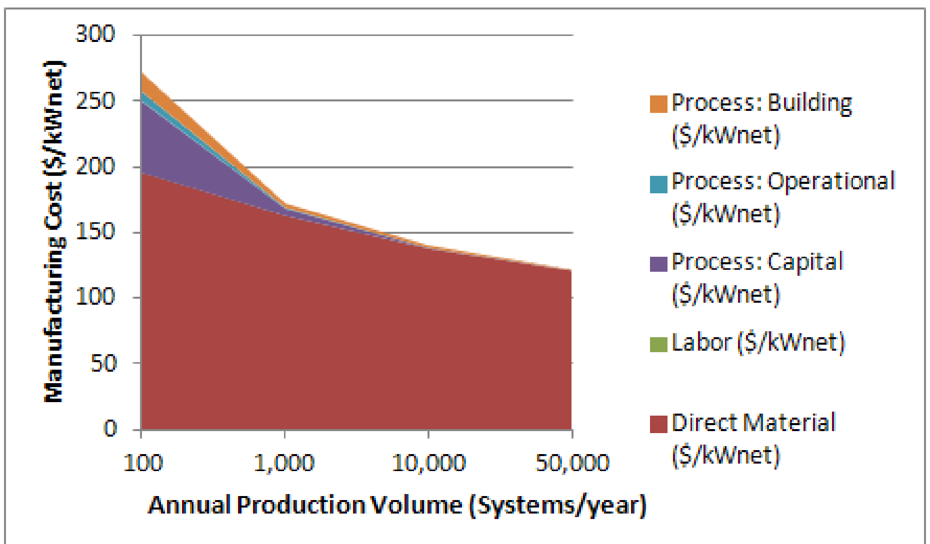
CCM Process Flow-Cathode Coating Line



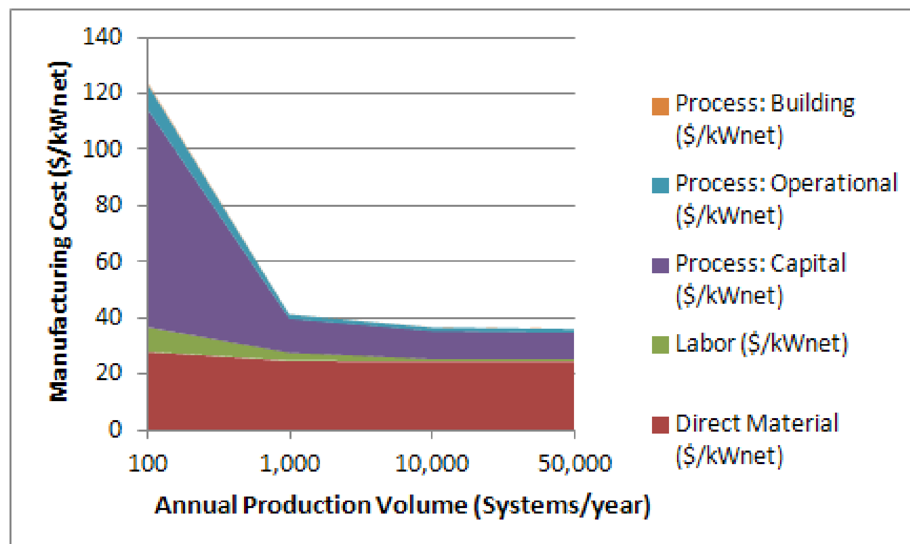
Metal Plate Process Flow



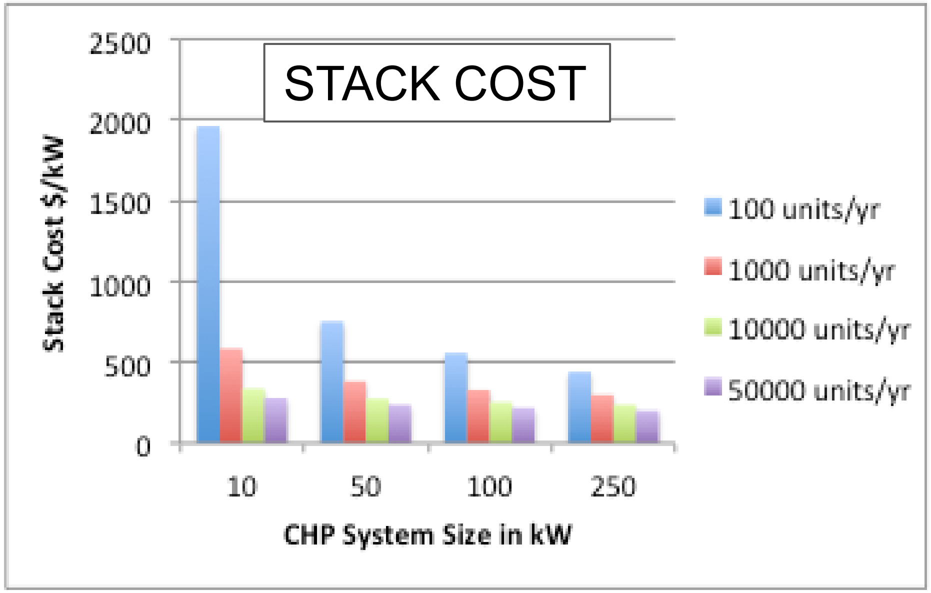
CCM Cost Plot - 100kW System

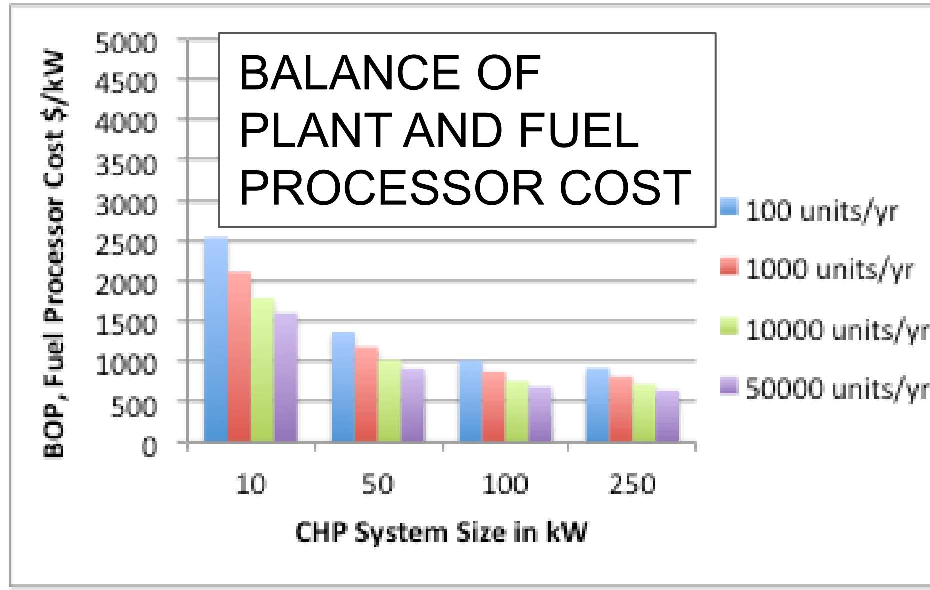


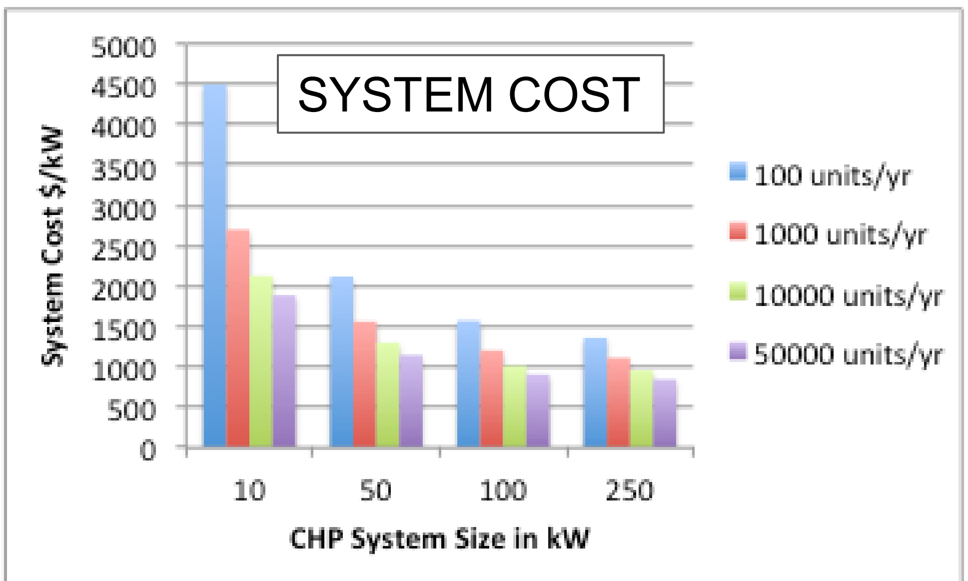
Plates Cost Plot - 100kW System



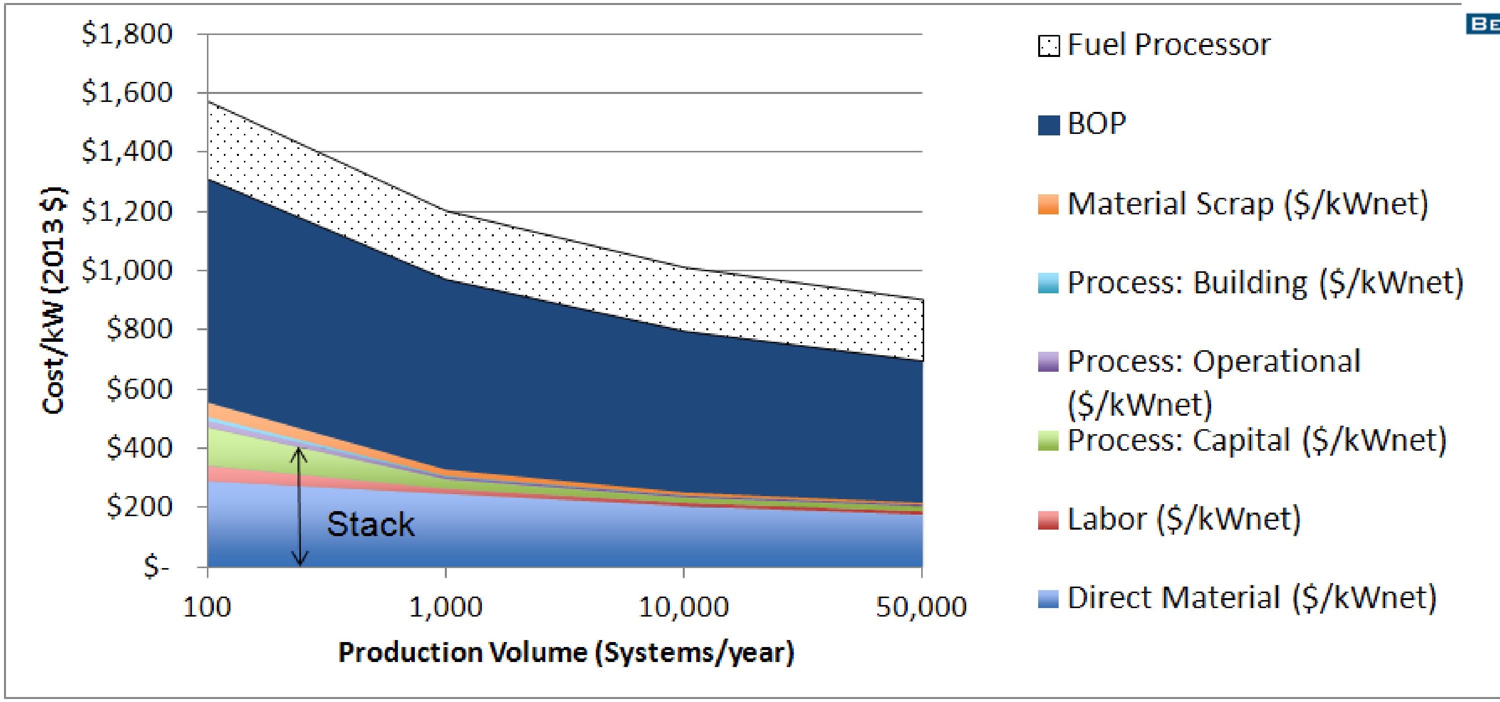
Summary of Cost vs. Volume for CHP System Sizes of 10, 50, 100, and 250 kW

