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

U.S. Department of Energy Annual Merit Review for Fuel Cell Research

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Project ID # **FC098**

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview AMR 2015

Timeline

- Project start date: Oct 2011
- Project end date: Sept 2016
- Percent complete: 90%

Budget

- Total project funding
  - DOE share: 1.9M
  - Contractor share: n.a.
- FY16 DOE Funding: 100k

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
- Strategic Analysis
- Other Industry Advisors and Experts

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 (P); COMBINED HEAT AND POWER (C)	1	C	C	C	C
	10	P, C	P, C	P,C	P,C
	50	P,C	P,C	P,C	P,C

2016 AOP

Quarter	Milestones/Deliverables Description	Go/No-Go Criteria
Q3'15	Policy and energy system scenario analysis completed for LT PEM total cost models for CHP and backup power systems	Done
Q4'15	Total cost of ownership model and report completed for SOFC systems	Total cost of ownership model satisfactorily completed for SOFC systems along with a report describing this work. (October 2015)
Q1'16	Policy and energy system scenario analysis completed for SOFC total cost models for stationary power and CHP power systems	Done
Q2'16	Revision of SOFC total cost of ownership model, including low power CHP systems (≤10kW), lower volume costing, sensitivity analysis, and cost benchmarking with other studies and available market data.	Done
Q3'16	Revision of LT PEM] total cost of ownership model, including low power CHP systems, lower volume costing, sensitivity analysis, and cost benchmarking with other studies and available market data.	In Progress
Q4'16	Complete final LBNL reports for LT PEM and SOFC total cost of ownership models	Project completion

Approach: 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

Life Cycle Impact Assessment Models

Monetized health and GHG impacts

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**

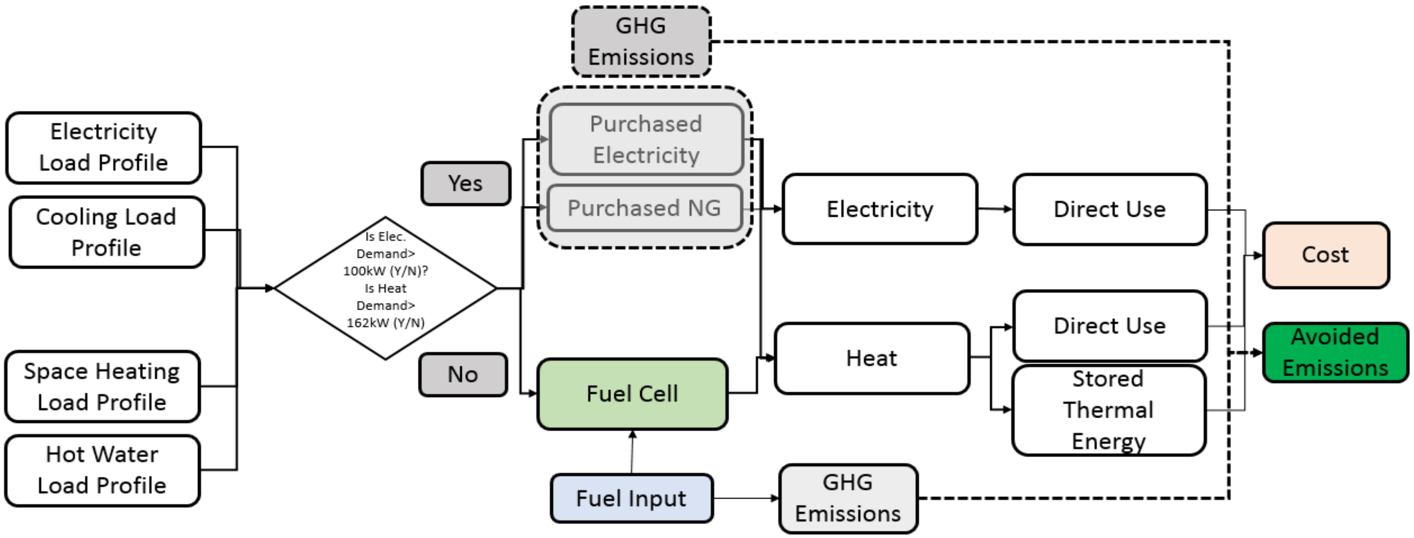
1 - Costing Approach

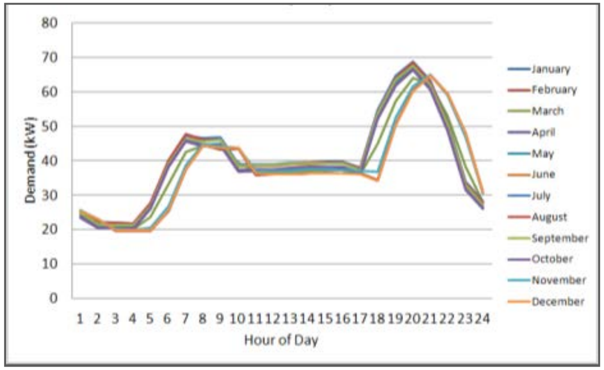
- **Direct Manufacturing Costs**
  - Capital costs
  - Labor costs
  - Materials costs
  - Consumables
  - Scrap/yield losses
  - Factory costs
- **Global Assumptions**
  - Discount rate, inflation rate
  - Tool lifetimes
  - Costs of energy, etc.
- **Other Costs:**
  - R&D costs, G&A, sales, marketing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

Source: Altergy Systems

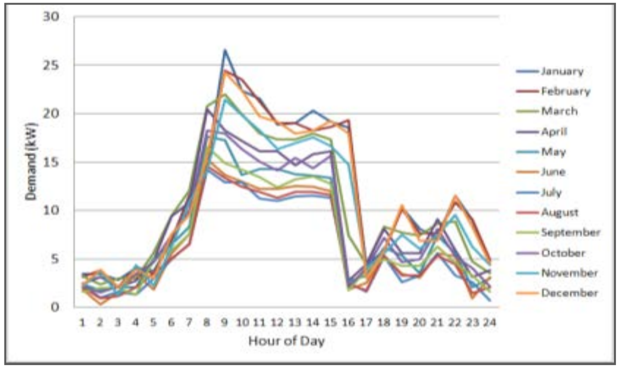
2 - Fuel Cell System Life Cycle Cost (Use Phase) Modeling

