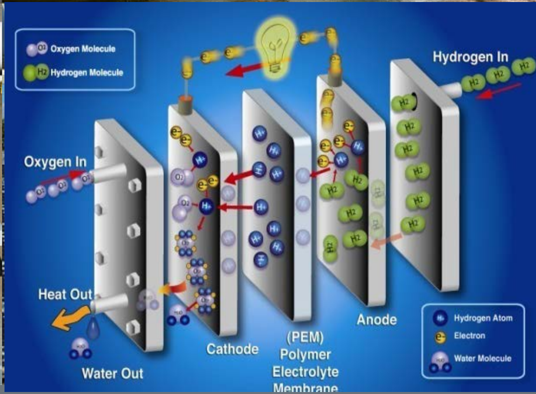
Fuel Cell Technologies Office Webinar

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



Total Cost of Ownership Modeling for Stationary Fuel Cell Systems

December 13, 2016

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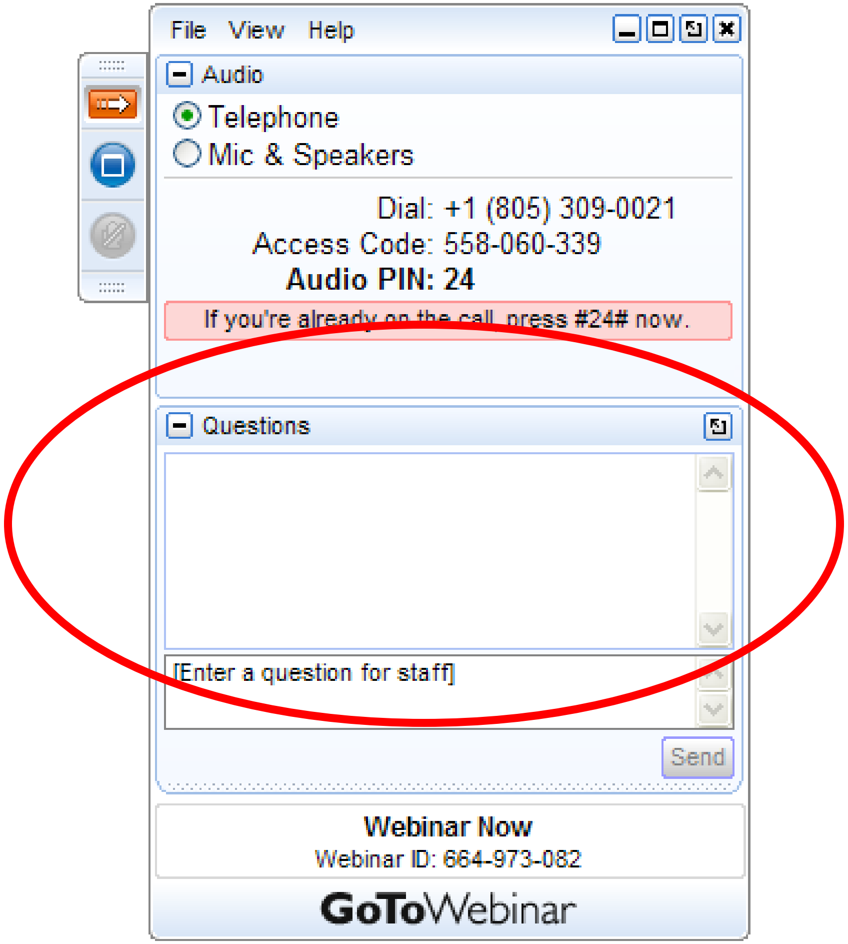
Lawrence Berkeley National Lab

Question and Answer

- Please type your questions into the question box



Research Team

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.

Outline

- Modeling Approach
- Direct Cost modeling
  - — Direct costs are estimated for PEM and SOFC FC CHP systems from 1 to 250kW sizes and for various manufacturing volumes.
- Cost comparisons to existing systems in
  - — Vs Japan micro-CHP
  - — U.S. backup power systems.
- Externality valuation (e.g., health and environmental impacts)
  - — Externality valuation example for FC CHP in small hotels
- Conclusions

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 (LT PEM)
  - Solid oxide fuel cell (SOFC)

- **Application Space:**

APPLICATION	SIZE (kWe)	PRODUCTION VOLUME (UNITS/YEAR)			
		100	1.000	10.000	50.000
Combined Heat and Power (CHP)	1	x	x	x	x
	10	x	x	x	x
	50	x	x	x	x
	100	x	x	x	x
	250	x	x	x	x

APPLICATION	SIZE (kWe)	PRODUCTION VOLUME (UNITS/YEAR)			
		100	1.000	10.000	50.000
Backup Power (BU)	1	x	x	x	x
	10	x	x	x	x
	50	x	x	x	x

- **DOE Cost Targets**

System Type	2015 Target	2020 Target
10 kWe CHP System	$1,900/kWe	$1,700/kWe
100-250 kWe CHP System	$2,300/kWe	$1,000/kWe

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

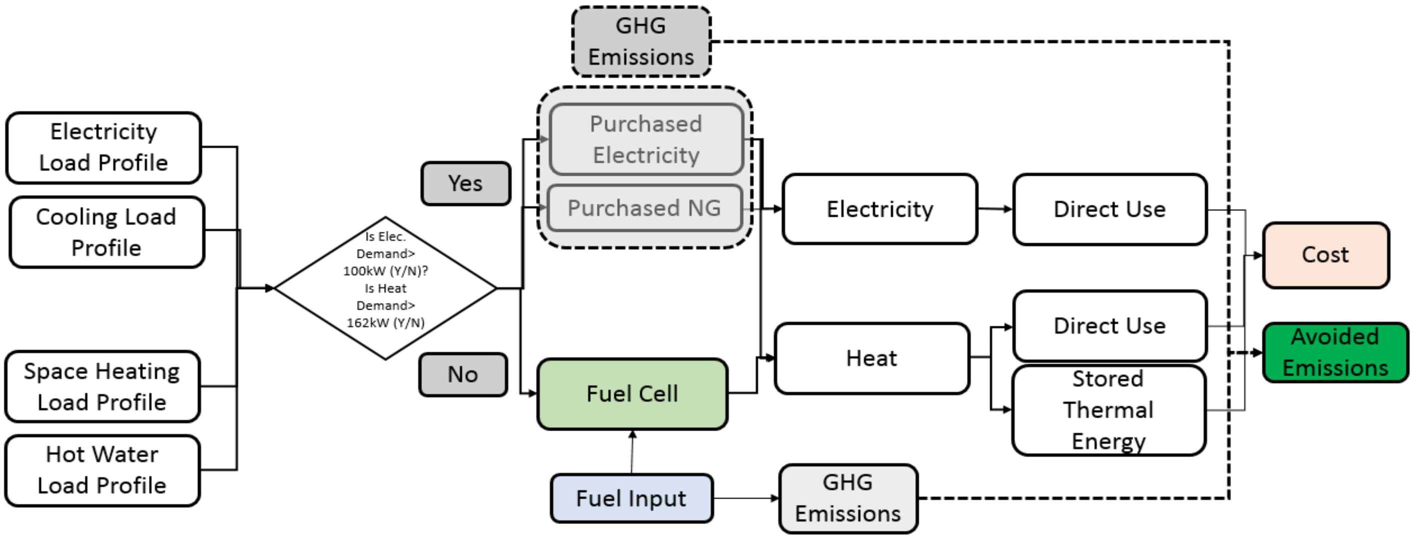
Annualized Cost of tool in constant currency (Haberl, 1994)