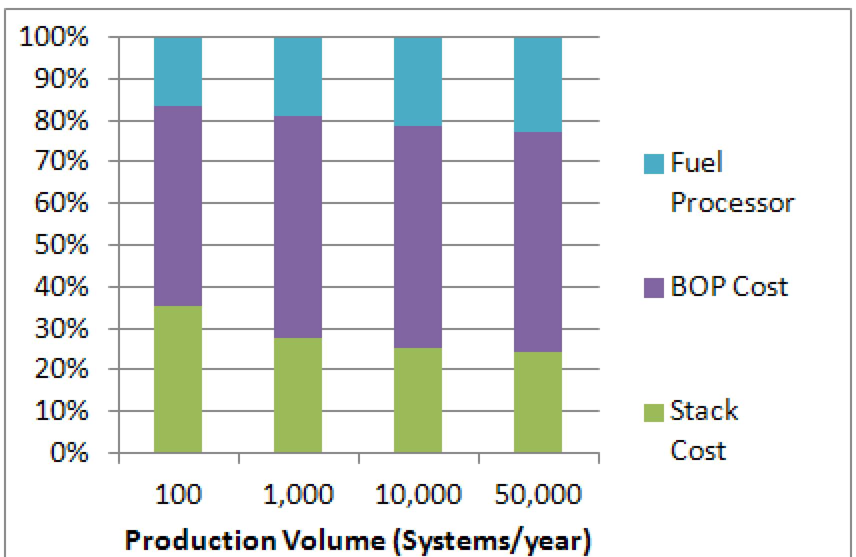


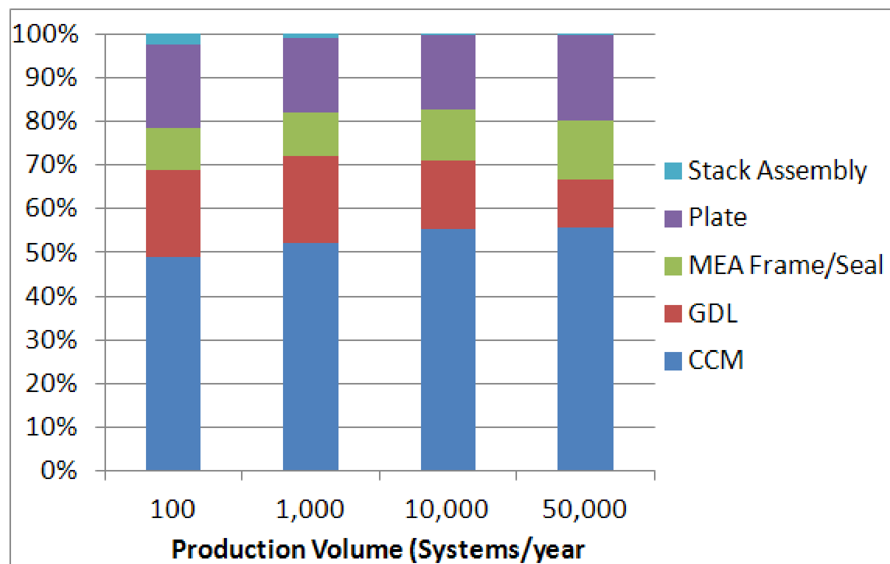




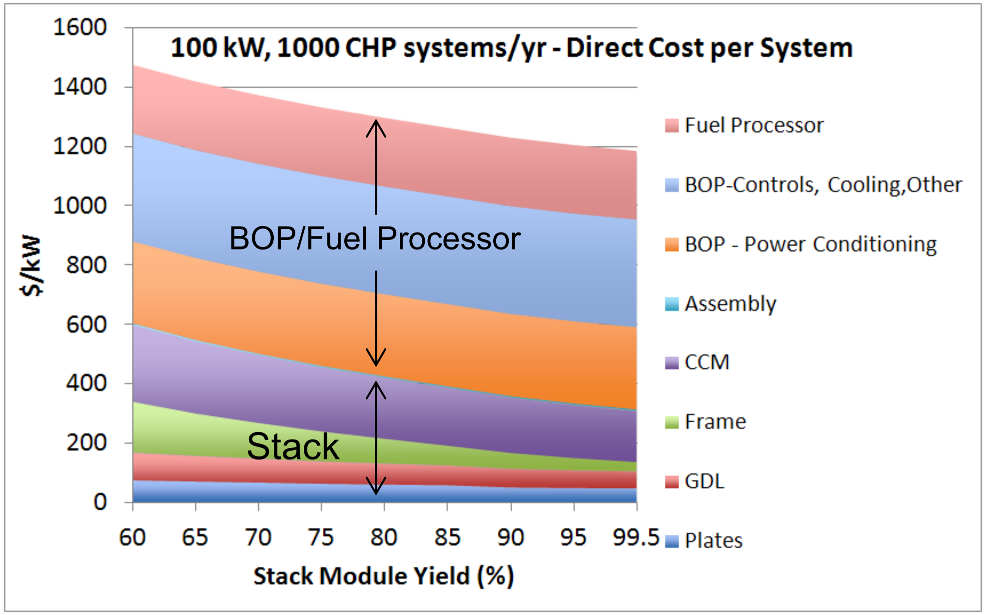
100kW CHP System Cost vs. Volume





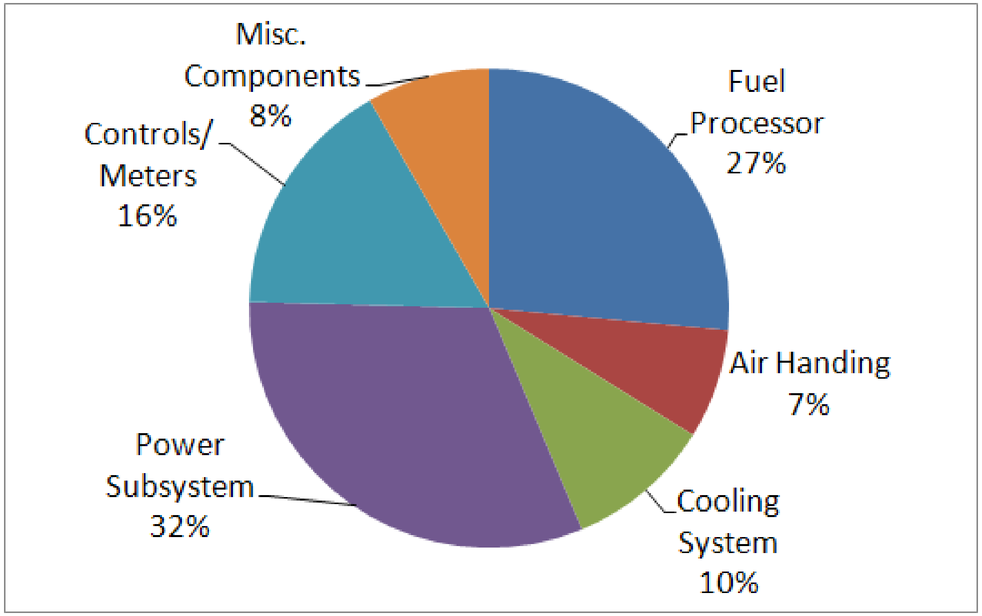


100kW CHP System Cost vs. Yield at Fixed Volume



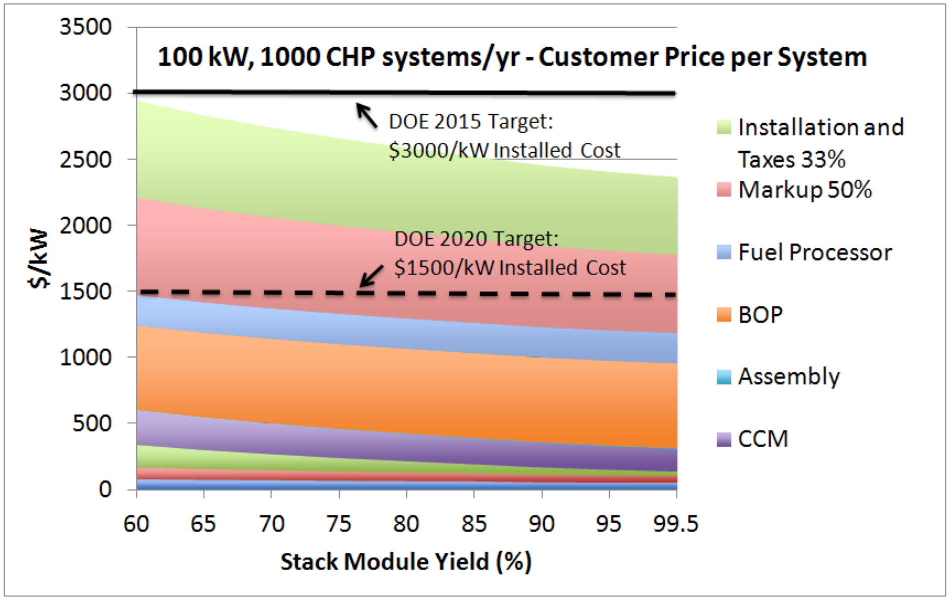
BOP/Fuel Processor are dominant fraction of system costs

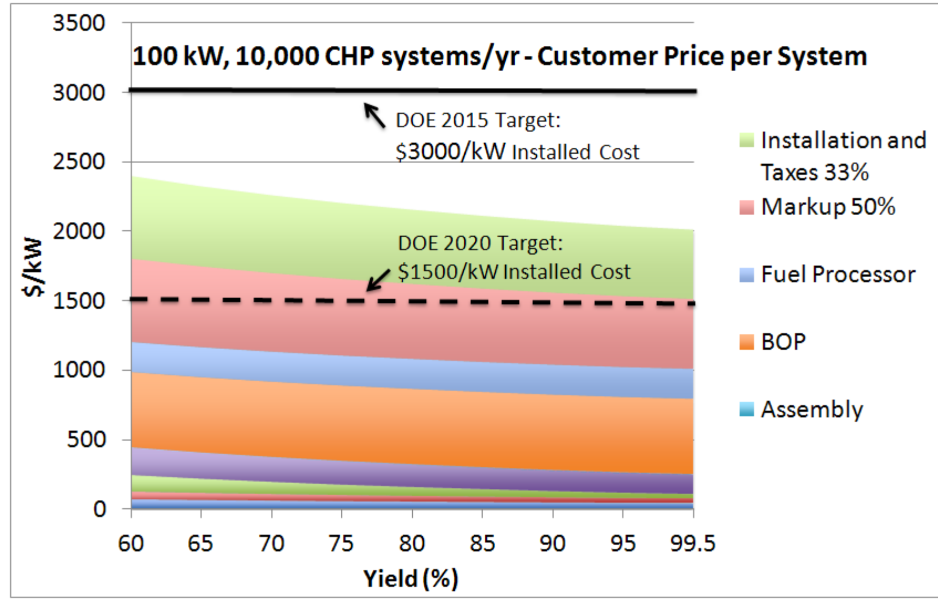
Stack costs are a strong function of stack module yield



Non-Stack component cost reduction opportunities in power subsystem and fuel processor