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



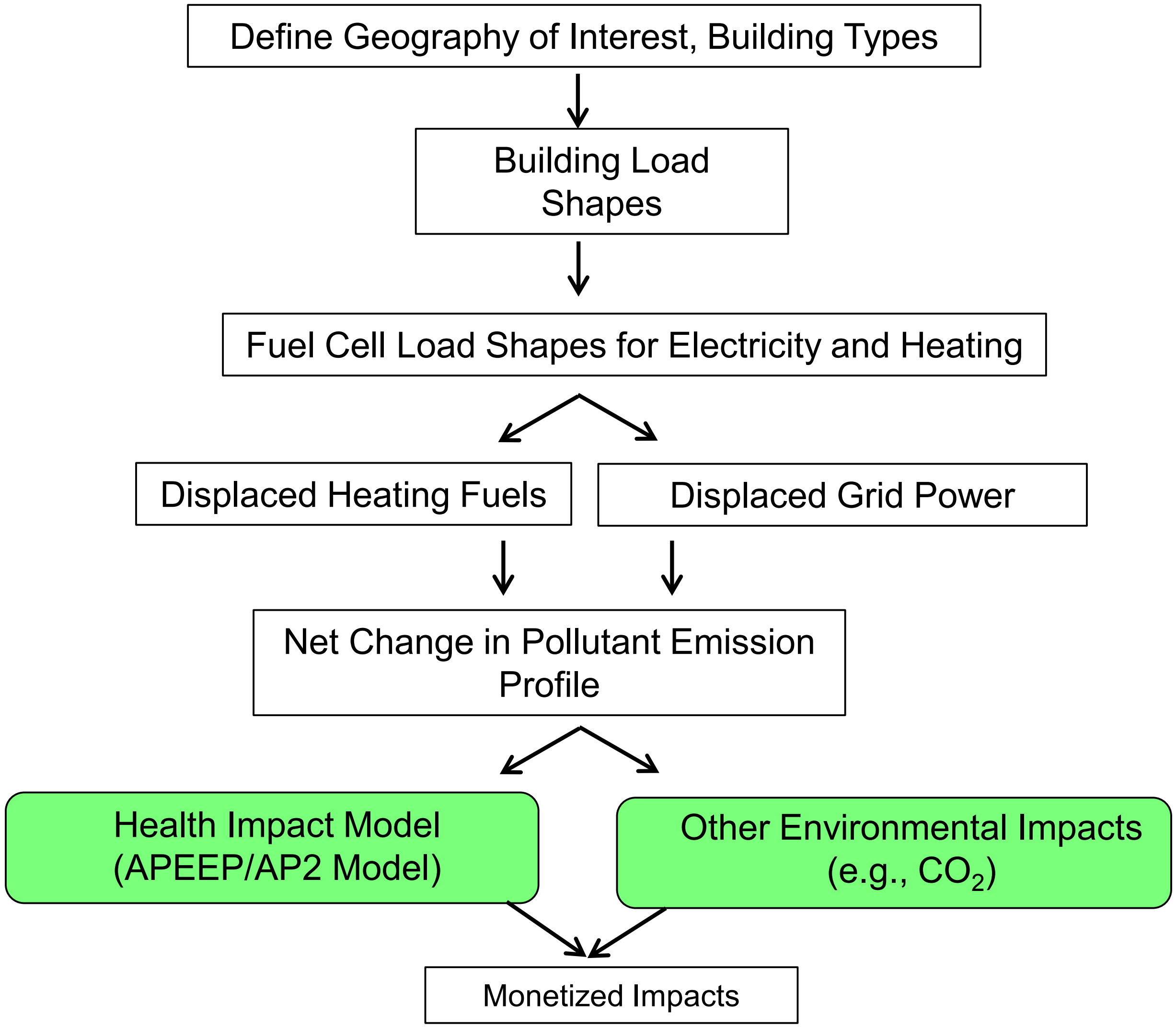


Daily electricity load profiles for small hotel in AZ



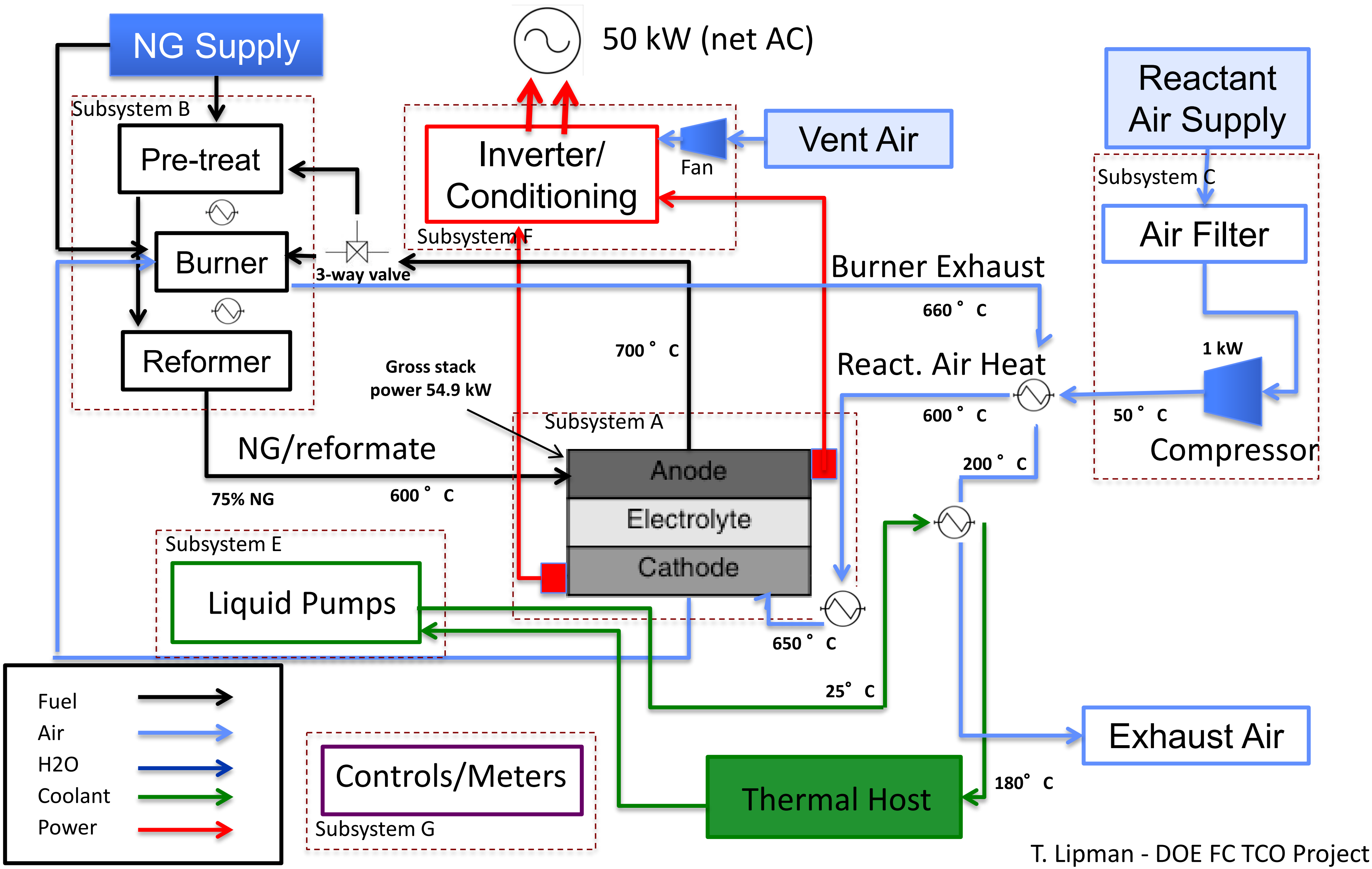
Daily hot water load profiles for small hotel in AZ

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



TECHNICAL PROGRESS: SOFC FC SYSTEM MANUFACTURING COST

50 kW SOFC CHP System with Reformate Fuel



T. Lipman - DOE FC TCO Project

CHP System Designs and Functional Specs

DFMA Manufacturing approaches for SOFC CHP and Power systems, anode-supported cell

Component	Primary Approach	Reference
Anode*	Ni / YSZ Tape casting	Patent review, Industry input
Interlayer*	Ni 50% / YSZ 50% Screen printing	Patent review, Industry input
Electrolyte*	YSZ – Screen printing	Literature, patents, industry input
Interlayer*	LSM 50 %/ YSZ 50% - Screen printing	Literature, patents, industry input
Cathode*	Conducting Ceramic– Screen printing	Literature, industry input
Plates*	Stamped metal plates with SS441	Literature, patents, industry input
Seal/Frame MEA*	Framed EEA	Patents, industry input
Stack Assembly*	Partial to fully automated	Patents, Industry input
Endplate/ Seals*	Metal endplate	Industry input, literature
Test/Burn-in	Post Assembly 3 hrs	Industry input

*Full DFMA Costing analysis was performed

Functional Specs 50kW CHP with Reformate Fuel

50 kW Size		Best. Ests.		Source
	Unique Properties:		Units:	
System	Gross system power	54.9	kW DC	
	Net system power	50	kW AC	
	Physical size	2x3x3	meter x meter x meter	Based on Bloom ES-5700 - Not incl. CHP eqpt
	Physical weight	3600	kg	Based on Bloom ES-5700 - Not incl. CHP eqpt
	Electrical output	480V AC	Volts AC or DC	
	DC/AC inverter effic.	95.5%	%	FCE 2013
	Waste heat grade	220	Temp. °C	From ~800 C. stack after air pre-heat
	Fuel utilization % (first pass)	85%	%	CFCL 2014
	Fuel input power (LHV)	84.23	kW	
	Stack voltage effic.	64%	% LHV	function of cell voltage
	Gross system electr. effic.	65.1%	% LHV	
	Avg. system net electr. effic.	59.4%	% LHV	CFCL 2014 60% electr. Eff.
	Thermal efficiency	24.4%	% LHV	70% recovery of avail. Heat
	Total efficiency	83.8%	Elect.+thermal (%)	FCE = 83.4% LHV; CFCL 82%
Stack	Stack power	54.86	kW	
	Total plate area	540	cm^2	Nextech for 10 kW: active=300 cm2 ; VersaPower 25x25 cm2
	Actively catalyzed area	329	cm^2	Est. 61% of tot. plate area
	Single cell active area	299	cm^2	10% less than CCM area
	Gross cell inactive area	45	%	
	Cell amps	105	A	
	Current density	0.35	A/cm^2	James 2012: 0.364mA/cm2
	Reference voltage	0.8	V	From James 2012 DOE
	Power density	0.282	W/cm^2	James 2012: 0.291 W/cm2
	Single cell power	84	W	Nextech: 103 W/cell
	Cells per stack	130	cells	
	Percent active cells	100	%	
	Stacks per system	5	stacks	

Updated SOFC direct manufacturing model from 2015 AMR

- Updated material costs
- Updated EEA module, plate costing and frame process sequence, process yield assumptions
- Detailed review of several modules with equipment vendors

- Similar overall bottom line costs to last year, with some reduction at high volumes as noted below