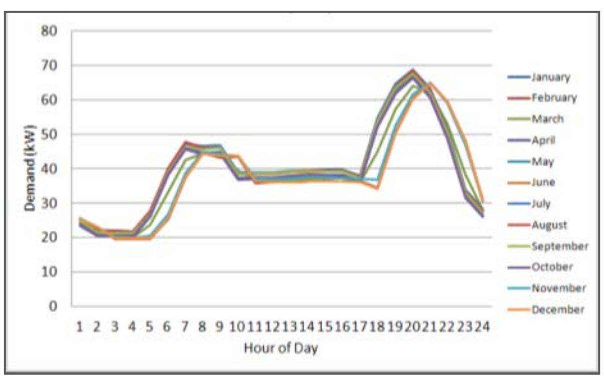
$$C_y = C_c - C_s + C_{oc} + C_{br} + C_p + C_m - C_{dep}$$

Capital and Interest C_c
End of Life Salvage Value C_s
Operating Energy Cost C_{oc}
Building or Floorspace Cost C_{br}
Property Tax C_p
Maintenance Cost C_m
Deduction due to the tool depreciation C_{dep}

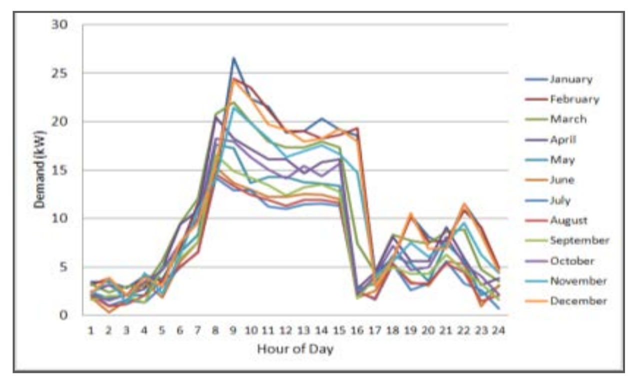
2 - Fuel Cell System Life Cycle Cost (Use Phase) Modeling