Installed Cost for 100kW CHP Systems



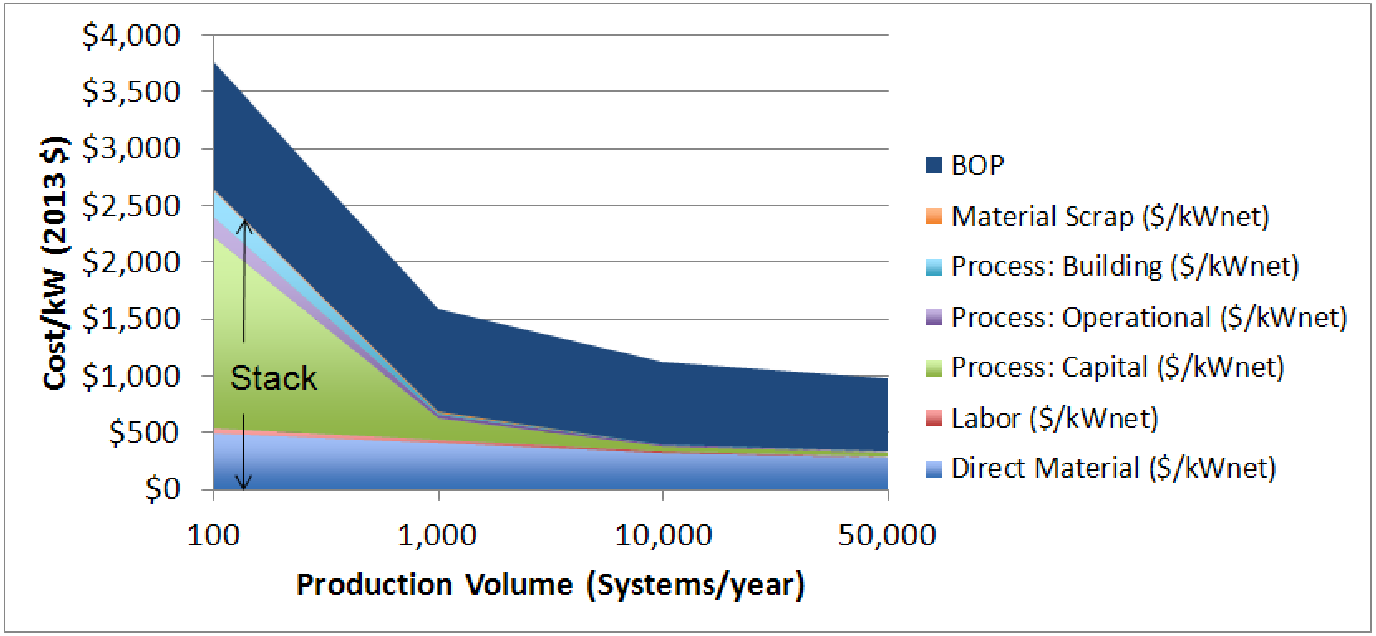


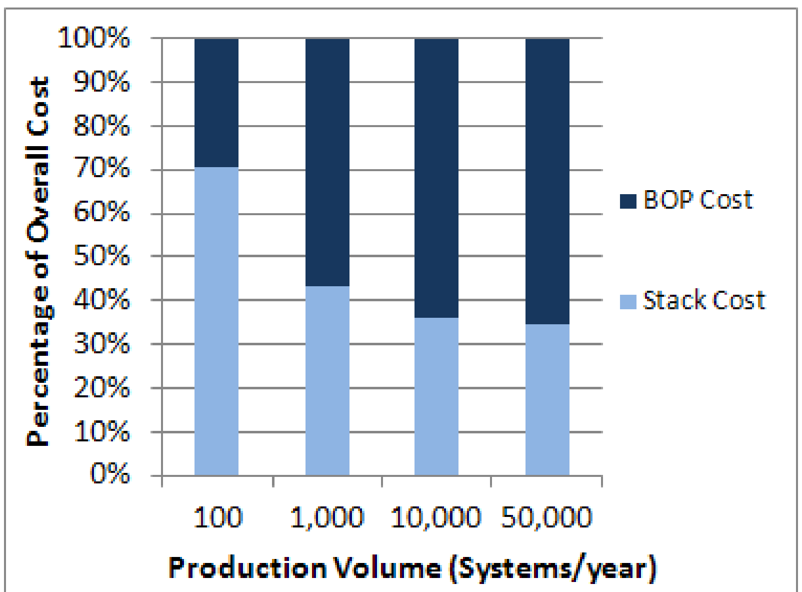
100kW CHP can meet 2015 DOE target

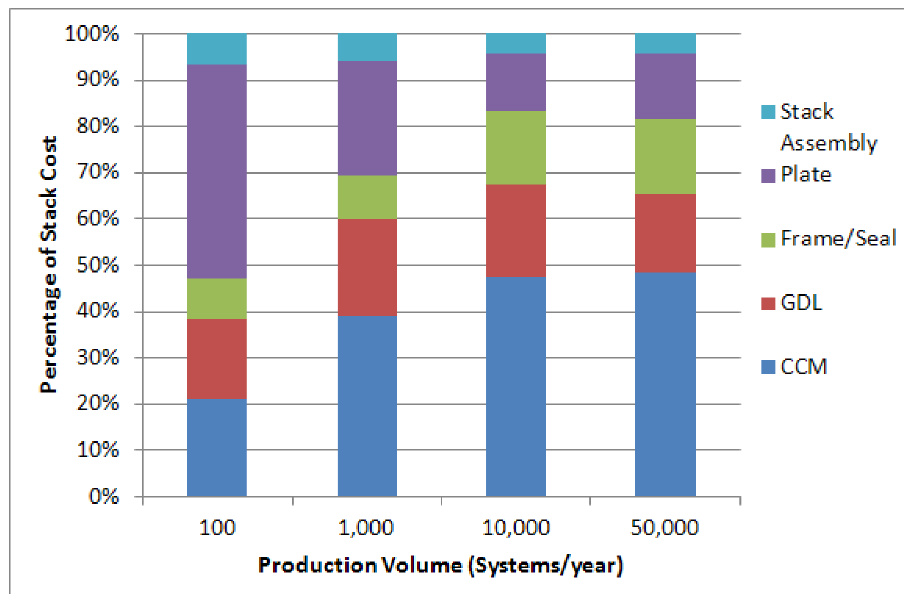
at 1,000 - 10,000 systems/year,

but further cost reduction needed to meet 2020 target

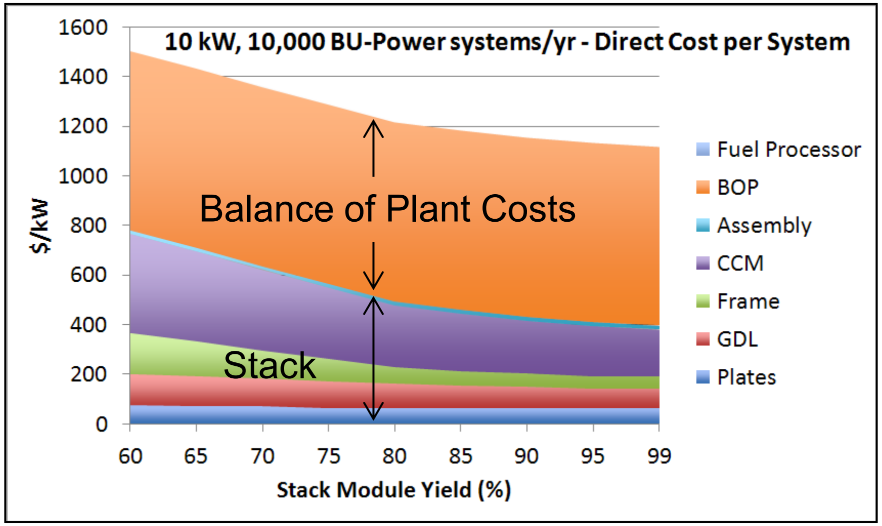
10kW Backup Power System Cost vs. Volume

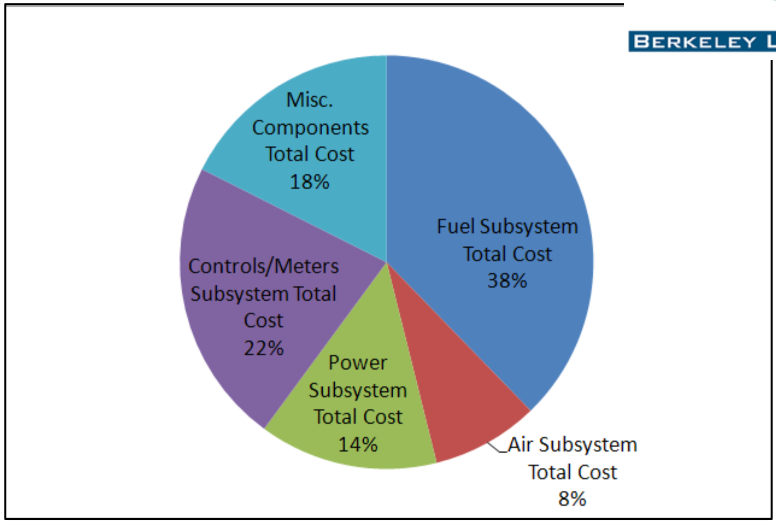






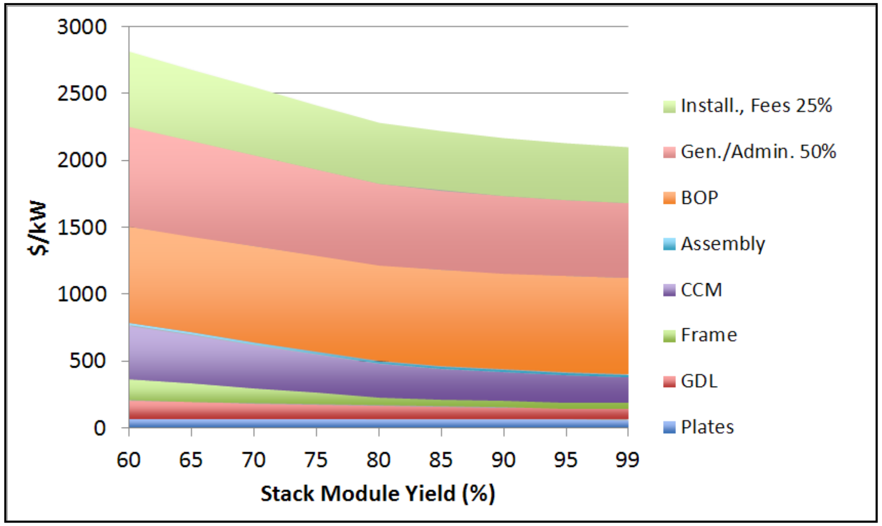
Backup Power System Cost Modeling at Fixed Volume

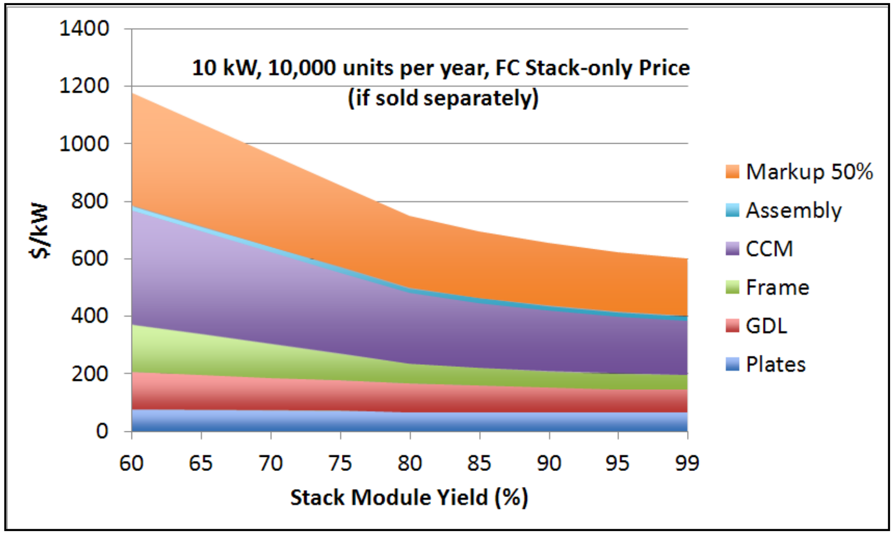




Stack costs are a strong function of stack module yield; Balance of plant costs are greater than FC Stack costs

BOP cost analysis highlights cost reduction opportunities in fuel subsystem and controls/meters





10kW Backup Power system total installed cost just under $2200/kW at 90% stack module yield

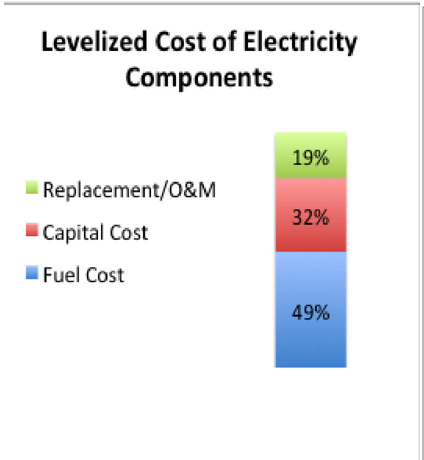
10kW Stack-only price is $650/kW at 90% stack module yield

TECHNICAL PROGRESS: TOTAL COST OF ELECTRICITY

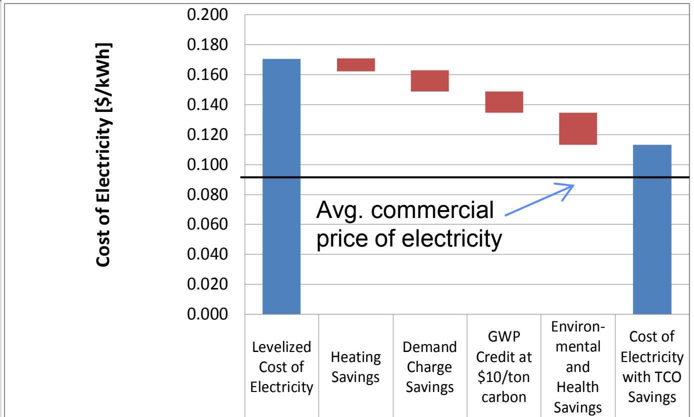
Total Cost of Ownership Modeling Example 100kW CHP System, Small Hotel