Materials Prices: Updates from 2015 to lower prices at high volumes

Table 4.4. Anode-supported cell material prices

Vendor/Country	Material	Order quantity (kg)	Price ($/kg)	Comments
AIICHI JITSUGYO (Japan)	Nickel Oxide	1000	68.5	CIF USA by sea
		5000	42.5	CIF USA by sea
		10000	37	CIF USA by sea
		20000	34	CIF USA by sea
AIICHI JITSUGYO (Japan)	8YSZ (8mol%YSZ)	100	78	CIF USA by sea
		1000	68	CIF USA by sea
		5000	63	CIF USA by sea
Daiichi (Japan)	8YSZ (8mol%YSZ)	10	97	CIF USA by sea
		100	95	CIF USA by air
		1000	83	CIF USA by sea
Inframat Advanced Materials (USA)	8YSZ (8mol%YSZ)	1	139.2	by rail or truck
		5	115.8	by rail or truck
		10	94.5	by rail or truck
		50	71.6	by rail or truck
		100	49.7	by rail or truck
		1000	35.2	by rail or truck
		10000	29.8	by rail or truck
Inframat Advanced Materials (USA)	LSM powder	100	170	by rail or truck
		1000	95	by rail or truck
		10000	70	by rail or truck
Qingdao Terio Corporation (China)	LSM powder	10	250	CIF USA by air
		100	150	CIF USA by air
		200	125	CIF USA by air
		500	105	CIF USA by air
		1000	80	CIF USA by air
		2000	75	CIF USA by air
		5000	60	CIF USA by air

CIF = price including cost, insurance and freight

Key updates from 2015:

8YSZ price
50% lower at high volume
($60/kg 2015 value to $29.80/kg)

LSM powder price
60% lower price at high volume
($150/kg value to $60/kg)

Yield assumptions updated from 2015

Process Yield assumptions, 2015

FC Size (kW)	10	10	10	10
Annual Production Volume	100	1,000	10,000	50,000
EEA Yield	95.00%	96.00%	97.00%	98.00%
Interconnect & Frame	85.00%	85.65%	92.67%	97.91%
Seal	85.00%	85.77%	92.79%	98.04%
Assembly	99.5%	99.5%	99.5%	99.5%
Stack Average Yield	89.8%	90.3%	95.0%	98.5%

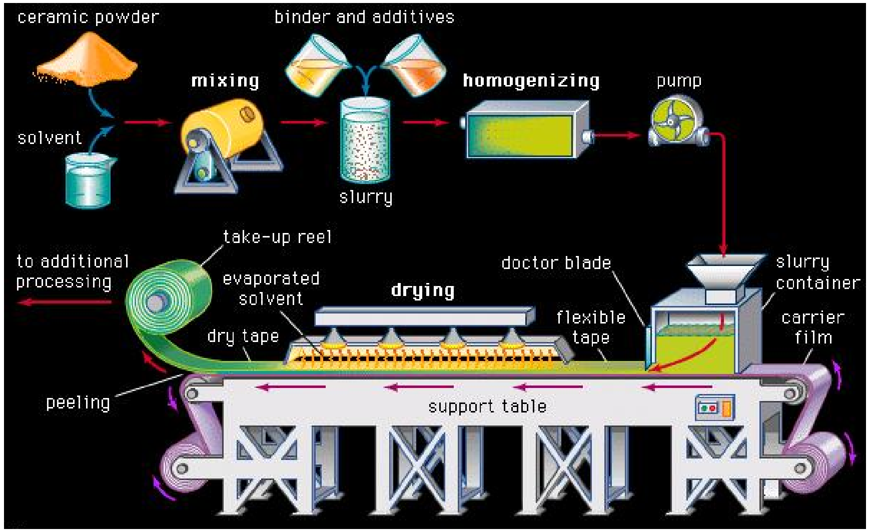
FC Size (kW)	50	50	50	50
Annual Production Volume	100	1,000	10,000	50,000
EEA Yield	96.00%	97.00%	98.00%	99.00%
Interconnect & Frame	85.00%	90.50%	97.91%	99.50%
Seal	85.00%	90.62%	98.04%	99.50%
Assembly	99.5%	99.5%	99.5%	99.5%
Stack Average Yield	89.8%	93.5%	98.5%	99.5%

Updated EEA process parameter assumptions

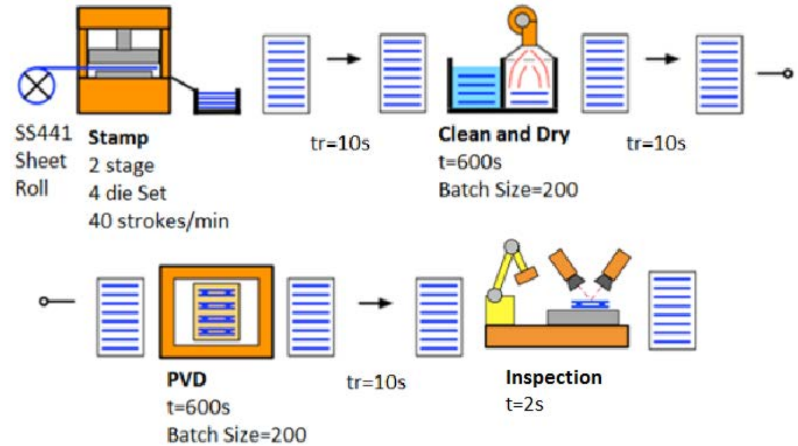
Power	Systems/year	Process Yield (%)	Availability (%)	Line Performance (%)
1	100	85.00%	80.00%	89.00%
	1,000	88.00%	80.00%	89.00%
	10,000	91.00%	80.79%	95.00%
	50,000	92.00%	85.79%	95.00%
10	100	88.00%	80.00%	89.00%
	1,000	91.00%	80.79%	95.00%
	10,000	92.00%	88.04%	95.00%
	50,000	93.00%	93.49%	95.00%
50	100	90.00%	80.00%	89.00%
	1,000	92.00%	85.79%	95.00%
	10,000	93.00%	93.49%	95.00%
	50,000	94.00%	95.00%	95.00%
100	100	91.00%	80.79%	95.00%
	1,000	92.00%	88.04%	95.00%
	10,000	94.00%	95.00%	95.00%
	50,000	95.00%	95.00%	95.00%
250	100	91.00%	83.60%	95.00%
	1,000	93.00%	91.10%	95.00%
	10,000	94.00%	95.00%	95.00%
	50,000	95.00%	95.00%	95.00%