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



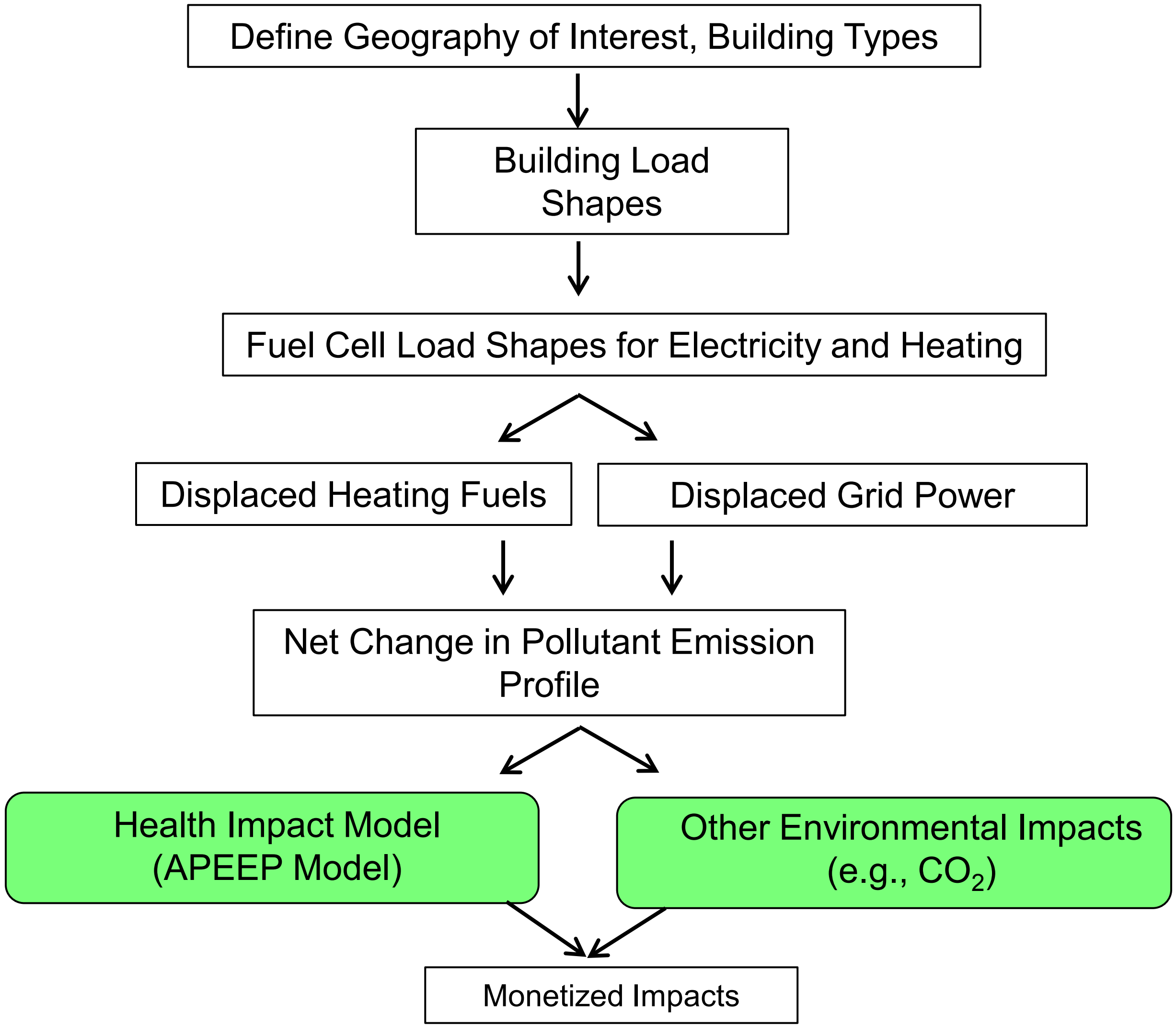


Daily electricity load profiles for small hotel in AZ



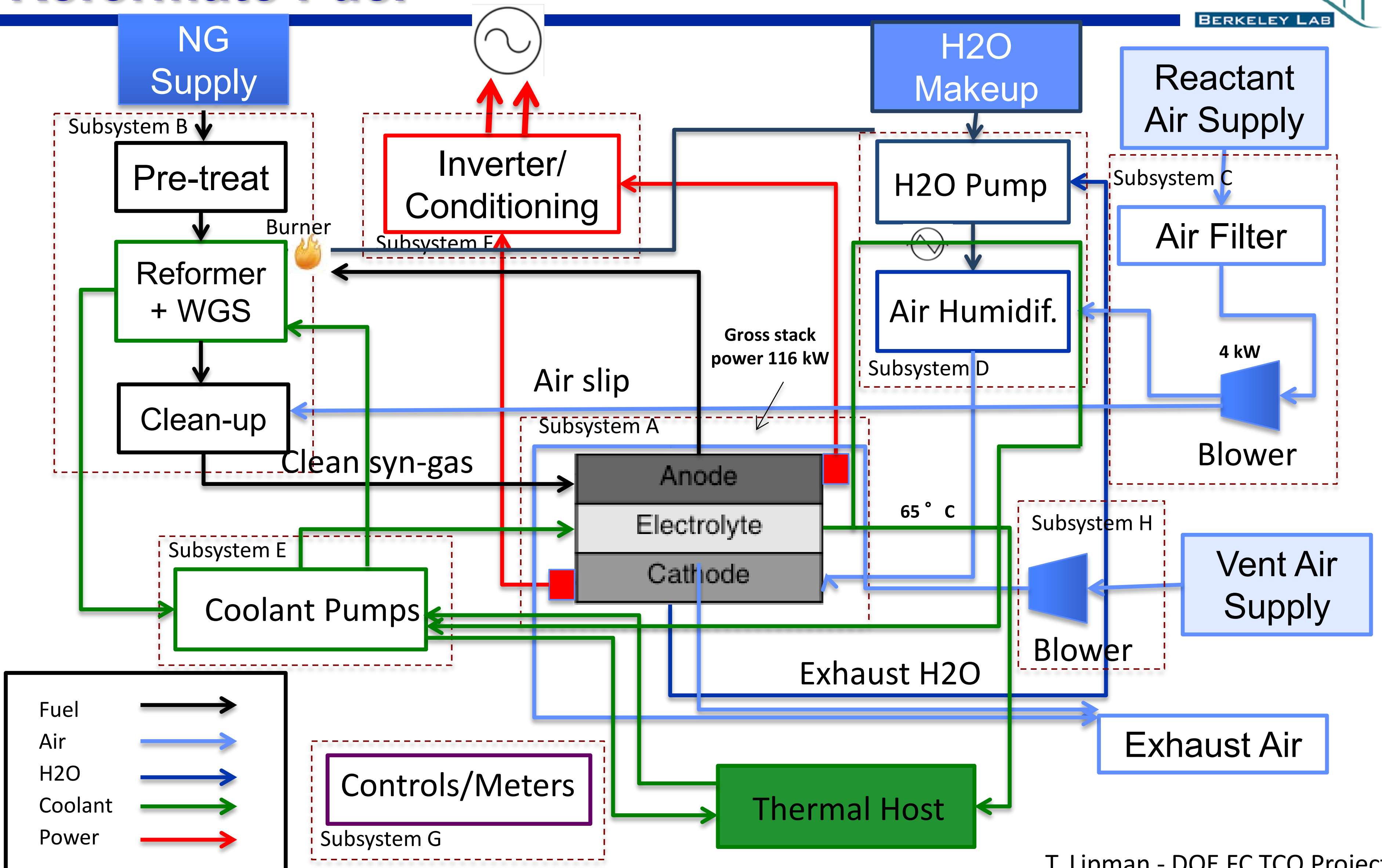
Daily hot water load profiles for small hotel in AZ

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



PEM AND SOFC FC SYSTEM DIRECT MANUFACTURING COSTS

100 kW PEM Stationary (CHP) Reformate Fuel



T. Lipman - DOE FC TCO Project

PEM 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

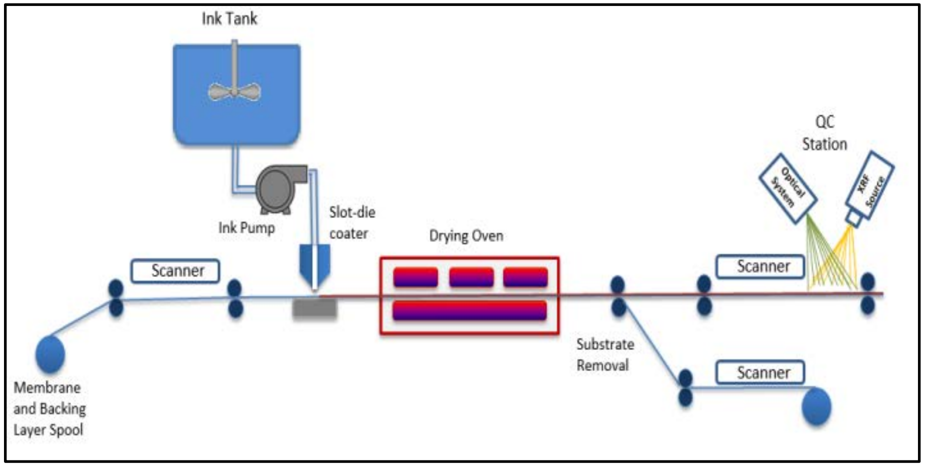
*Full DFMA Costing analysis was performed

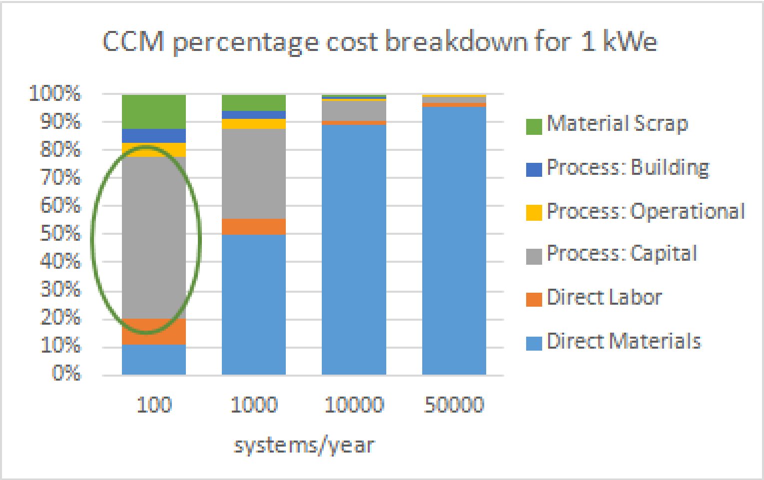
Functional specs for 100kW CHP system operating with reformate fuel, 0.5mg/cm^2 Pt