$2,500/kW installed cost | $1,500/kW installed cost

Minneapolis

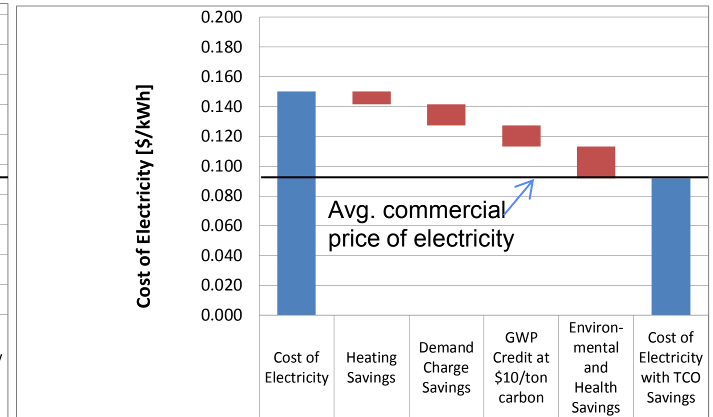


$2,500/kW installed cost



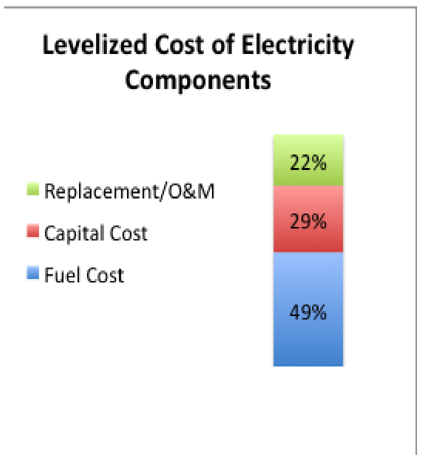
	Levelized Cost of Electricity	Heating Savings	Demand Charge Savings	GWP Credit at $10/ton carbon	Environ-mental and Health Savings	Cost of Electricity with TCO Savings
Total Cost of Ownership Savings Items		0.008	0.014	0.014	0.022	
Levelized Cost of Electricity	0.171	0.162	0.149	0.135	0.113	0.113

$1,500/kW installed cost

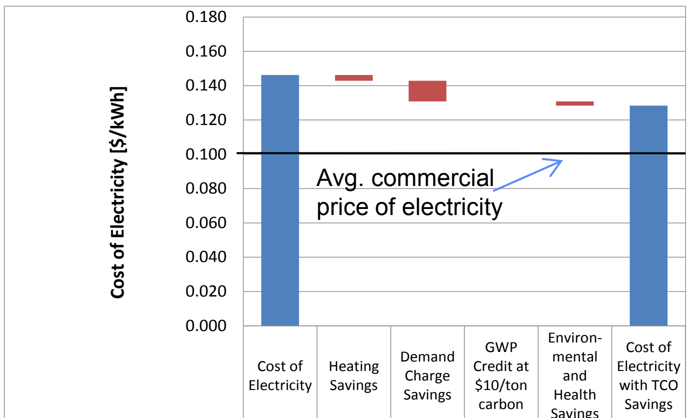


	Cost of Electricity	Heating Savings	Demand Charge Savings	GWP Credit at $10/ton carbon	Environ-mental and Health Savings	Cost of Electricity with TCO Savings
Total Cost of Ownership Savings Items		0.008	0.014	0.014	0.022	
Cost of Electricity	0.150	0.142	0.127	0.113	0.092	0.092

Phoenix

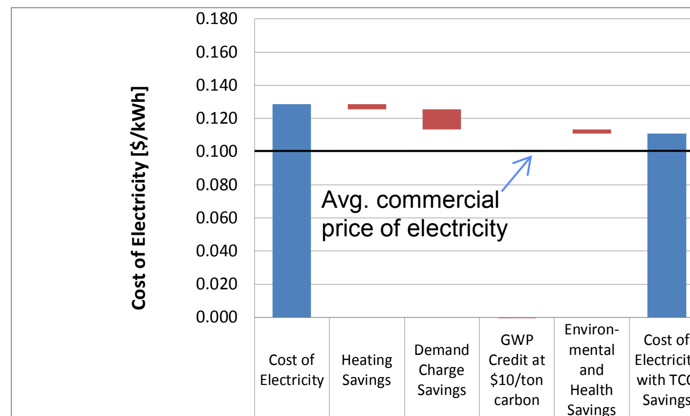


$2,500/kW installed cost



	Cost of Electricity	Heating Savings	Demand Charge Savings	GWP Credit at $10/ton carbon	Environ-mental and Health Savings	Cost of Electricity with TCO Savings
Total Cost of Ownership Savings Items		0.003	0.012	0.0000	0.002	
Cost of Electricity	0.146	0.143	0.131	0.131	0.128	0.128

$1,500/kW installed cost



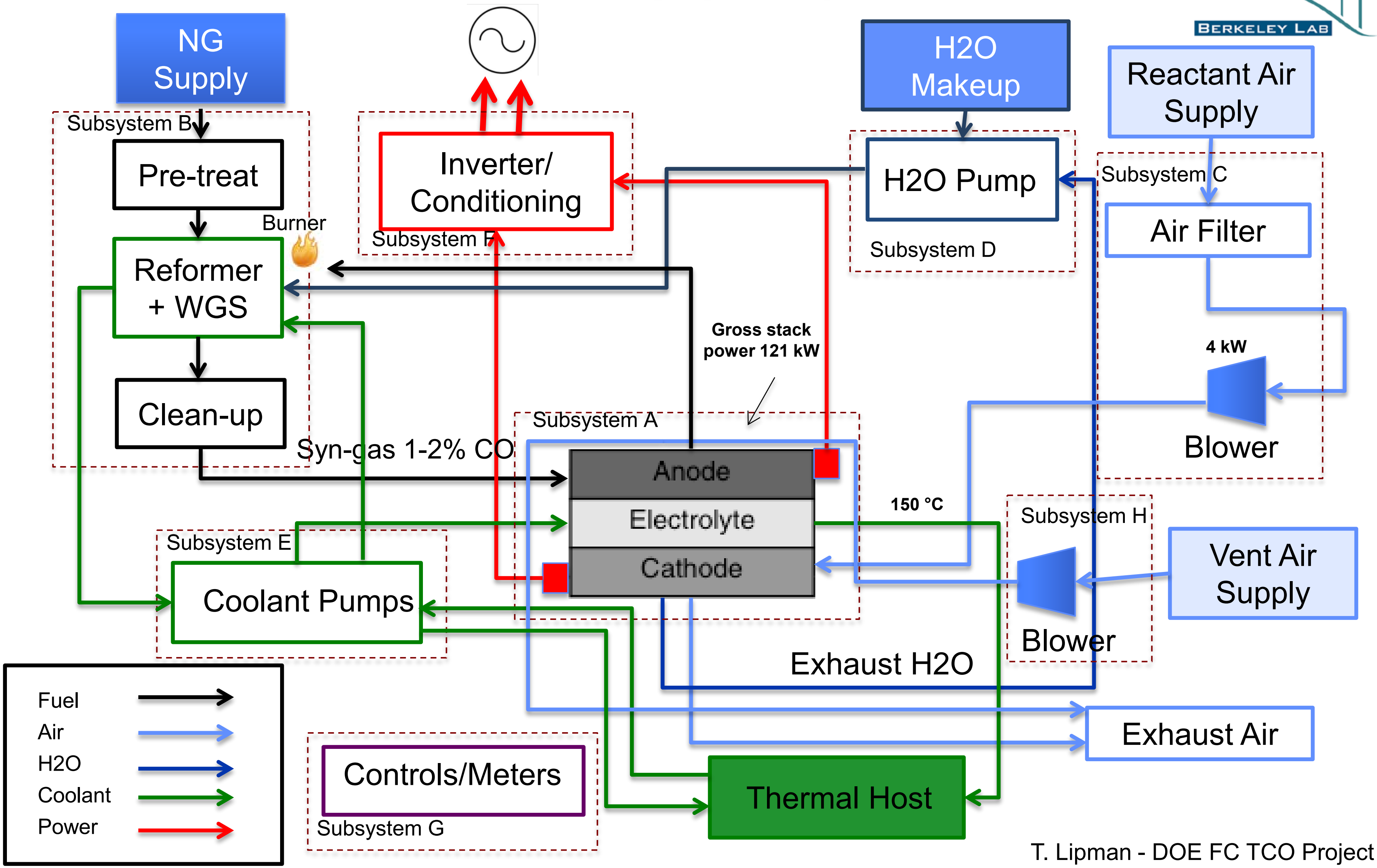
	Cost of Electricity	Heating Savings	Demand Charge Savings	GWP Credit at $10/ton carbon	Environ-mental and Health Savings	Cost of Electricity with TCO Savings
Total Cost of Ownership Savings Items		0.003	0.012	0.0000	0.0025	
Cost of Electricity	0.129	0.125	0.113	0.113	0.111	0.111

Externality valuation (GHG, health) contributes up to 20-24% savings in "total cost of electricity" in regions with "dirty electricity" such as upper Midwest

Up to 39% overall reduction in total cost of electricity including all TCO items

TECHNICAL PROGRESS: HT-PEM FC SYSTEM MANUFACTURING COSTS

100kW HT-PEM Stationary (CHP) with Reformat



T. Lipman - DOE FC TCO Project

System simplifications: No membrane humidification, no air-slip for CO tolerance, less CO clean up requirement

CHP Functional Specifications

100kW CHP system operating with reformate fuel

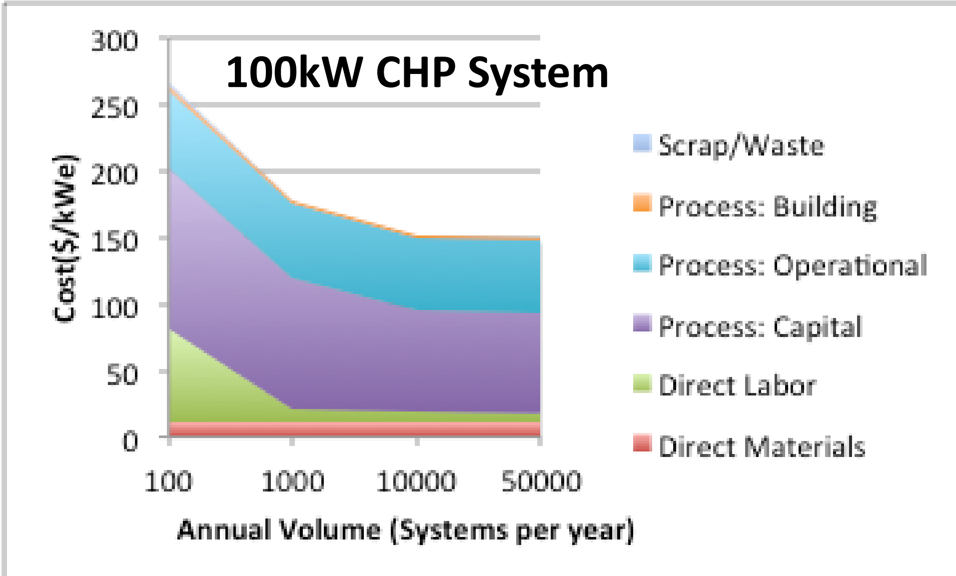
100 kW Size	Unique Properties:	Best. Ests.	Units:
System	Gross system power	121	kW
	Net system power	100	kW (AC)
	Physical size	2.9x4.2x3.6	meter x meter x meter
	Physical weight	14080	kg
	Electrical output	480V AC	Volts AC or DC
	DC/AC inverter effic.	93%	%
	Peak ramp rate	0.372	kW/sec - size dep
	Waste heat grade	150	Temp. °C
	Reformer efficiency	75%	%
	Fuel utilization % (first pass)	80%	%
	Fuel utilization % (overall)	95%	%
	Fuel input power (LHV)	335	kW
	Stack voltage effic.	51%	% LHV
	Gross system electr. effic.	36%	% LHV
	Avg. system net electr. effic.	30%	% LHV
	Thermal efficiency	53%	% LHV
	Total efficiency	83%	Elect.+thermal (%)
Stack	stack power	8.08	kW
-	total plate area	720	cm^2
	CCM coated area	464	cm^2
	single cell active area	422	cm^2
	gross cell inactive area	41	%
	cell amps	106	A
	current density	0.25	A/cm^2
	reference voltage	0.625	V
	power density	0.157	W/cm^2
	single cell power	66	W
	cells per stack	122	cells
	percent active cells	100	%
	stacks per system	15	stacks
Addt'l Parasitics	Compressor/blower	4	kW
	Other paras. loads	9.72	kW
	Parasitic loss	13.72	kW