Manufacturing Cost Model – EEA, Metal Plates

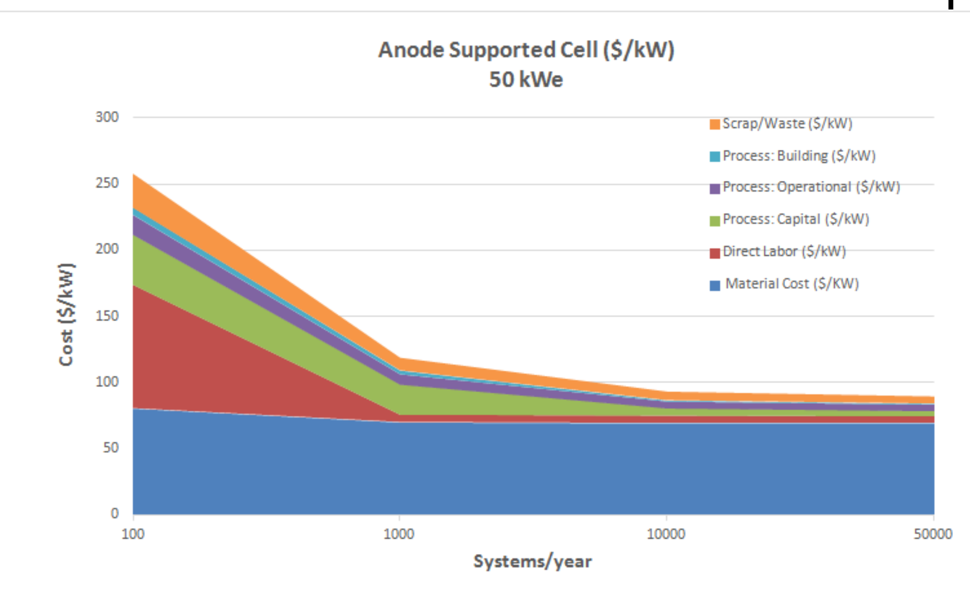
EEA Process Flow-Cathode Coating Line



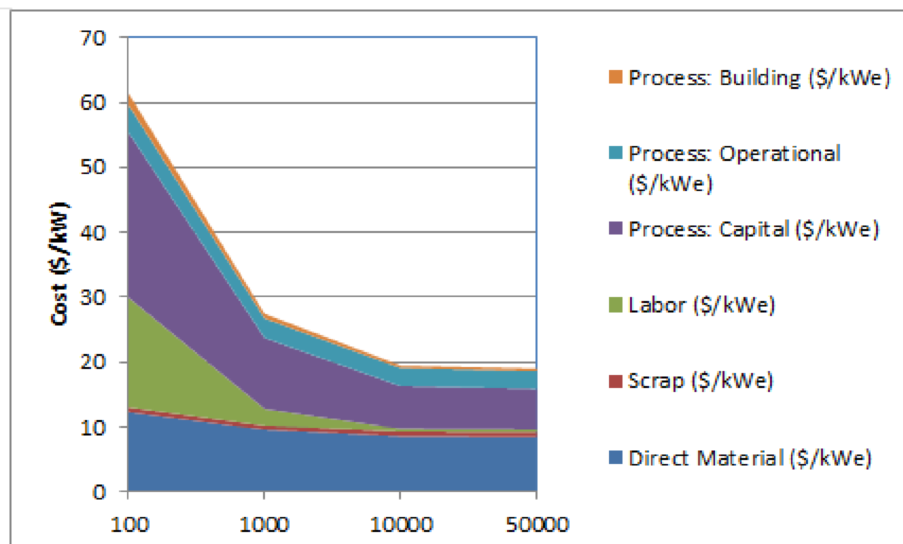
Metal Plate Process Flow



EEA Cost Plot - 50kW System

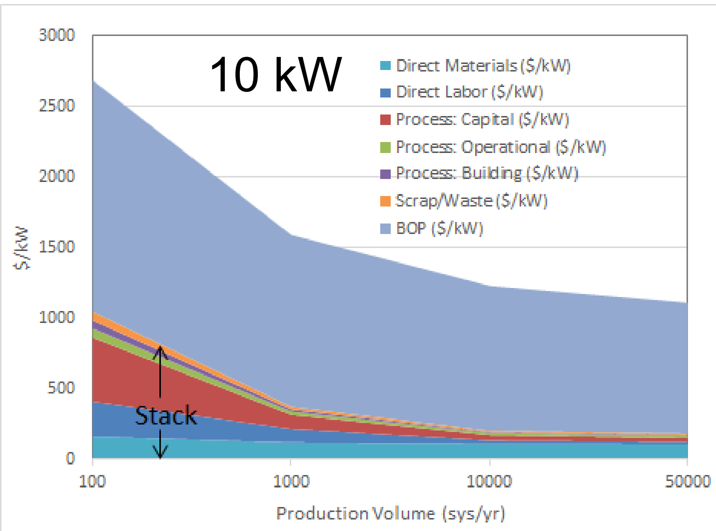


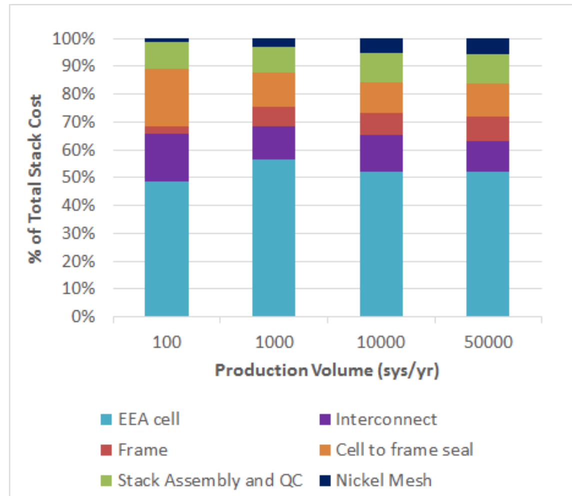
Plates Cost Plot - 50kW System

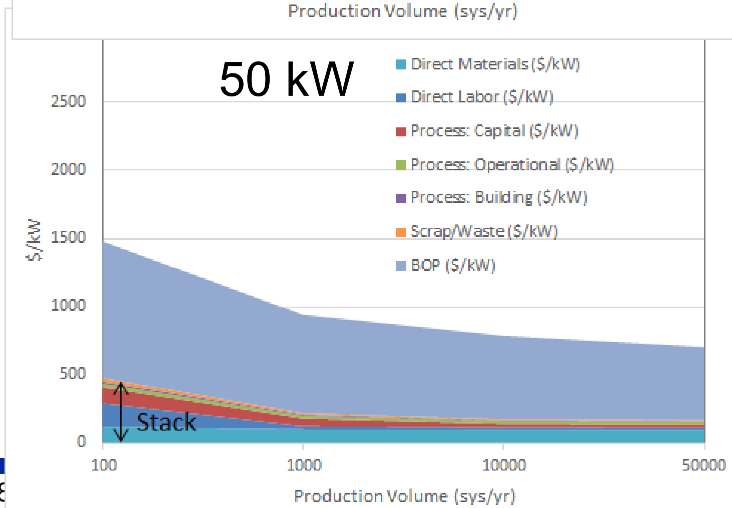


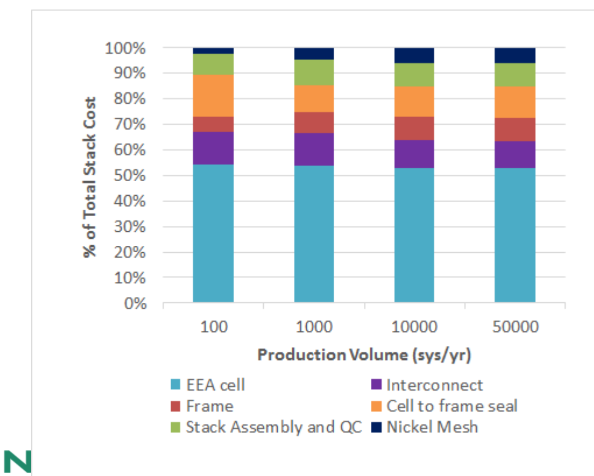
System Cost for 10kW, 50kW CHP SOFC updated

- Stack cost dominated by EEA then seal/frame at lower volumes
- BOP is 60%-80% of overall cost
- System direct cost < $750/kW at high volumes









Equipment Cost Estimates vs. DOE Targets

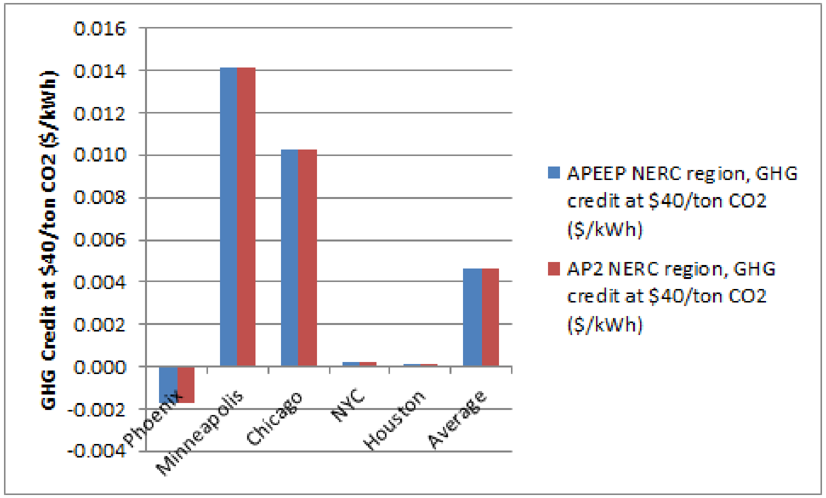
System	Units/yr	2020 DOE Target w/ Markup ($/kW)	LT PEM direct cost ($/kW)	LT PEM cost with 50% markup ($/kW)	SOFC direct cost ($/kW)	SOFC cost with 50% markup ($/kW)
		DOE Targets	This Work (last year in paranthesis)			
10kW CHP System	50,000	$1,700	$1,724	**$2,586**	$1,170	**$1655 ($1755)**
100kW CHP System	1000	$1000	$1,200	**$1,800**	$940	**$1139 ($1410)**

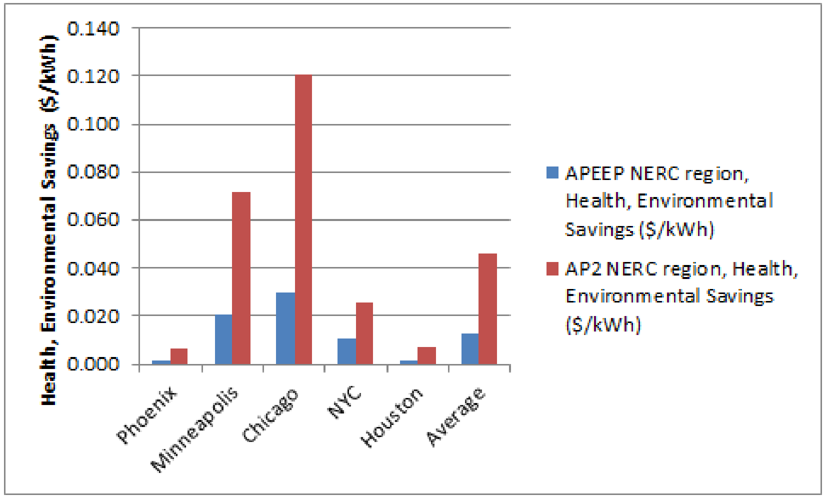
10 kW SOFC system now meeting the 2020 DOE target