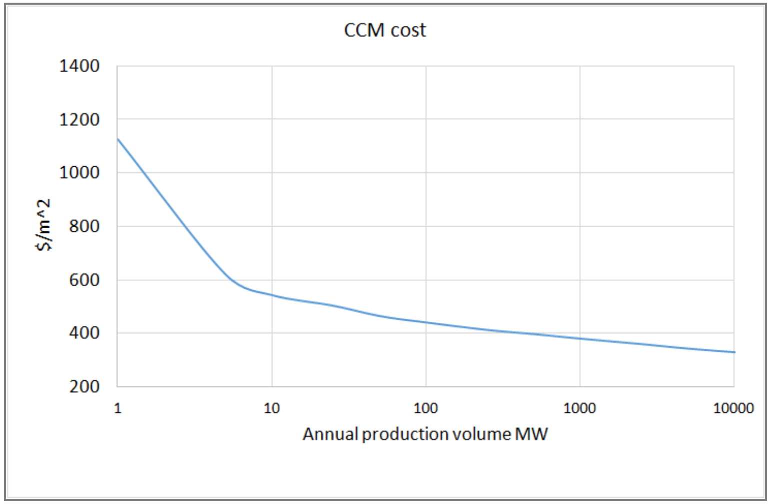
Parameter	Value	Unit
Gross system power	124	kW
Net system power	100	kW
Electrical output	480V AC	Volts AC or DC
Waste heat grade	65	Temp. °C
Fuel utilization	80-95	%
Avg. System Net Electrical efficiency	32	% LHV
Thermal efficiency	51	% LHV
Total efficiency	83	Elect.+thermal (%)
Stack power	9.5	kW
Total 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

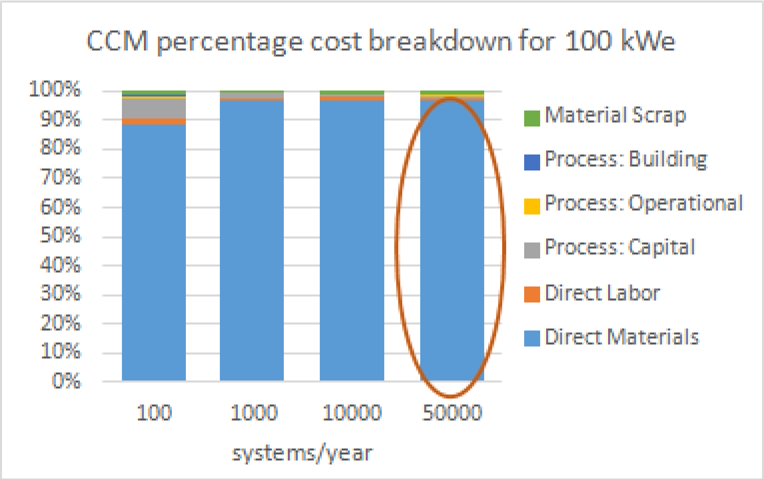
Manufacturing Cost Model – CCM, Metal Plates