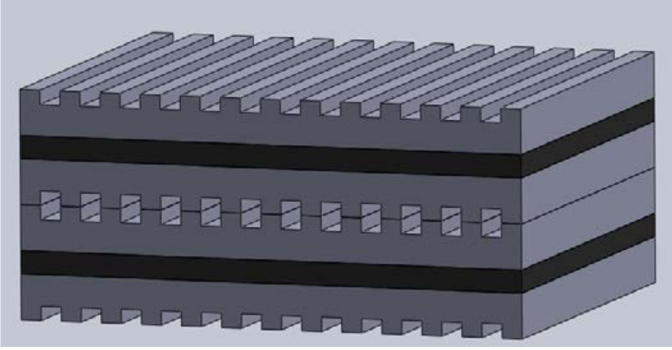
DFMA Manufacturing Approaches for HT-PEM CHP Applications

Component	Primary Approach	Reference	*LT-PEM Approach*
Membrane*	**PBI-PPA process**	Patent review, Industry/University inputs	*Purchase Nafion®*
Catalyst Layer*	Gas Diffusion Electrode (GDE) with slot die coating Catalyst loading 0.7mg/cm² Pt	Literature, industry input	*CCM with Dual Decal, slot die coating – Catalyst loading 0.5mg/cm²*
GDL*	Carbon paper Spray coat MPL	Literature, industry input	*Carbon Paper Spray coat MPL*
Bipolar Plates*	**Compression molded graphite/resin plates with separator layer**	Patent review, Industry/University inputs	*Injection molded graphite –carbon composite*
Seal/Frame MEA*	Framed MEA	Patents, industry input	*Framed MEA*
Stack Assembly*	Partial to fully automated	Patents, Industry input	*Partial to fully automated*
Endplate/ Gaskets	Graphite composite/ Screen printed	Industry input, literature	*Graphite composite/ Screen printed*
Test/Burn-in	Post Assembly 3 hrs	Industry input	*Post Assembly 3hrs*

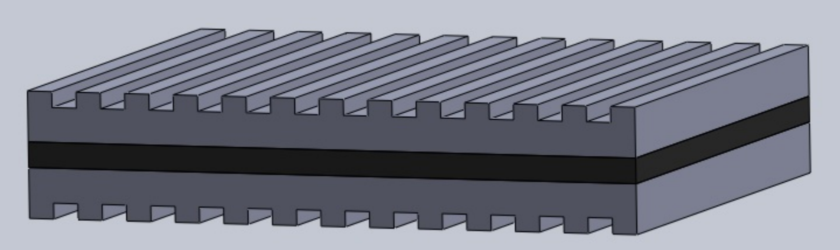
Key modules: Membrane, Plates; Others similar to LT-PEM case.

Plates with Separator Layer

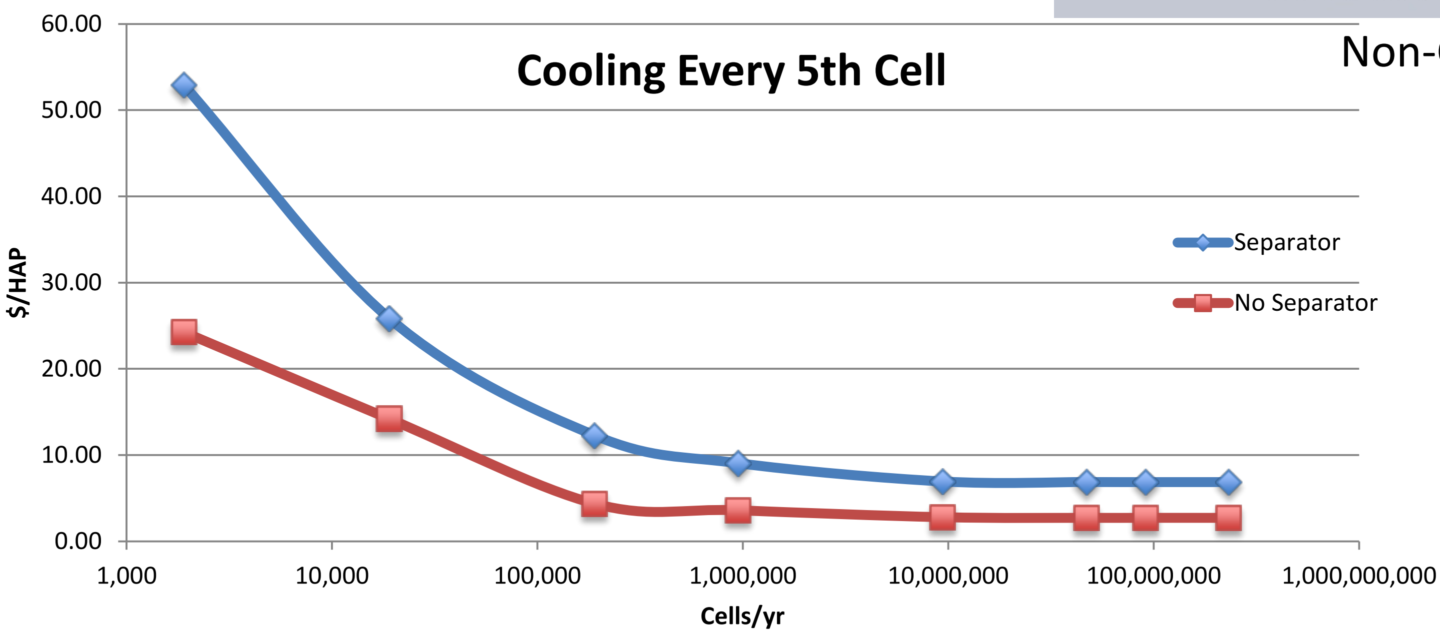




Cooling Cell (Two HAP)

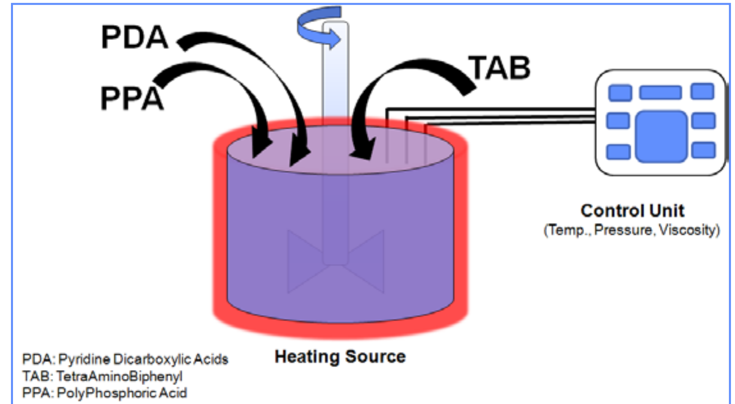


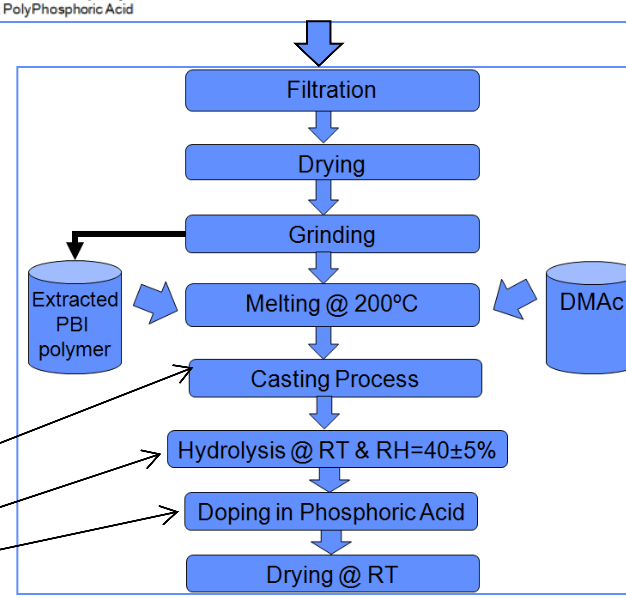
Non-Cooling Cell (One HAP)



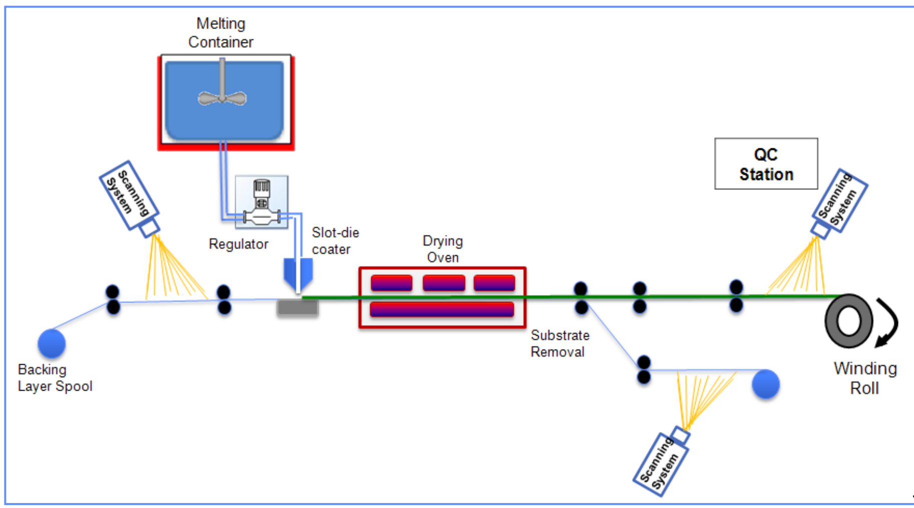
PBI Membrane Process Flow

Mixing/heating monomers

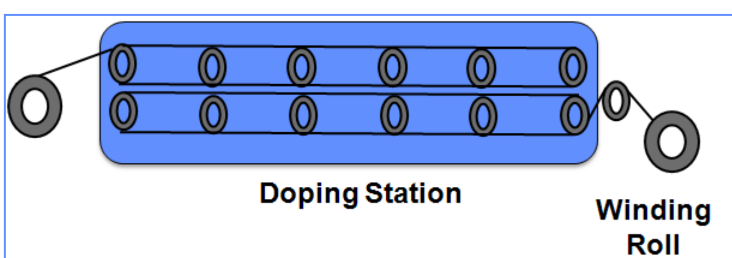




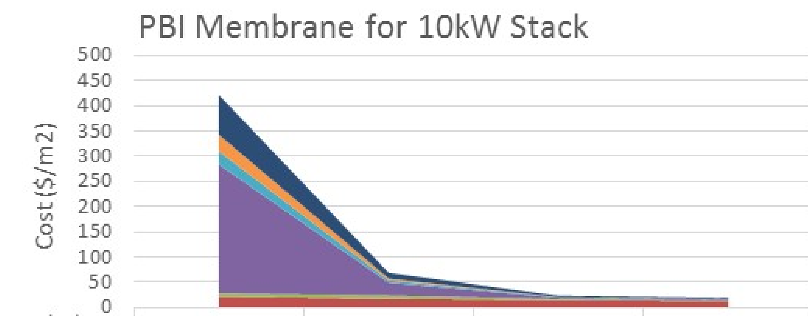
Casting



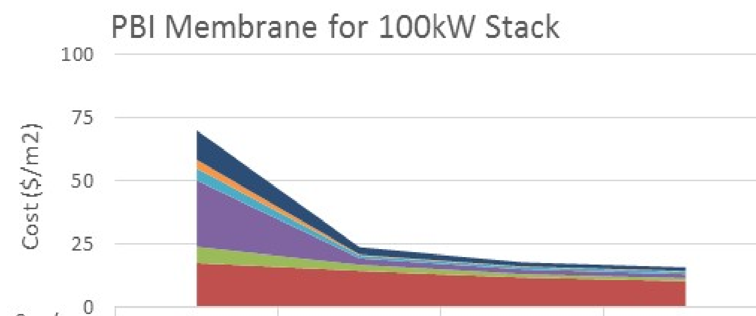
Hydrolysis and Doping



PBI Membrane- Cost Breakdown

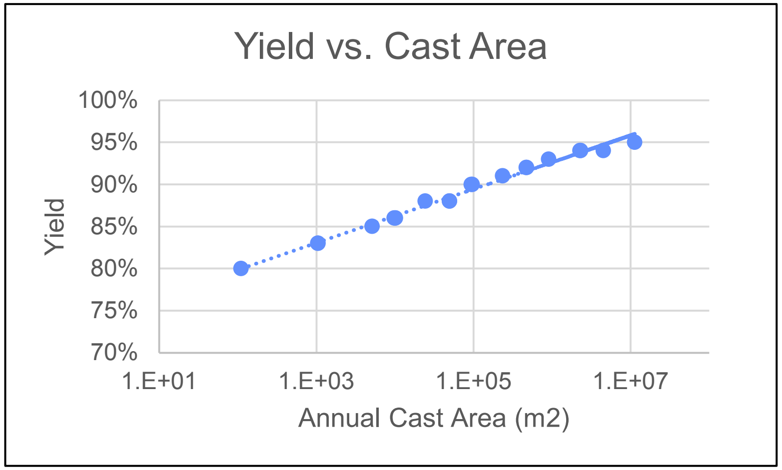


Sys/yr)	100	1,000	10,000	50,000
Scrap/Waste	78.56	11.47	2.86	1.95
Process: Building	33.09	3.31	0.33	0.26
Process: Operational	26.08	4.69	1.10	0.98
Process: Capital	255.55	25.55	2.56	2.00
Direct Labor	6.89	6.40	2.43	1.16
Direct Materials	21.34	17.43	14.30	12.48