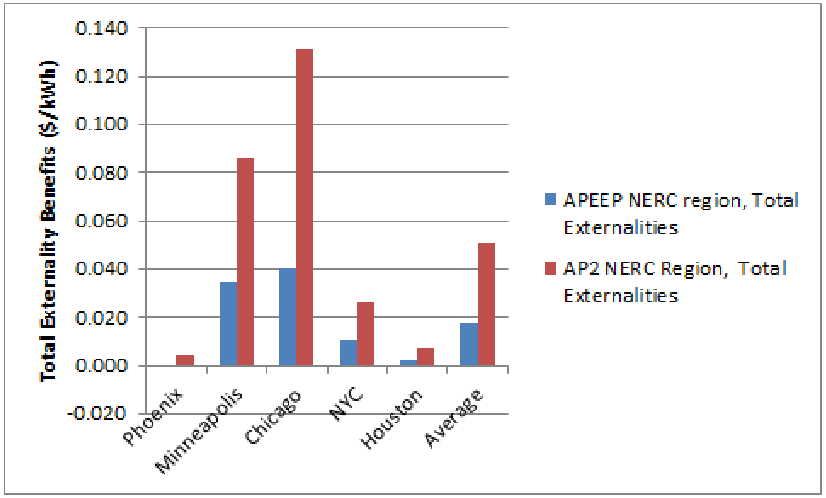
TECHNICAL PROGRESS: LCIA (LIFE CYCLE IMPACT ASSESSMENT) MODEL

1 - Updated marginal benefits of abatement from APEEP model to AP2 (APEEP2) model

- **50kW small hotel CHP example shown (LT PEM)**







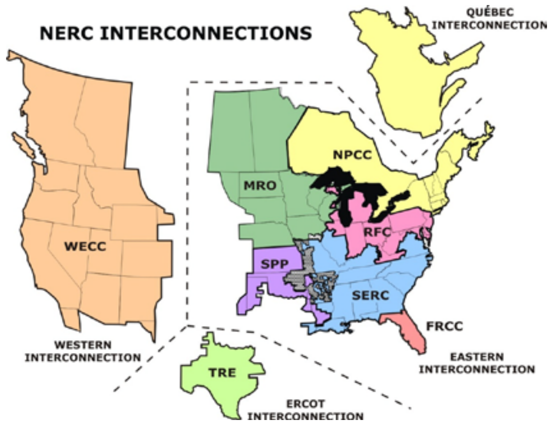
AP2: Health, Environmental benefits are increased by a factor of 3-5X over previous APEEP estimates

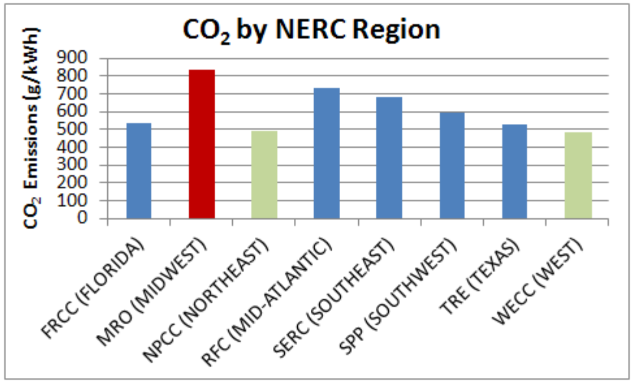
New marginal benefits of abatement are more commensurate with latest estimates from the EPA.

2 - Updated this year – NERC region to eGRID subregional CO2, criterion pollutant emission rates

BERKELEY LAB

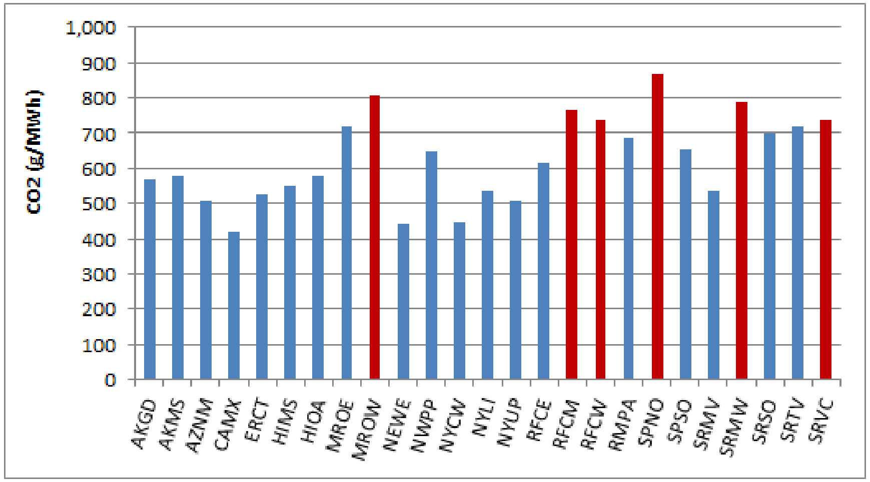
Previous Years:





This year:

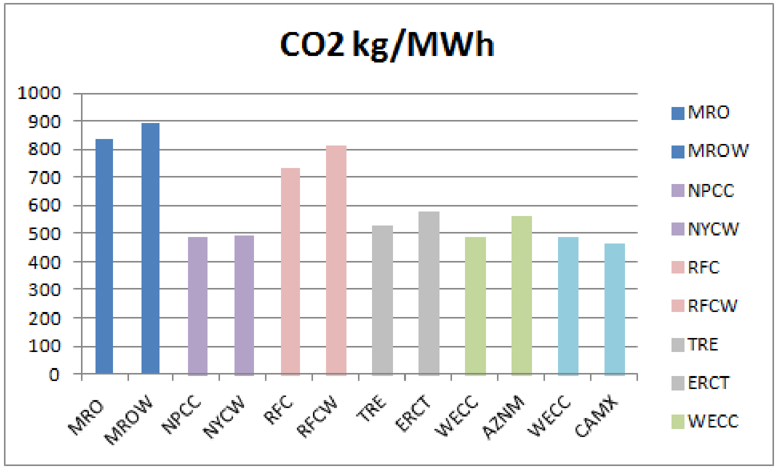
USEPA eGRID2012

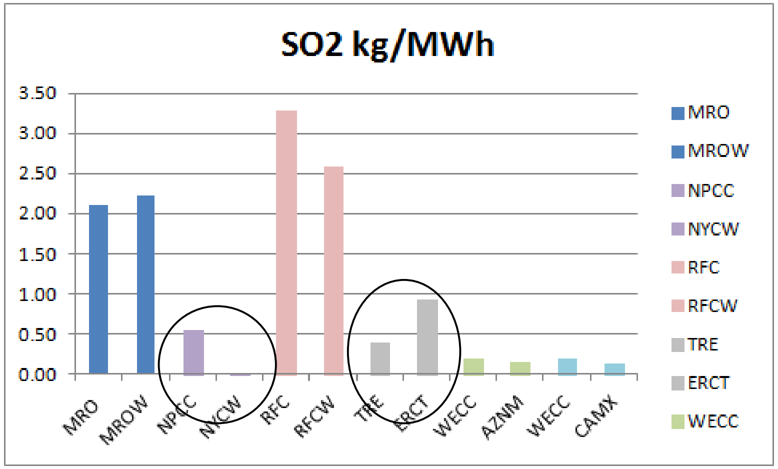


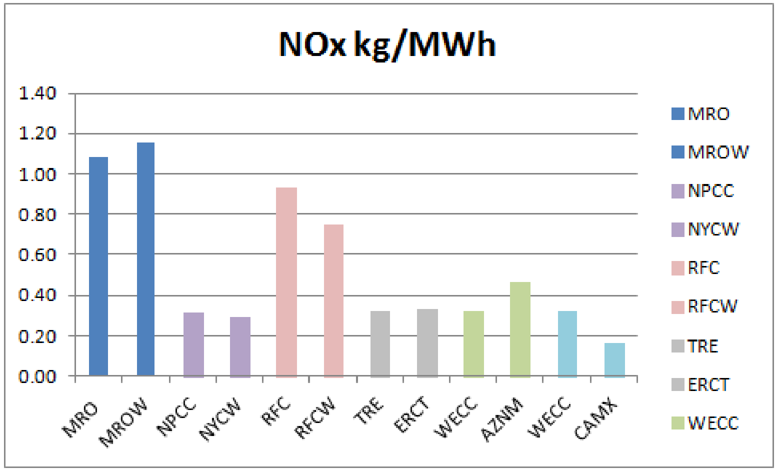
Earlier work used marginal emission factors by NERC region. This year, eGRID subregional emission rates are utilized for improved spatial resolution