CCM Process Flow-Cathode Coating Line



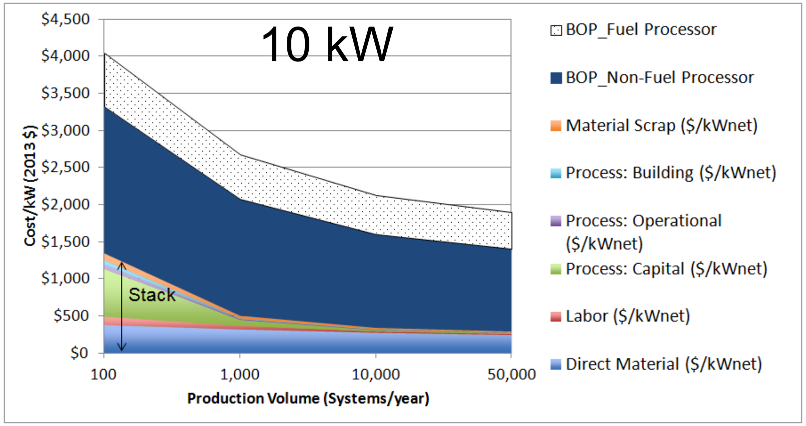


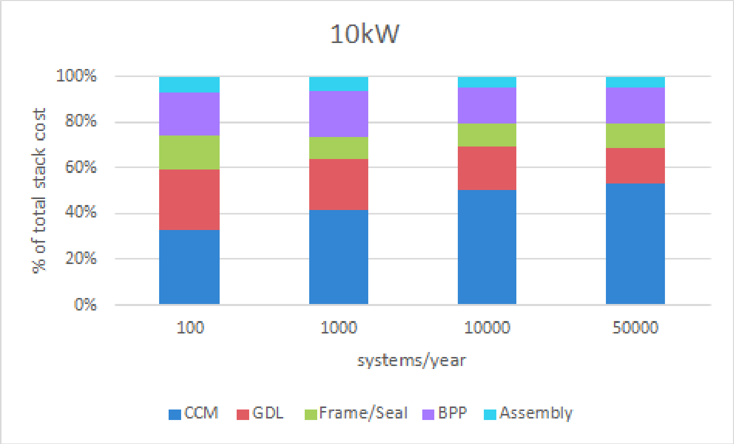


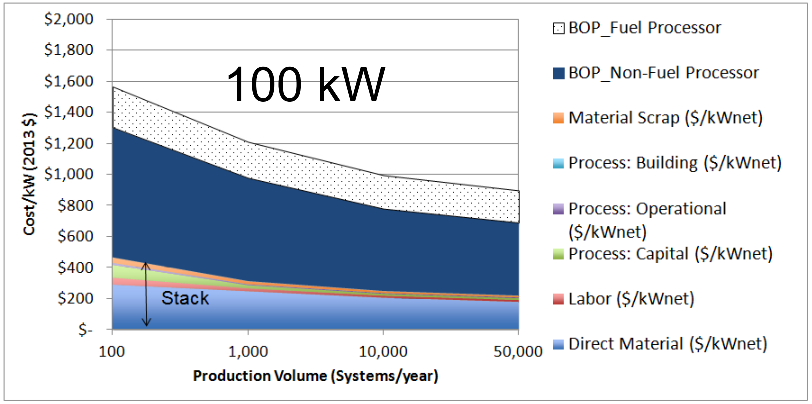


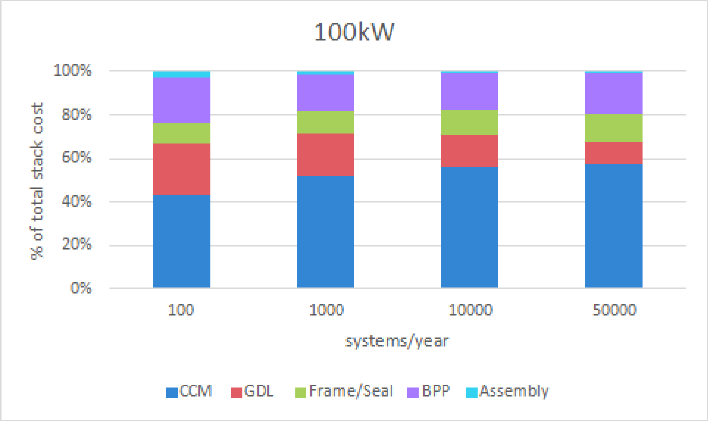
System Cost for 10/100kW CHP LTPEM

- Stack cost dominated by CCM then GDL and plate
- BOP_Non-FP and BOP_Fuel processor are 70%-85% of overall cost
- System direct cost < $900/kW at high volumes



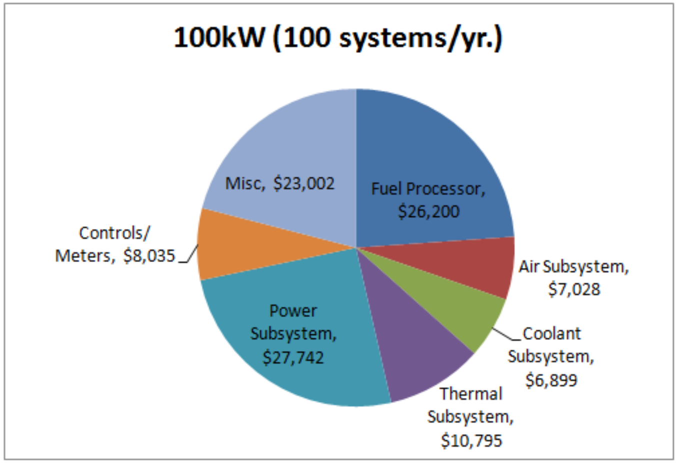


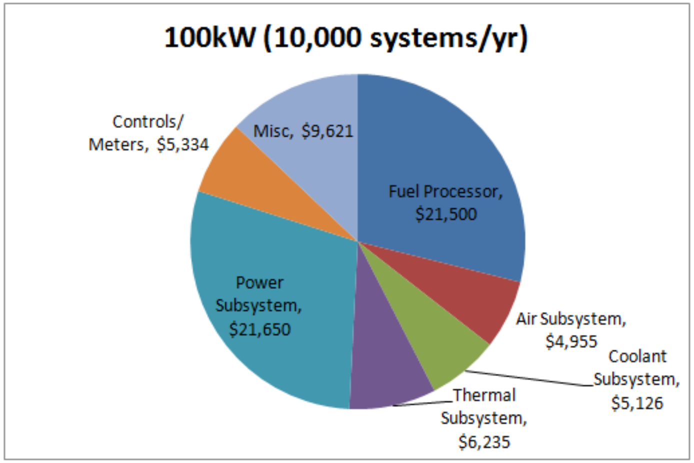


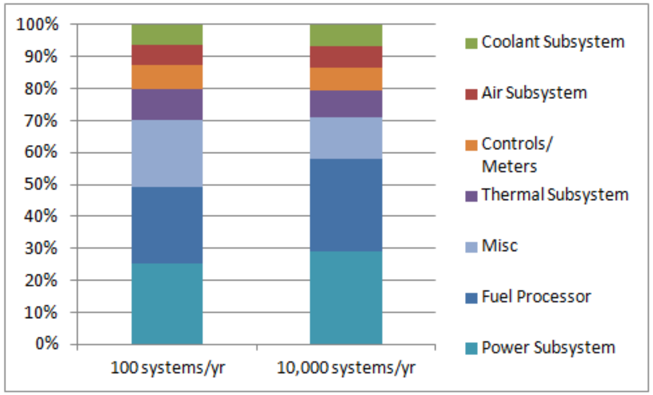


PEM BOP Components Cost Breakdown

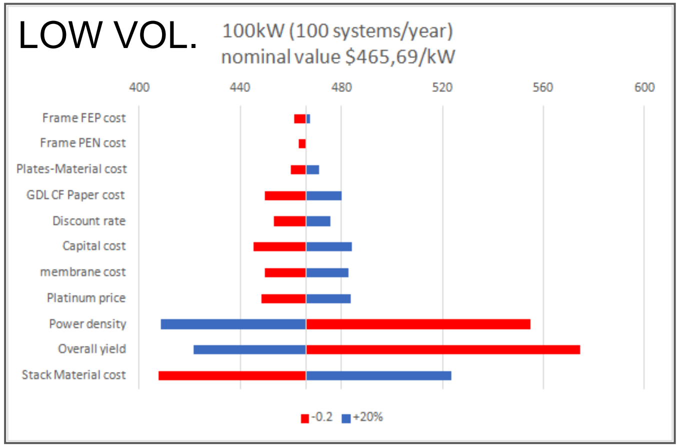
- **Balance of plant: about 27% power subsystem, 26% fuel processing, 17% misc.**