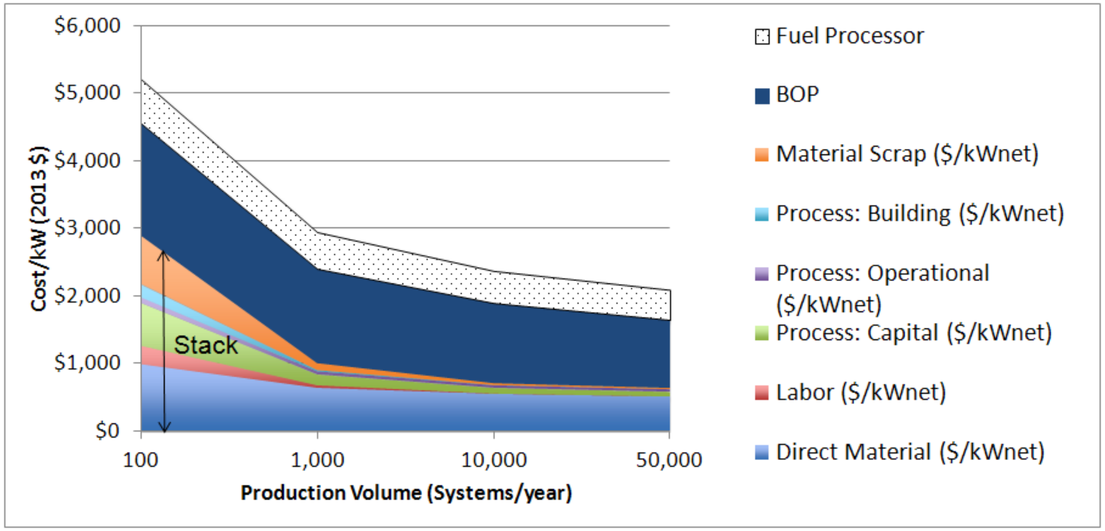


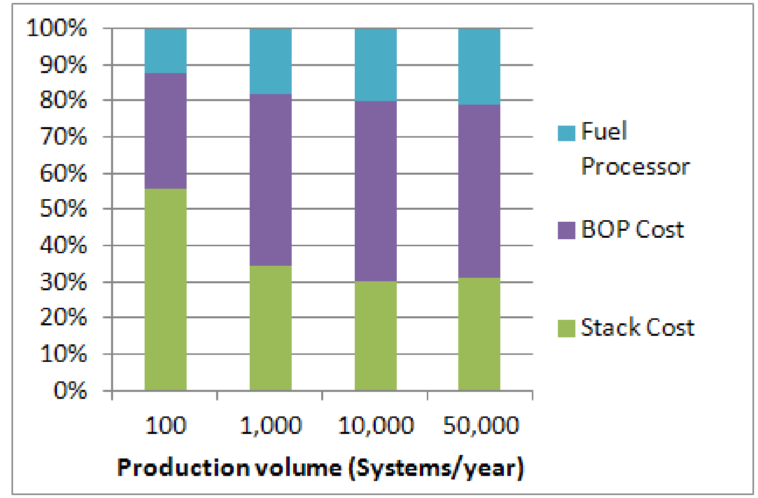
Sys/yr	100	1,000	10,000	50,000
Scrap/Waste	11.65	2.88	1.70	1.45
Process: Building	3.40	0.34	0.24	0.21
Process: Operational	4.76	1.11	0.96	0.99
Process: Capital	26.25	2.63	1.80	1.60
Direct Labor	6.40	2.43	1.30	1.15
Direct Materials	17.48	14.34	11.81	10.33

Materials	Price
Isophthalic acid	$103 for 5kg
Terephthalic acid	$377 for 10kg
3,3′,4,4′-Tetraaminobiphenyl (TAB)	$380 for100 g
Polyphosphoric acid (115%)	$60 for1 kg
Ammonium Hydoroxide	$253.5 for 6 ltrs
N,N-DiMethylAcetamide (DMAc)	$62.2 for 2 ltrs

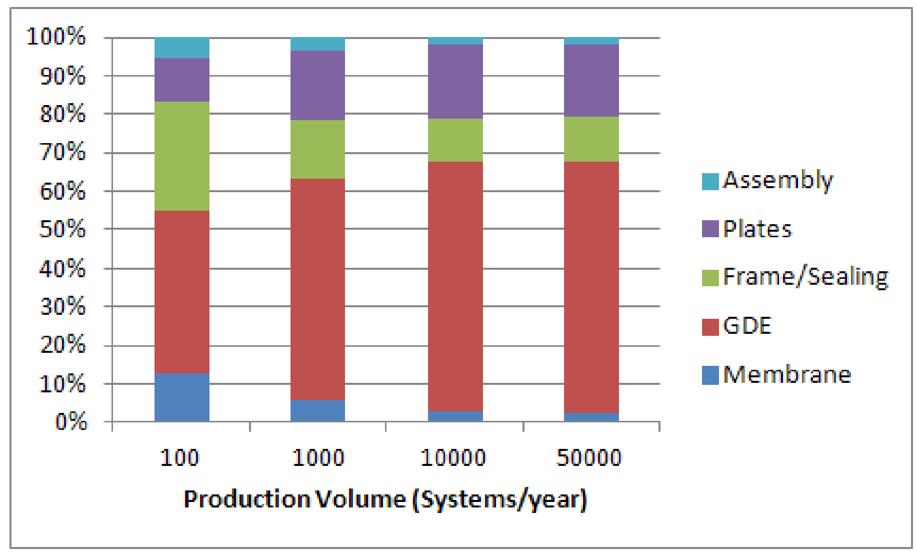


Preliminary Cost for 10kW HT-PEM CHP System

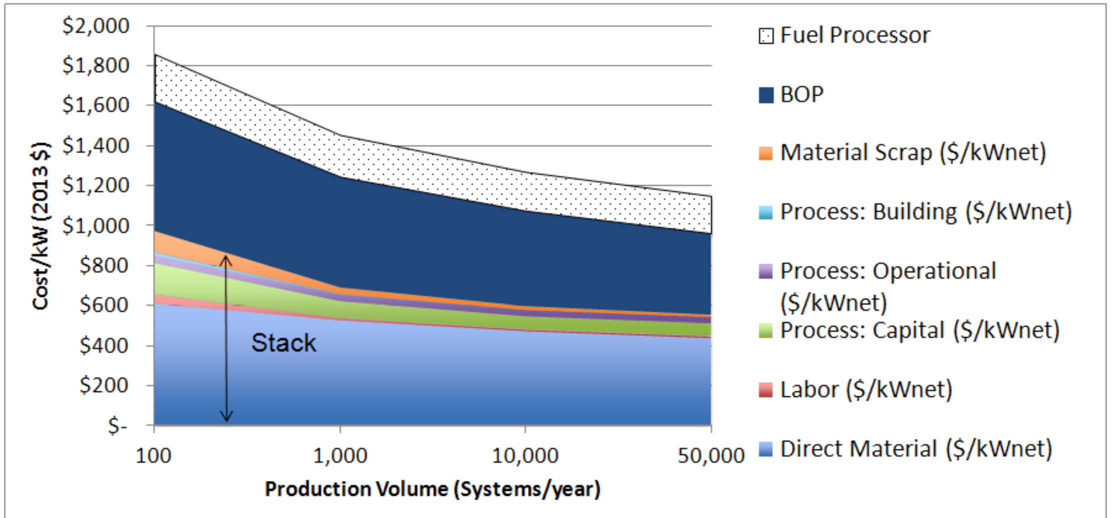


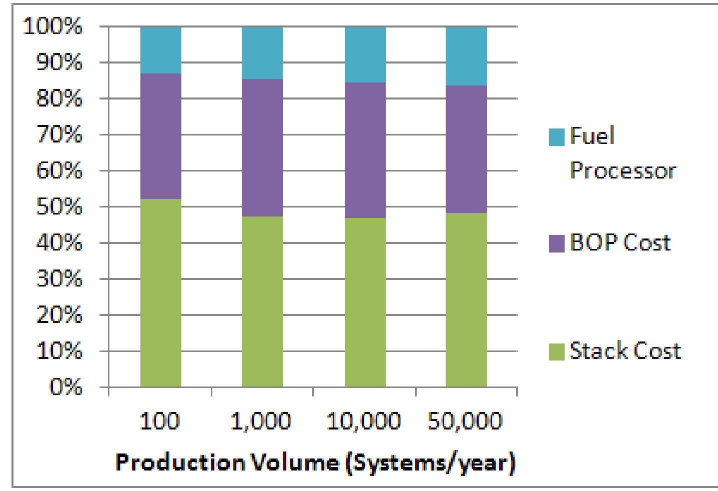


Power (kW)	10	10	10	10
Systems/Yr	100	1000	10000	50000
Direct Materials ($/kW)	$ 990	$ 640	$ 552	$ 511
Direct Labor	$ 277	$ 45	$ 10	$ 9
Process: Capital	$ 632	$ 158	$ 83	$ 67
Process: Operational	$ 88	$ 45	$ 36	$ 35
Process: Building	$ 190	$ 18	$ 3	$ 2
Scrap/Waste	$ 722	$ 106	$ 32	$ 22
Final Stack Cost ($/kW)	$ 2,898	$ 1,013	$ 717	$ 646
BOP_non FP	$ 1,664	$ 1,395	$ 1,185	$ 1,006
BOP_FP	$ 653	$ 542	$ 475	$ 444
Total Cost ($/kW)	**$ 5,215**	**$ 2,950**	**$ 2,377**	**$ 2,096**

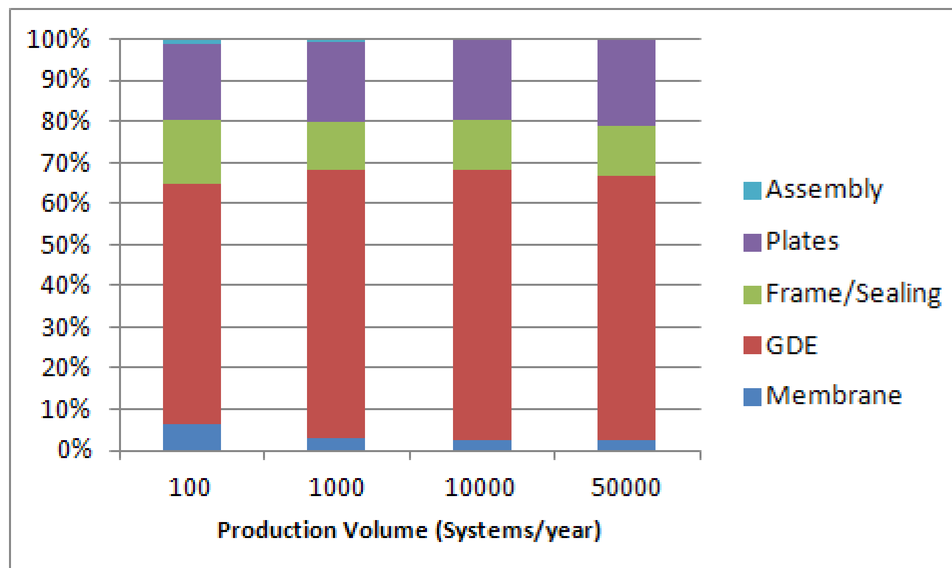


Preliminary Cost for 100kW HT-PEM CHP System





Power (kW)	100	100	100	100
Ssystems/Yr	100	1000	10000	50000
Direct Materials ($/kW)	$ 613	$ 528	$ 474	$ 440
Direct Labor	$ 41	$ 9	$ 7	$ 7
Process: Capital	$ 158	$ 83	$ 64	$ 62
Process: Operational	$ 44	$ 36	$ 34	$ 34
Process: Building	$ 11	$ 3	$ 1	$ 1
Scrap/Waste	$ 106	$ 32	$ 18	$ 11
Final Stack Cost ($/kW)	$ 973	$ 691	$ 598	$ 555
BOP_non FP	$ 648	$ 555	$ 479	$ 410
BOP_FP	$ 236	$ 208	$ 194	$ 186
Total Cost ($/kW)	**$ 1,857**	**$ 1,454**	**$ 1,271**	**$ 1,151**



Responses to 2013 AMR Reviewer Comments

1. **How does this fit in with other DOE cost analysis work?**

Response: This work is part of a complimentary portfolio of DOE analysis projects. Other projects have focused on different applications (e.g., MHE) and other technologies (SOFC). This project also expands the direct cost modeling approach to include life-cycle costing and ancillary financial benefits (GHG credits, health and environmental impacts).