Note: More than a factor of 2X between regional CO2 emission rates

eGRID subregional emission rates vs NERC-level MEF: reasonable CO2 agreement but local differences in SO2, NOX



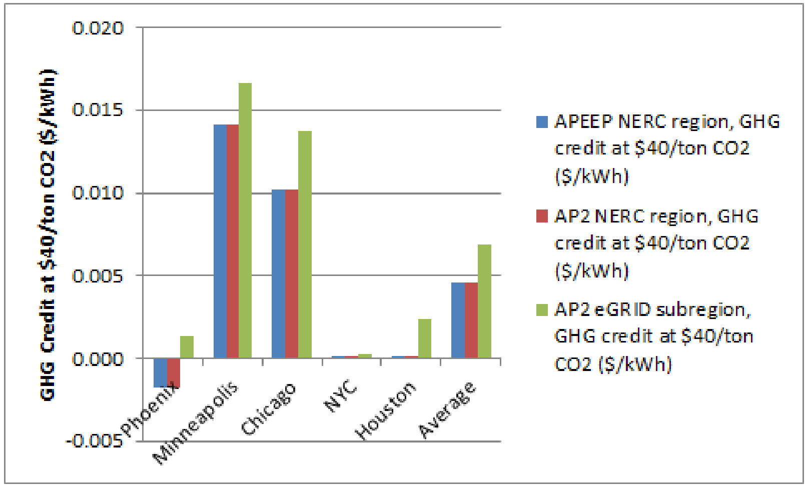


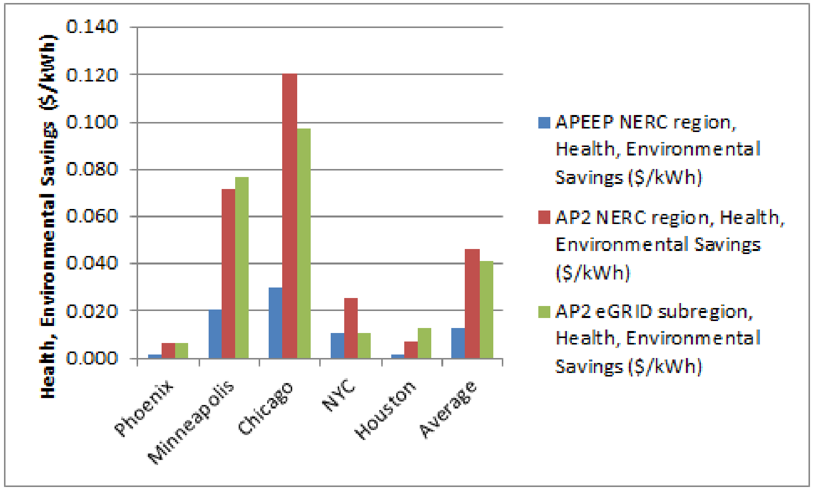


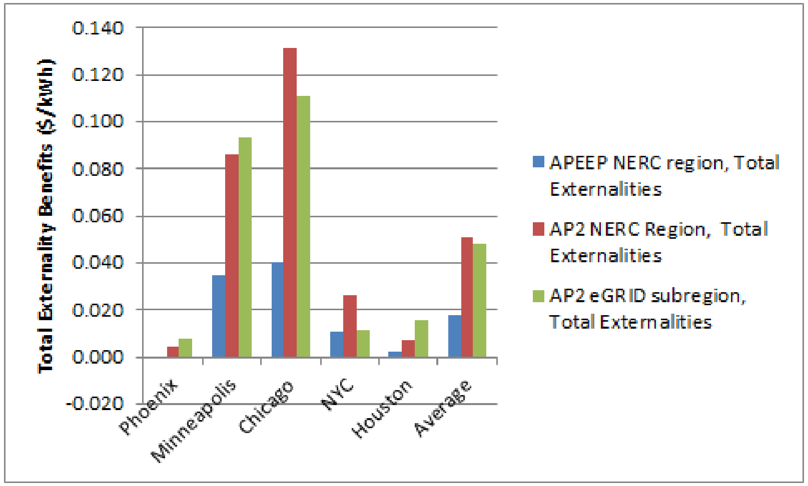
- For each pair- first bar is larger NERC region (Old value); 2nd bar eGRID sub-region (updated value)
- Reasonably matched except: SOX much lower in NYC; SOX much higher in Texas (ERCT)

1 + 2: Updated marginal benefits of abatement from APEEP to AP2 (APEEP2) model and updated emission factors from NERC to subregions

- **50kW small hotel CHP example shown (LT PEM)**



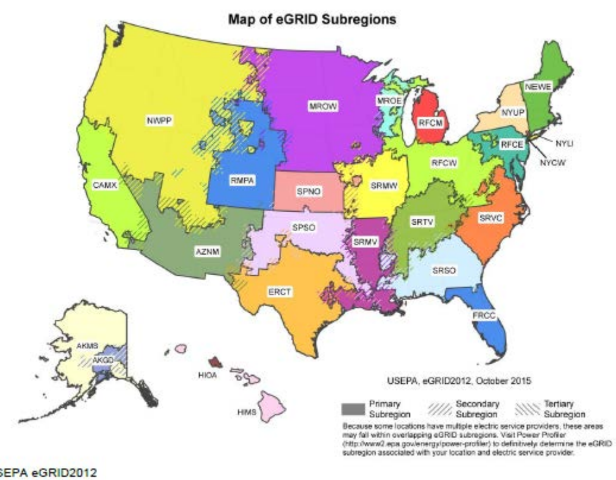




GHG benefits are higher since subregion GHG emission factors are higher (red to green bars)

Overall externality benefits similar – but lower in NYC and higher in Houston, driven by local SO2 differences from NERC-level SO2 (red to green bars)

Estimated Clean Power Plan impacts for six representative regions



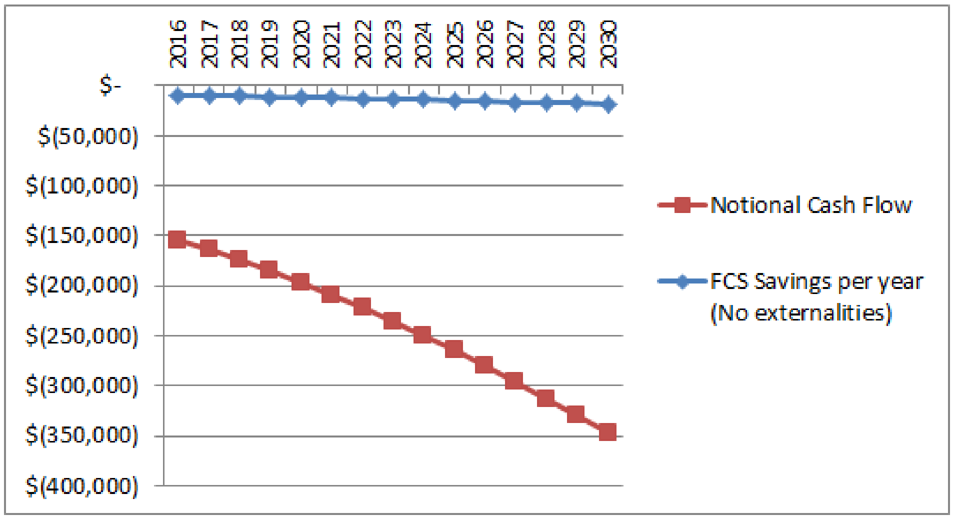
		kg/MWH			kg/MWh			% Reduction 2030 from 2012		
City	EGRID subregion	EGRID for 2012, released 10/15			2030 Projection with Clean Power Plan					
		CO2 AEF eGRID	SO2 AEF eGRID	NOx AEF eGRID	CO2 AEF	SO2 AEF	NOx AEF	CO2	SO2	NOx
Minneap.	MROW	646	1.33	0.73	489	0.25	0.45	24%	81%	38%
NYC	NYCW	316	0.03	0.15	322	0.00	0.05	-2%	97%	64%
Chicago	RFCW	626	1.54	0.55	510	0.40	0.34	19%	74%	37%
Houston	ERCT	518	0.87	0.28	440	0.09	0.11	15%	90%	61%
Phoenix	AZNM	523	0.20	0.59	459	0.07	0.30	12%	64%	50%
S. Diego	CAMX	295	0.09	0.15	259	0.03	0.08	12%	62%	46%
Average								**13%**	**78%**	**49%**