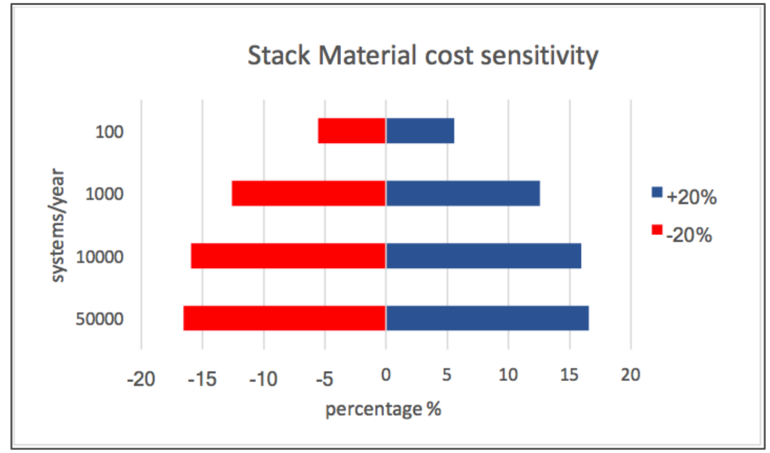


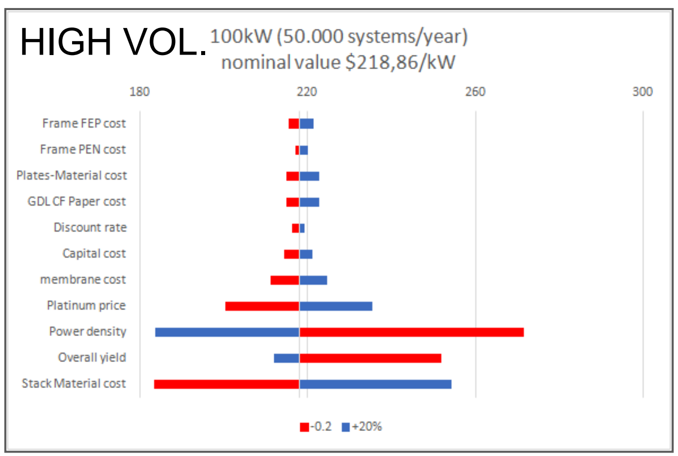


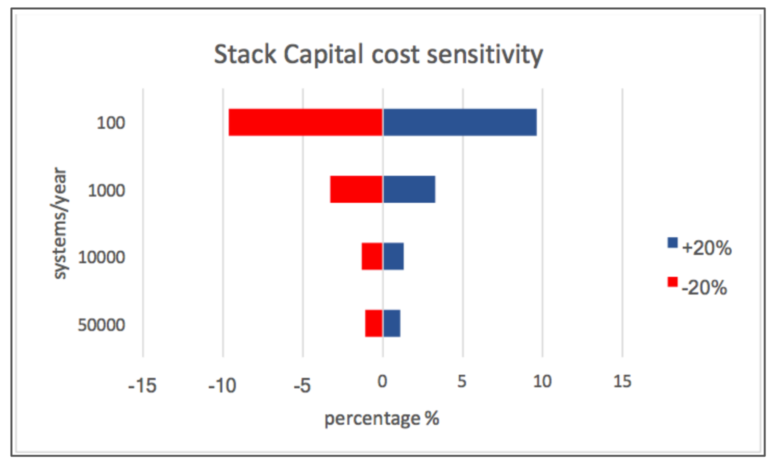


LT PEM Stack Cost Sensitivity



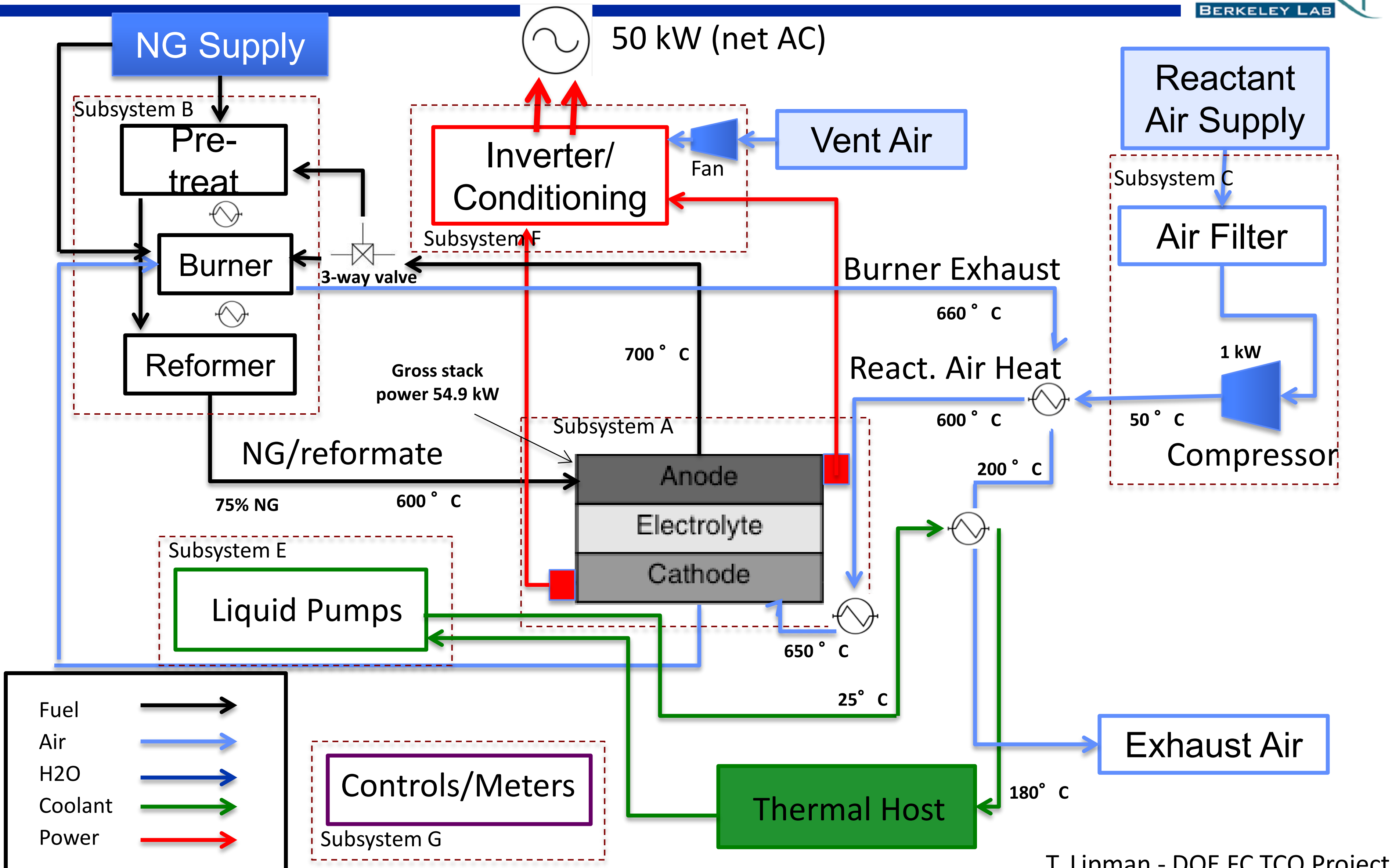






- Process yield and Power density dominate the cost sensitivity at all production levels
- Stack material cost more at high production volumes
- Stack capital cost less sensitive at high production volumes

50 kW SOFC CHP System with Reformate Fuel



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SOFC 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