2. **More vendor/OEM input and feedback is needed for costing validation.**

Response: Extensive vendor/OEM feedback was obtained for stack module equipment and process parameters (e.g., roll-to-roll processing, plate processing), balance of plant components (vendor quotes), functional specifications (Ballard Power Systems), and overall costing (Ballard Power Systems and Altergy Systems). Further feedback and OEM input is being sought from international companies such as Panasonic Corporation and Nedstack Fuel Cell Technology B.V. for smaller power CHP systems and backup power systems, respectively.

2. **What are cost reduction opportunities beyond volume scaling? Why does balance of plant appear so large and what are cost reduction opportunities there?**

Response: This work has shown the importance and sensitivity of stack module yield on stack costs (e.g., the need for improved defect metrology and inline to end of line defect characterization) and the importance of balance of plant cost reduction for overall system cost reduction (e.g., power conditioning, potential cost reduction from design and integration). We have identified power conditioning as a key area for CHP systems. There are many parts in the balance of plant contributing to the overall cost, and increased parts-integration is a potential cost reduction opportunity. For back-up power and smaller size CHP systems, we are revising the BOP components, integration, and resultant cost in consultation with industry advisors.

Collaborations

Partners

University of California Berkeley

Laboratory for Manufacturing and Sustainability, Dept. of Mechanical Engineering:

— Manufacturing process analysis, DFMA analysis

Transportation Sustainability Research Center and DOE Pacific Region Clean Energy Application Center:

— System and BOP design, functional specs, BOM definition, parametric relationships

— CHP applications and functional requirements

Ballard Power Systems

— Consultation on fuel cell system design and manufacturing processes

Strategic Analysis:

— Fuel processor systems and DFMA costing

Other Collaborators

Altergy Systems: Consultation on backup power system

Panasonic Corporation: will review of low power CHP systems

Remaining Challenges & Future Plans

Challenges

- Lack of HT-PEM vendors and OEM contacts – have started discussion with Advent Technologies, PAFC contacts
- Refined estimate of lower power CHP and backup power balance of plant – engagement planned w/ Panasonic, Nedstack
- SOFC vendor/OEM industry advisors – industry contacts being developed
- Lack of data for system availability – will add as a sensitivity factor to LCC model, HT-PEM pilot data

Plans

- Currently refining DFMA cost model for High Temperature PEM CHP and developing LCC/TCO model
  - Membranes; High temperature, long lifetime plates
  - LCC with absorption cooling option
- Solid oxide fuel cell functional spec definition, system design, and DFMA in next few months
- Also automating LT-PEM TCO model for user enabled interface in Analytica

Project Summary

Relevance: ***Provide more comprehensive cost analysis for stationary and materials handling fuel cell systems in emerging markets including ancillary financial benefits.***

Approach: ***Design for manufacturing and assembly (DFMA) analysis cost model and integrated lifecycle cost analysis (LCA) impacts including life cycle costs, carbon credits, and health and environmental benefits***

Technical Accomplishments and Progress: ***Total cost of ownership model for LT-PEM CHP systems (manufacturing cost model, LCC model and externality valuation); Direct cost model for HT-PEM CHP system***

Collaboration: ***Partnerships with UC-Berkeley manufacturing analysis and transportation sustainability research groups and Ballard Power Systems. Collaboration with Strategic Analysis and Altergy Systems***

Proposed Next-Year Research: ***Total cost of ownership model for HT-PEM systems and Manufacturing Cost model for SOFC CHP and power-only system***

Max Wei
510-486-5220
mwei@lbl.gov

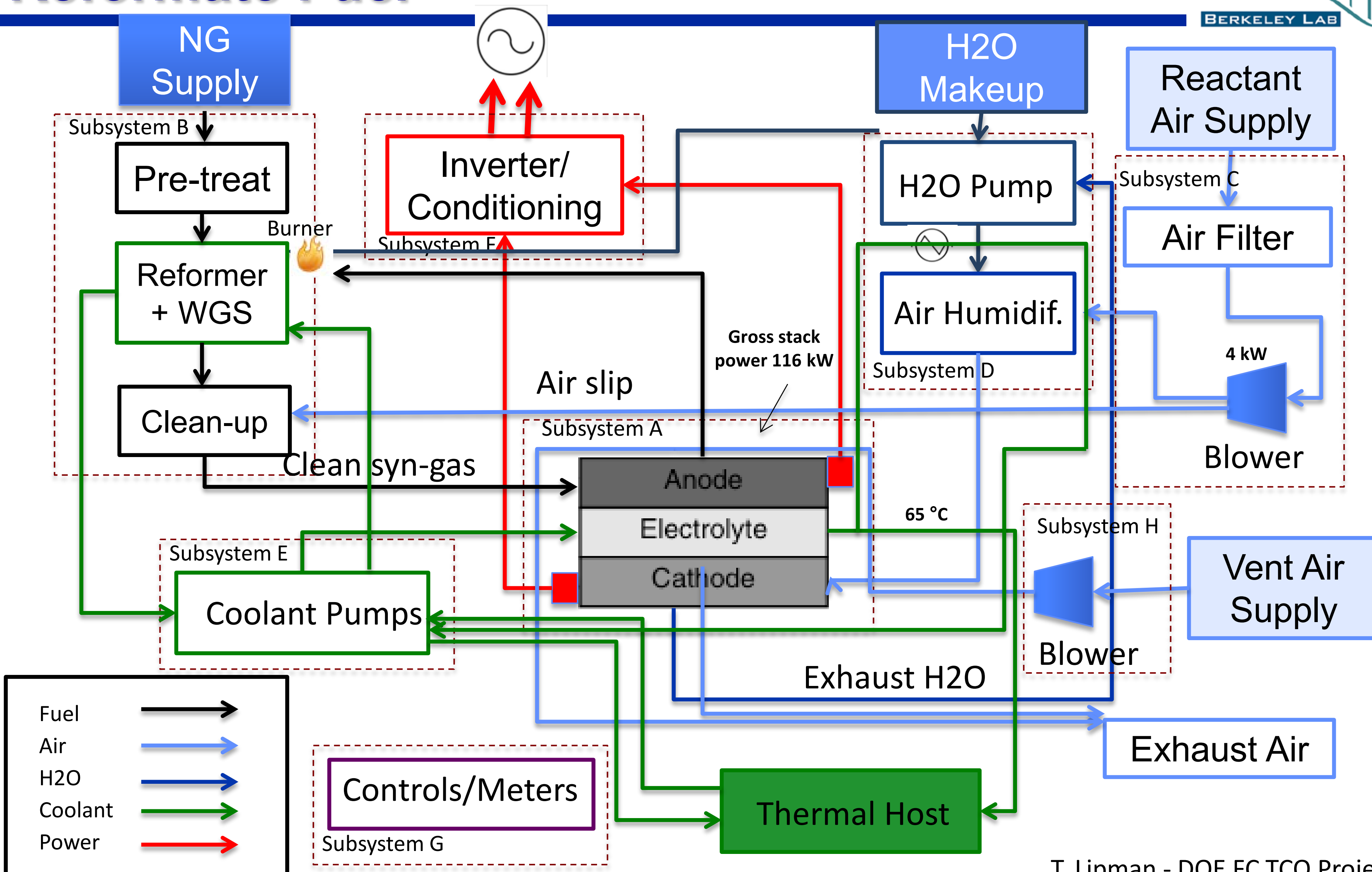
Tom McKone
510-486-6163
TEMcKone@lbl.gov