- Average reductions (in average emission factors)
- ~13% reduction in CO2
- ~80% average reduction in SO_2 tons/kWh 2012-2025
- ~50% average reduction in NOx tons/kWh 2012-2025

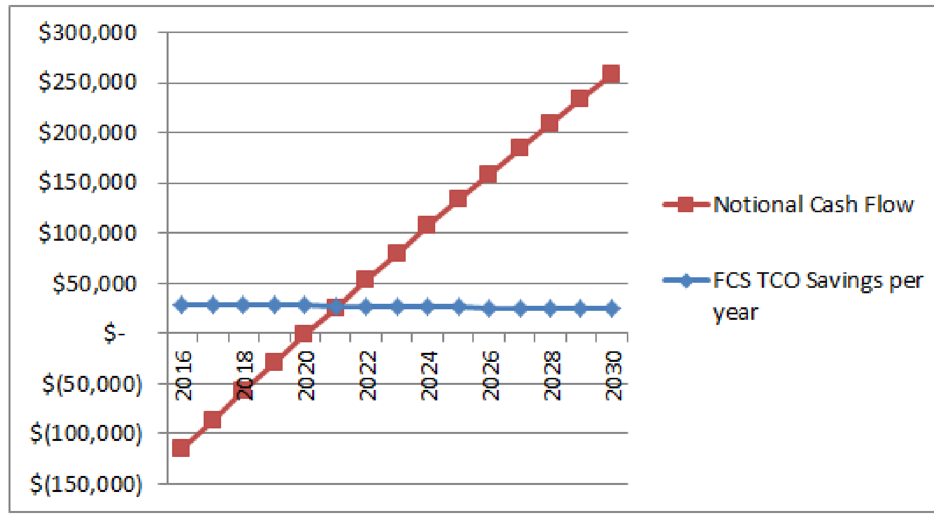
Notional Cash Flow example – Static marginal emission factors, escalating social cost of CO2

- **50kW LT PEM CHP in small hotel in Chicago 2016-2030**, with
  - (1) No reduction in MEFs assumed
  - (2) Escalating social cost of carbon at 3% discount rate
- Not a real cash flow, but including private costs and public benefits
- Installed cost of $2900/kWe assumed; NPV(societal)=0 at $5700/kWe installed cost

FCS vs Grid, No Externalities



FCS vs Grid, Including Externalities

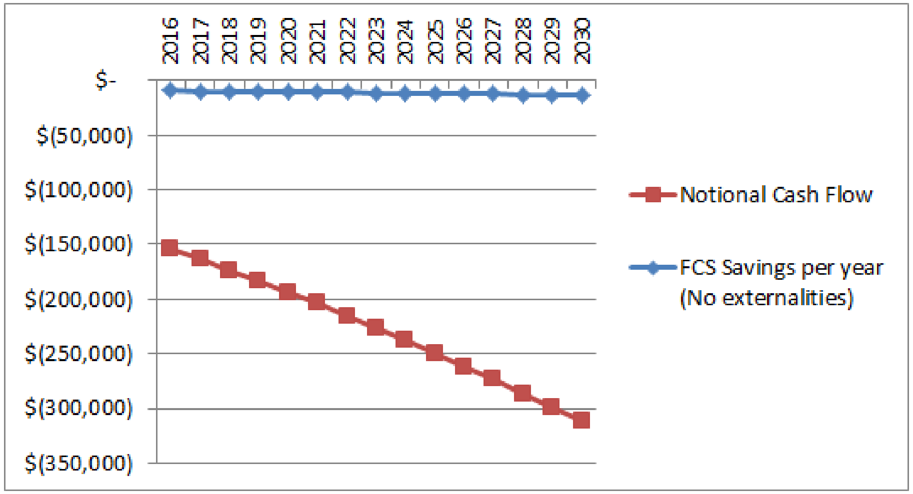


Private costs: Not favorable to owner   ***For society, cash positive investment***

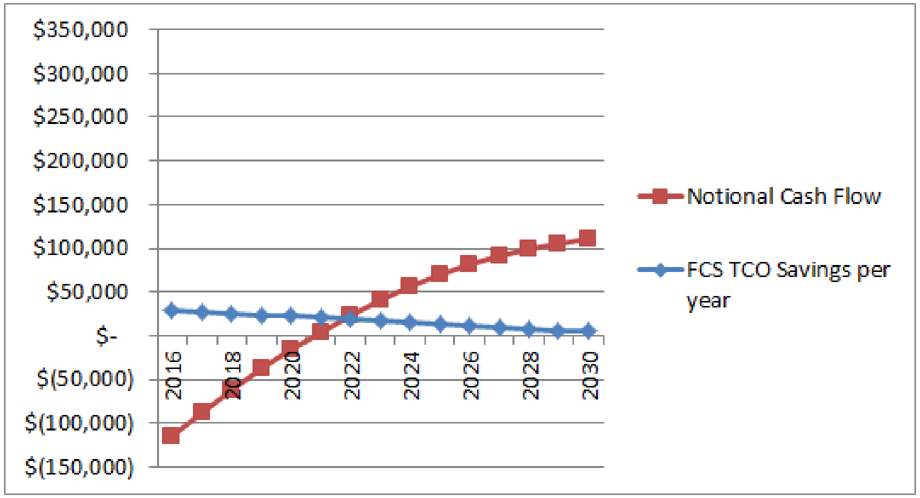
Notional Cash Flow example – Reduction in marginal emission factors, escalating social cost of CO2

- **50kW LT PEM CHP in small hotel in Chicago 2016-2030**, with
  (1) Reduction in MEFs tracking estimated reduction in AEF assumed
  (2) Escalating social cost of carbon at 3% discount rate
- Not a real cash flow, but including private costs and public benefits
- Installed cost of $2900/kWe assumed; NPV(societal)=0 at $3850/kWe installed cost

FCS vs Grid, No Externalities



FCS vs Grid, Including Externalities



Private costs: Not favorable to owner

For society, cash positive investment

These last two figs. on lower right are "bounding cases" for this building case – no change in MEF to full changes from AEF in CPP

Responses to 2015 AMR Reviewer Comments

1. **Highlight key results–** Key results highlighted in particular changes to LCIA modeling and SOFC direct manufacturing cost modeling and rationale for changes from last year
2. **More on LCIA and externality analysis** – Some reviewers suggesting focusing more on this since other groups are also working on direct manufacturing cost analysis. We provide more detailed description in the main presentation and backup slides on the externality analysis assumptions and projections to 2030.
3. **Highlight key cost reduction opportunities–** This work continues to highlight the importance of balance of plant cost reduction for overall system cost reduction (e.g., power conditioning, potential cost reduction from design and integration) but assumes high throughput stack manufacturing processes achieving higher process yields through continued “learning-by-doing.”

Collaborations

Partners

University of California, Berkeley

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

— Manufacturing process analysis, DFMA analysis

University of California, Berkeley

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

Strategic Analysis

— SOFC system design and functional specifications

Other Collaborators

— No other funded subcontracts, but many industry contacts and expert reviewers, shown on next slide.

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: ***Direct cost model for SOFC CHP systems extensively revised; Life cycle impact assessment modeling and externality valuation for FC CHP systems to 2030 estimating impacts of Clean Power Plan.***

Collaboration: ***Partnerships with UC-Berkeley manufacturing analysis and transportation sustainability research groups.***

Proposed Next-Year Research: ***NA***

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Thank you

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Technical Back-Up Slides

Functional specs – common properties

		Fuel Type:	Pipeline Natural Gas
Common properties:	**Near-Term**	**Future**	**Unit**
System life	15	20	years
Stack life	24000	40000	hours
Reformer life (if app.)	5	10	years
Compressor/blower life	7.5	10	years
WTM sub-system life	7.5	10	years
Battery/startup system life	7.5	10	years
Turndown % (>50 kW)	**0**	**25**	**percent**
Turndown % (<50 kW)	**25**	**50**	**percent**
Expected Availability	96	98	percent
Stack cooling strategy	Air+off gas	Air+off gas	cooling

Turndown an area for further discussion but taking 25% for < 50kW systems currently