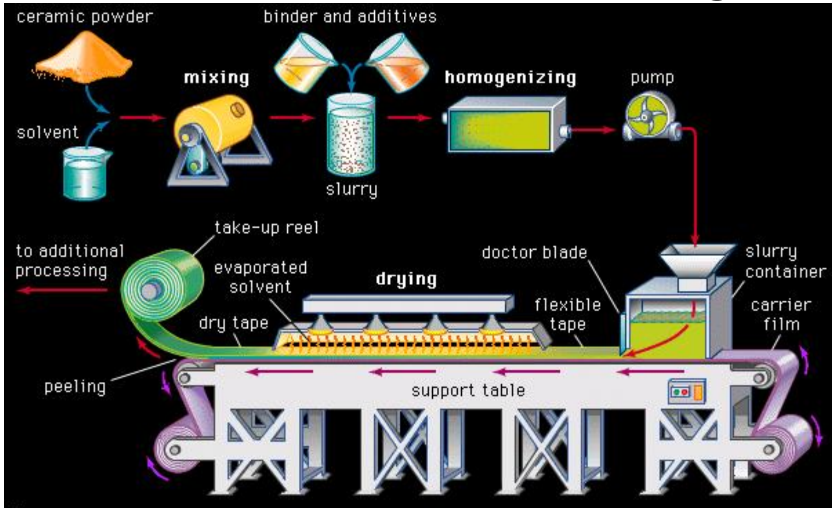
*Full DFMA Costing analysis was performed

Functional Specs 50kW CHP with Reformate Fuel

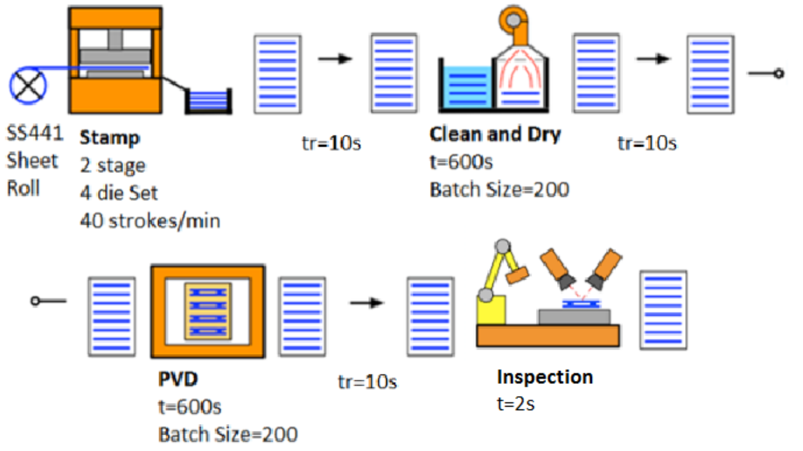
50 kW Size		Best. Ests.		Source
	Unique Properties:		Units:	
System	Gross system power	54.9	kW DC	
	Net system power	50	kW AC	
	Physical size	2x3x3	meter x meter x meter	Based on Bloom ES-5700 - Not incl. CHP eqpt
	Physical weight	3600	kg	Based on Bloom ES-5700 - Not incl. CHP eqpt
	Electrical output	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	