Thank you

mwei@lbl.gov

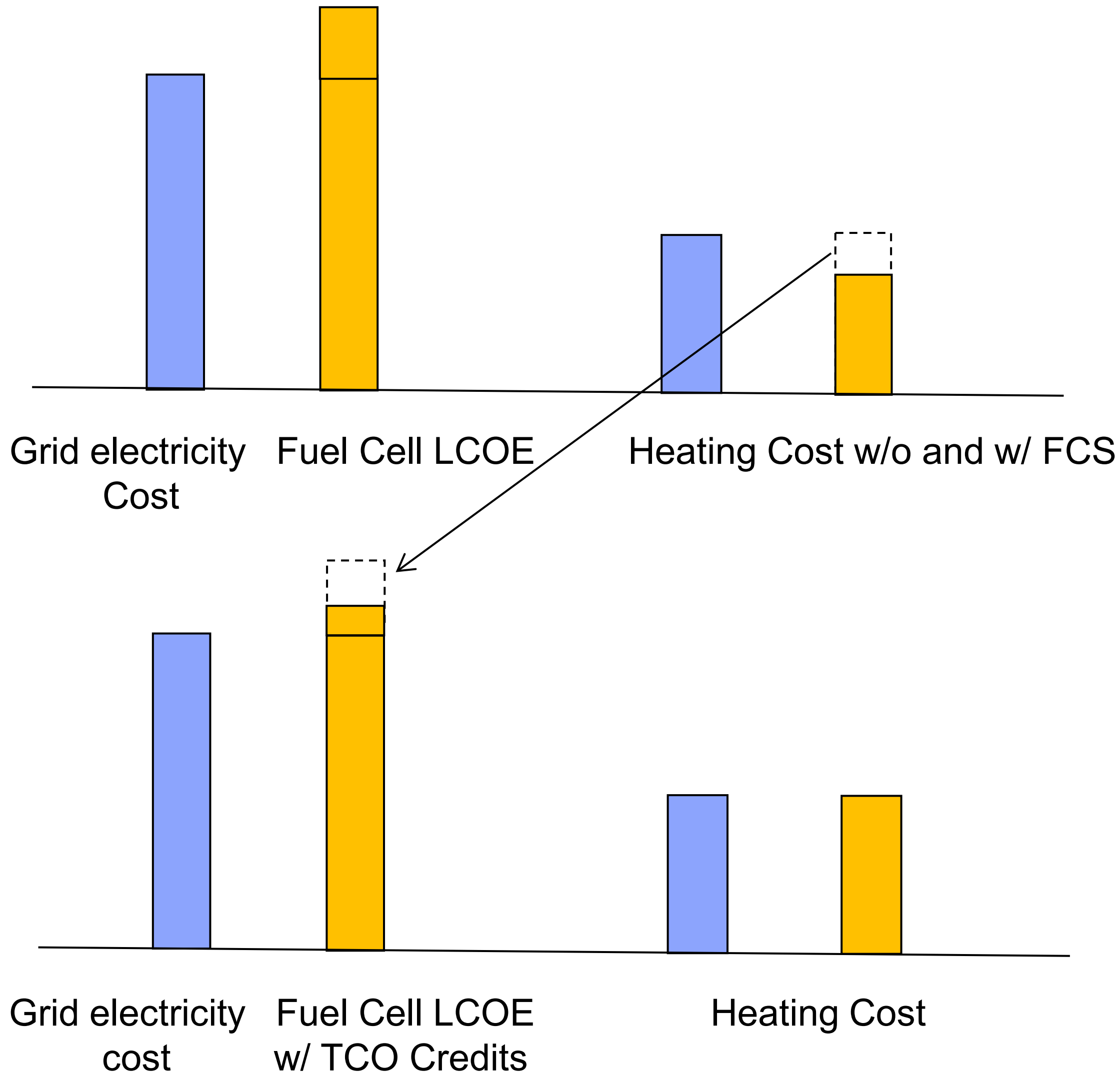
Technical Back-Up Slides

100 kW PEM Stationary (CHP) Reformate Fuel



T. Lipman - DOE FC TCO Project

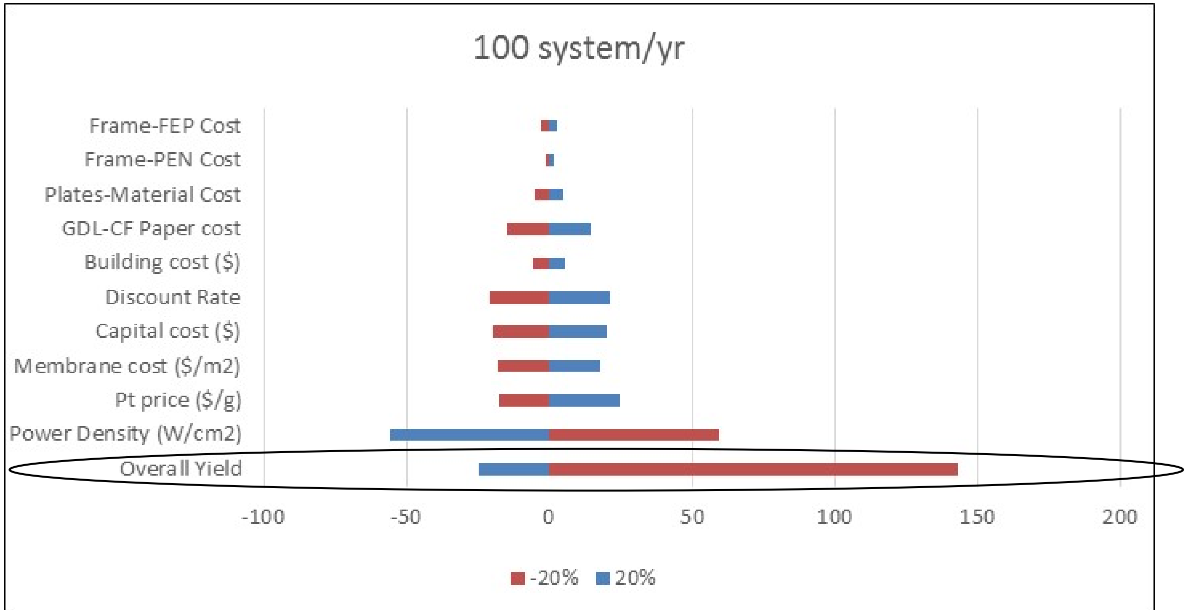
Cost of Energy Service with FC CHP

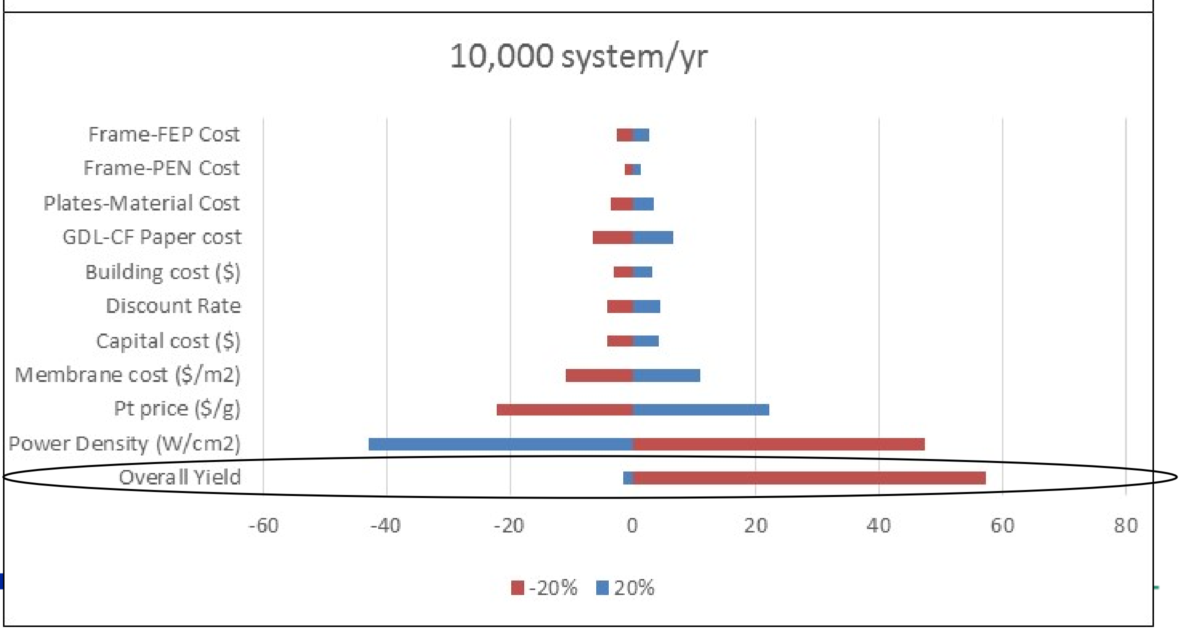


Take heat savings as a credit to FC cost of electricity, and similarly with other TCO credits.

Then compare Fuel Cell "Levelized Cost of Electricity With TCO credits" to Grid Electricity cost ($/kWh)

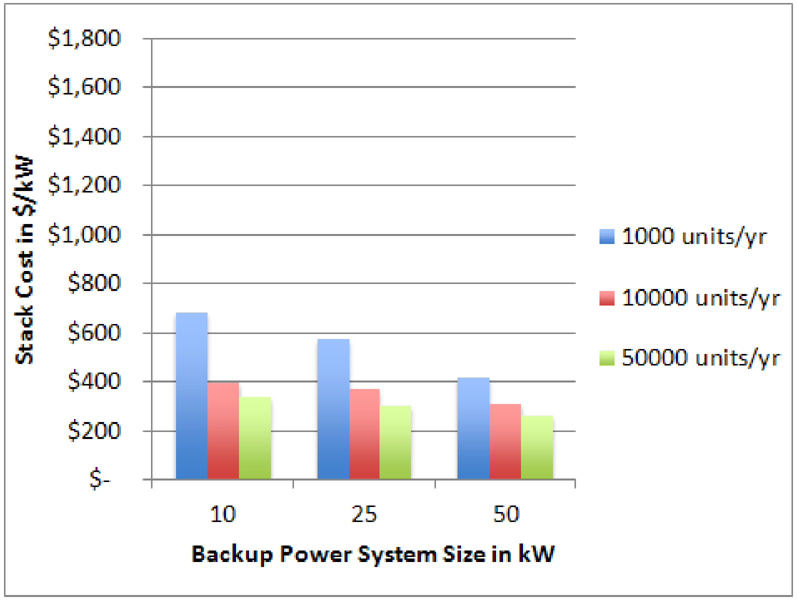
Stack Manufacturing Cost Sensitivity ($/ kW)

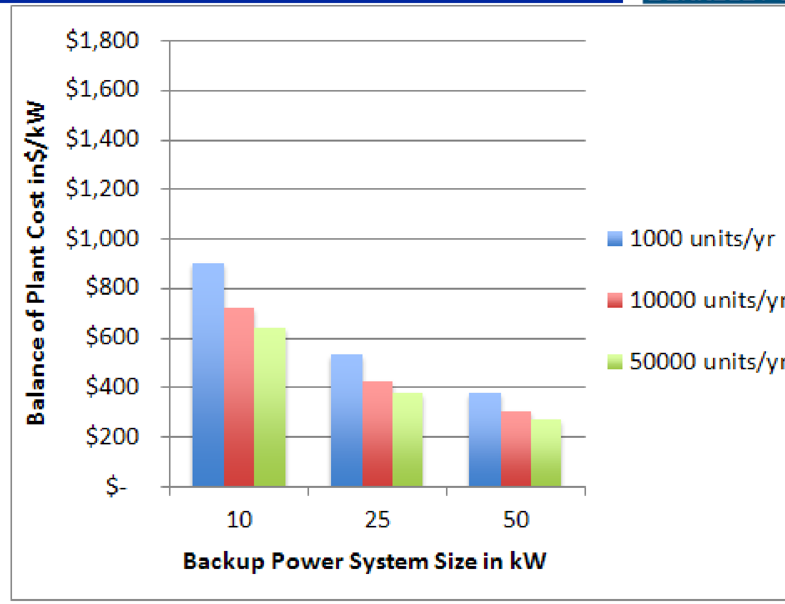


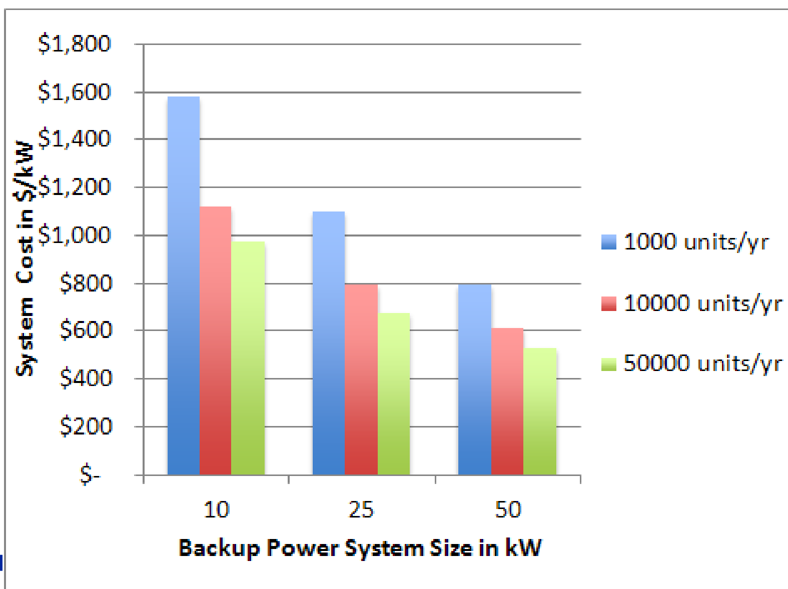


Yield (module level) dominates followed by power density and Pt price

Direct Cost vs. Volume for FC Backup Power Systems







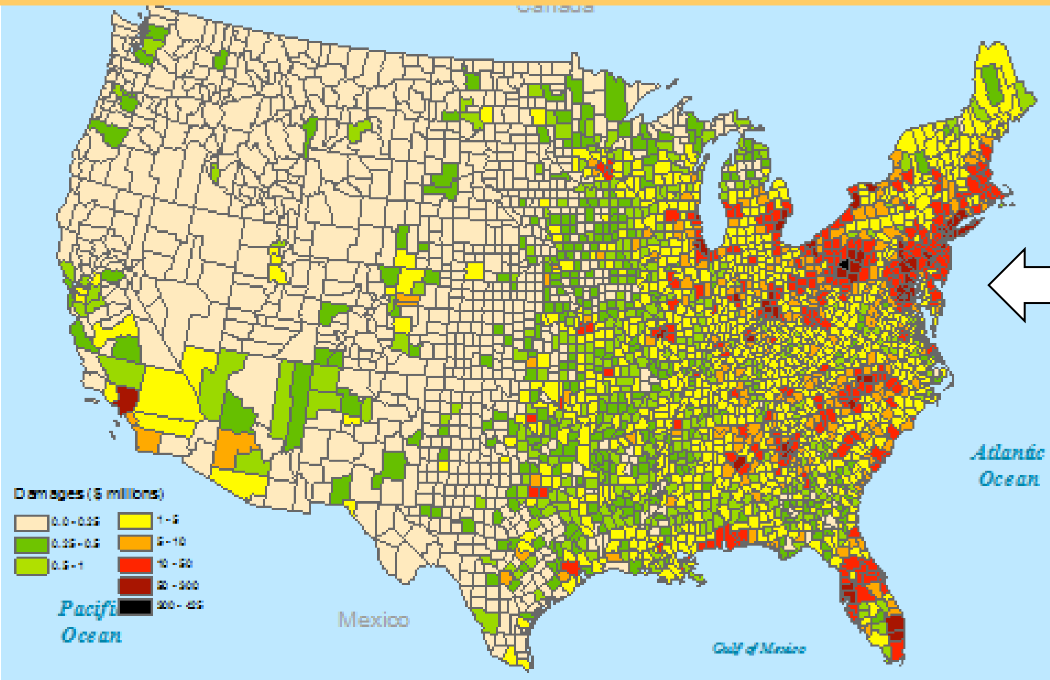
	kWe	1000 units/yr	10000 units/yr	50000 units/yr	1000 to 10000 units	10000 to 50000 units	10,000 to 100,000 units extrap.
STACK	10	$ 683	$ 402	$ 338	41%	16%	29%
	25	$ 573	$ 369	$ 303	36%	18%	32%
	50	$ 417	$ 311	$ 260	25%	17%	30%
BOP	10	$ 902	$ 720	$ 639	20%	11%	21%
	25	$ 532	$ 425	$ 377	20%	11%	21%
	50	$ 380	$ 303	$ 269	20%	11%	21%
SYSTEM	10	$ 1,585	$ 1,122	$ 977	29%	13%	24%
	25	$ 1,105	$ 794	$ 680	28%	14%	27%
	50	$ 797	$ 614	$ 529	23%	14%	26%

Note: Stack costs in $/kWe based on bottom-up direct manufacturing cost analysis; BOP costs are purchased components

Air Pollution Emissions Experiments and Policy Analysis Model (APEEP)

Emissions → **Air Quality Model** → **National Ambient Concentrations** → **National Exposures** → **Dose-Response: Human Health, Agriculture, Timber, Visibility, Recreation, Materials** → **Economic Valuation** →

External Damages from all Pollutants by County



Nicholas Muller

- **Focus on ambient concentrations of $PM_{2.5}$ and O_3 (dominant health and environmental externalities)**
- **Model adopted by U.S. National Academy of Sciences for “Hidden Cost of Energy” study (2010)**