Global DFMA Costing assumptions

Parameter	Symbol	Value	Units	Comments
Operating hours	t_{hr}	varies	Hours	8 hours base shift; (2-3 shifts per day)
Annual Operating Days	t_{dy}	240	Days	52wks*5days/wk-10 vacation days-10 holidays
Avg. Inflation Rate	j	0.023		US avg. for past 10 years (Phillips, 2008)
Avg. Mortgage Rate	j_m	0.051		(Trading Economics , 2015)
Discount Rate	j_d	0.1		
Energy Inflation Rate	j_e	0.056		US avg of last 3 years (Phillips, 2008)
Income Tax	i_i	0		No net income
Property Tax	i_p	0.01035		US avg from 2007 (Tax-rates.org, 2015)
Assessed Value	i_{av}	0.4		
Salvage Tax	i_s	0.5		
EOL Salvage Value	k_{eol}	0.02		Assume 2% of end-of-life value
Tool Lifetime	T_t	15	Years	Typical value in practice
Energy Tax Credits	ITC	0	Dollars	
Energy Cost	c_e	0.1	$/kWhe	e.g., the cost of electricity in the industrial sector was $0.109/kWhe in New England, and $0.102/kWhe in the Pacific contiguous states in October 2014 (https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a, accessed 29 December 2015))
Floor space Cost	c_{fs}	1291	$/m²	US average for factory (Selinger, 2011)
Building Depreciation	j_{br}	0.031		BEA rates (U.S. Department of commerce, 2015)
Building Recovery	T_{br}	31	Years	BEA rates (U.S. Department of commerce, 2015)
Building Footprint	a_{br}	Varies	m²	
Line Speed	v_l	Varies	m/min	
Hourly Labor Cost	c_{labor}	29.81	$/hr	Hourly wage per worker

MInor updates from 2015:

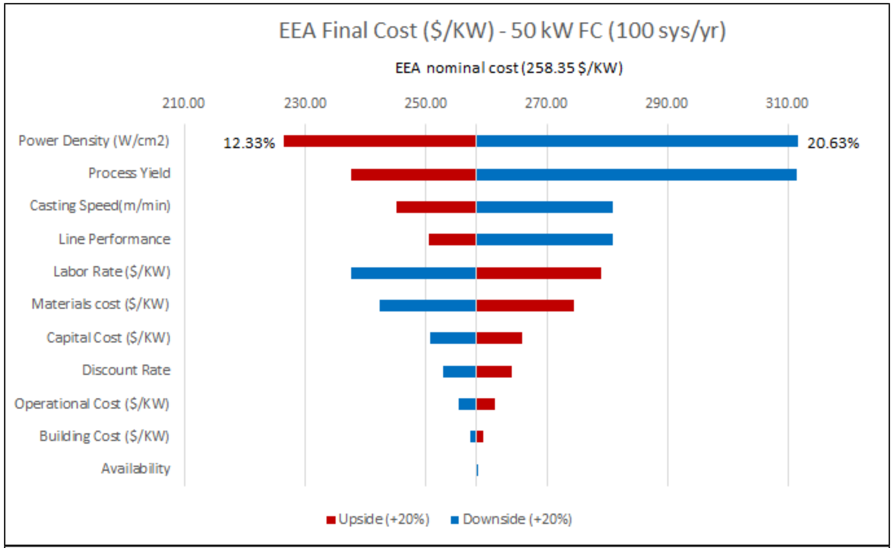
Ann. Op. days from 250 to 240

Avg. Inflation rate from 2.5% to 2.3%

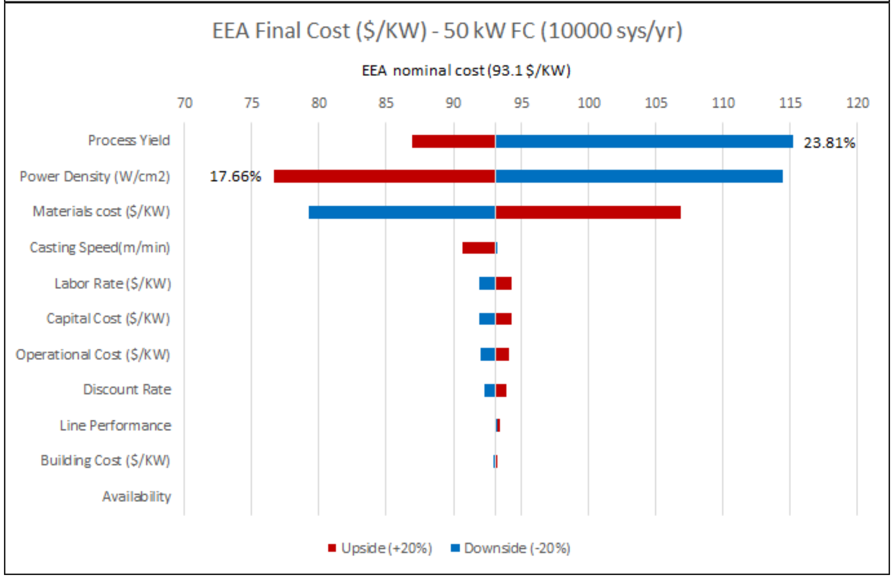
Hourly wage from $28.08/hr. to $29.81/hr

Sensitivity of Stack EEA costing for SOFC 50kW CHP

- **At low volume:**
  - Yield
  - Power Density
  - Coating speed

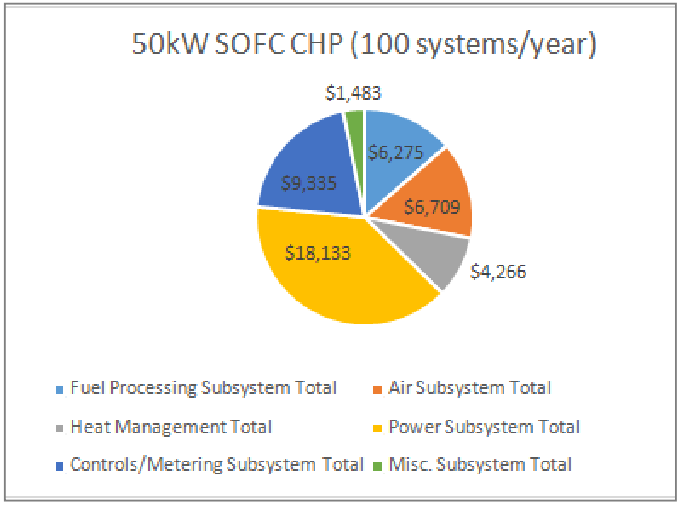


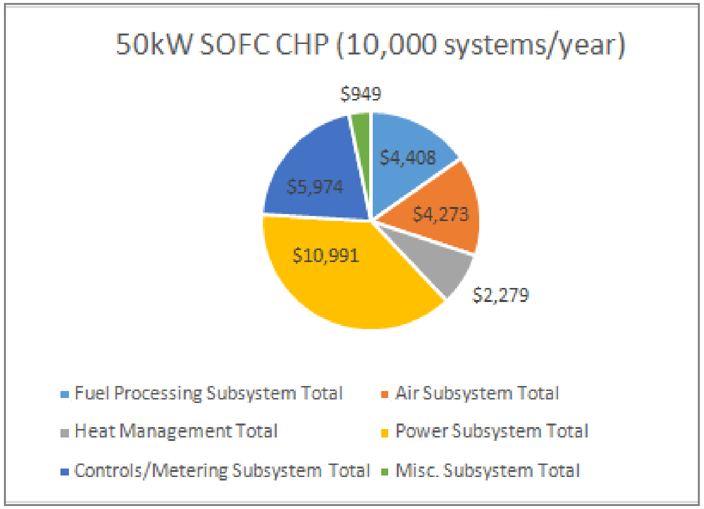
- **At high volume:**
  - Yield
  - Power Density
  - Materials cost

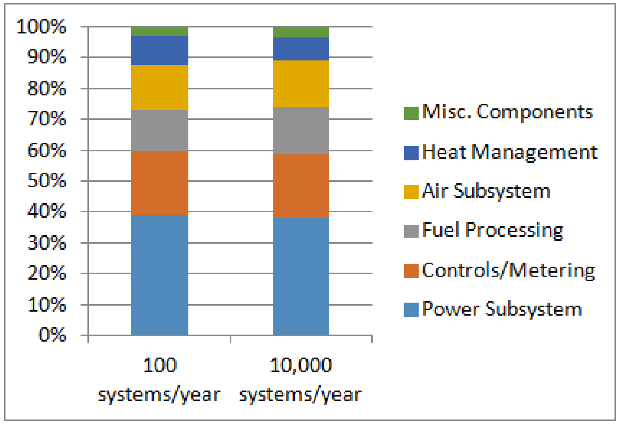


BOP Components Cost Breakdown

- **Balance of plant: about 40% power subsystem, 20% controls/metering, 15% fuel processing**







Displaced Grid Electricity and Life-Cycle Impact Assessment Modeling

Type	Item	Units	Assumed source of emissions	Spatial Regime	Temporal Regime	Reference
Electricity	MEF	Tons/MWh	Stack-height level	eGRID Subregions	Annual	eGRID 2015
Electricity	MBA	$/Ton	Stack-height level	State level	Annual	AP2, Muller (2014)
Fuel	MEF	Tons/MWh	Ground level	Site level	Annual	AP2, Muller (2014)
Fuel	MBA	$/Ton	Ground level	County level	Annual	AP2, Muller (2014)

LCIA modeling for health/environmental valuation includes both displaced electricity and displaced onsite fuel