Manufacturing Cost Model – EEA, Metal Plates

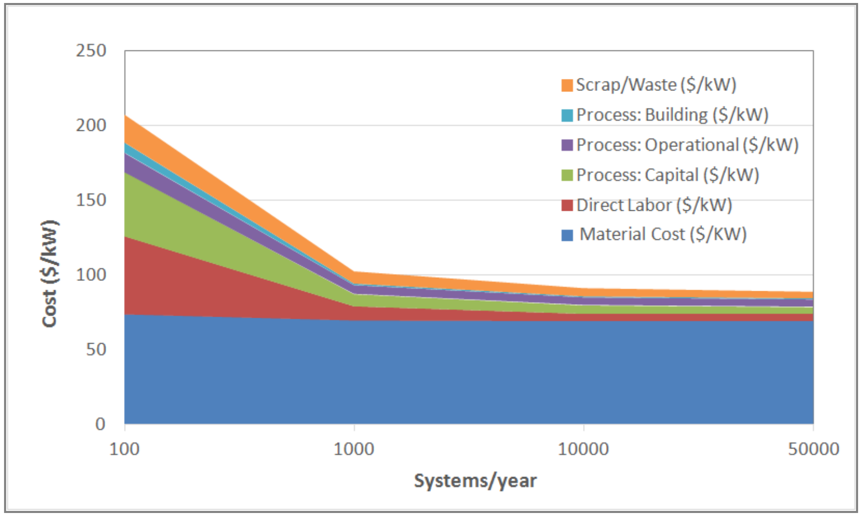
EEA Process Flow-Cathode Coating Line



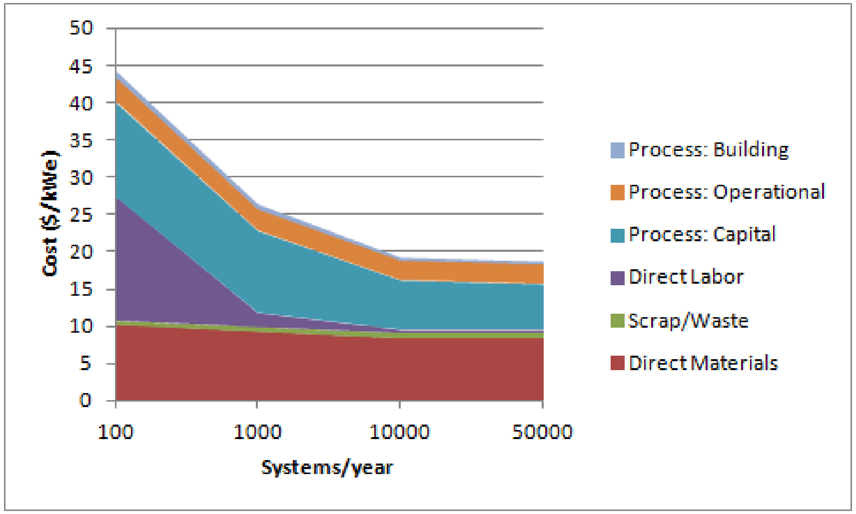
Metal Plate Process Flow



EEA Cost Plot - 100kW System

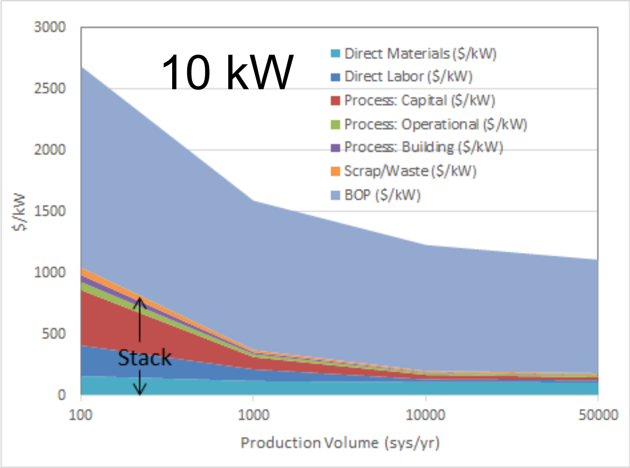


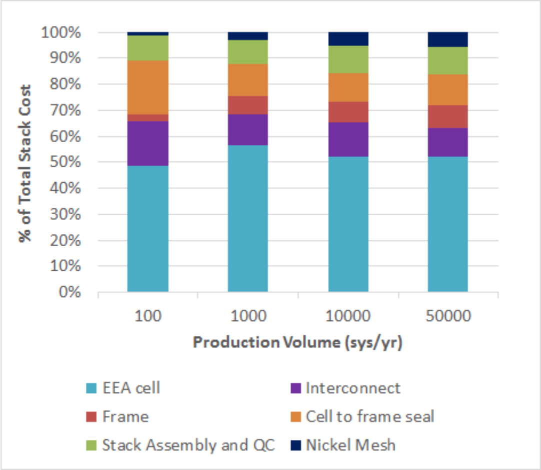
Plates Cost Plot - 100kW System

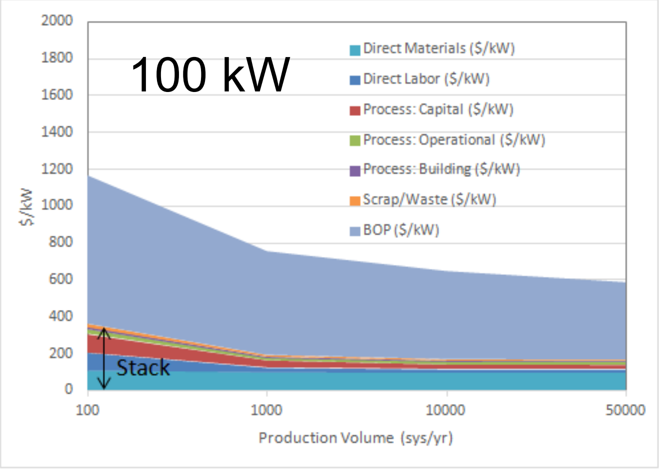


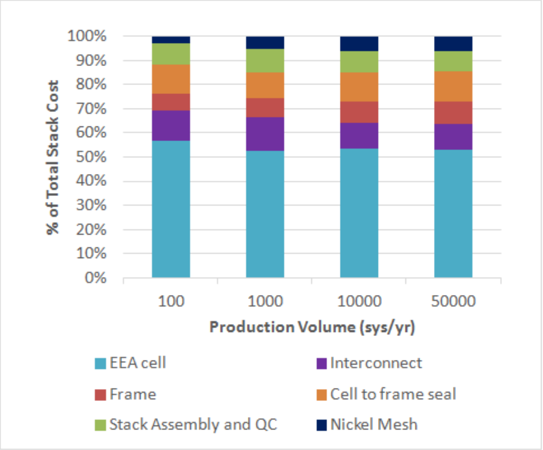
System Cost for 10/100kW CHP SOFC

- Stack cost dominated by EEA then seal/frame at high volumes
- BOP are 60%-85% of overall cost
- System direct cost < $600/kW at high volumes



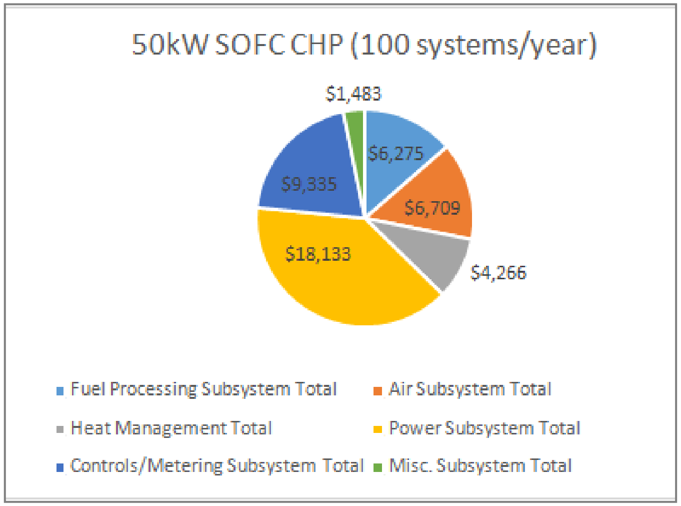


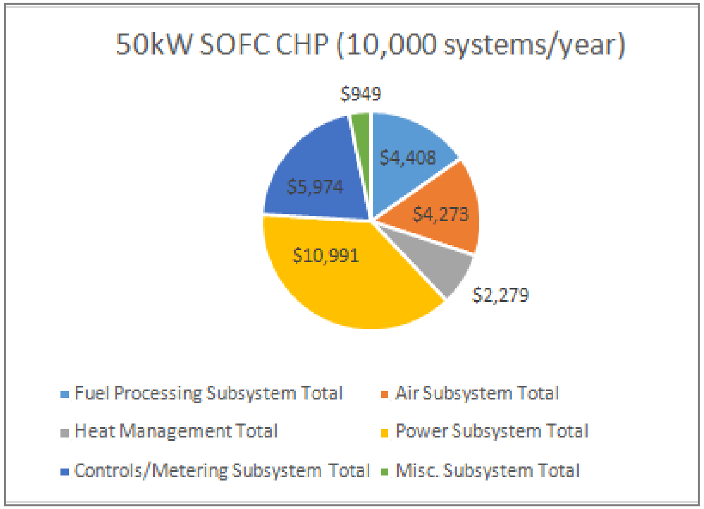


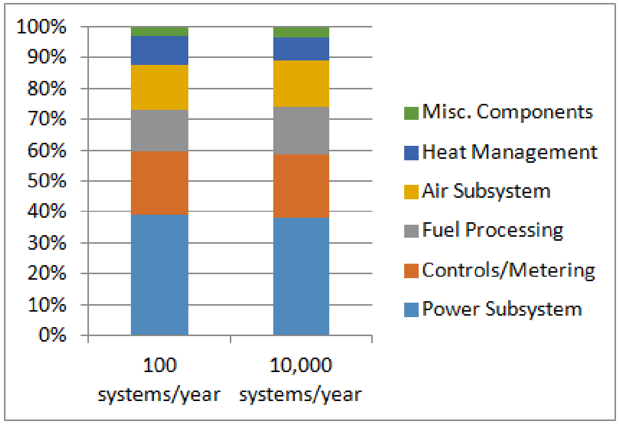


SOFC BOP Components Cost Breakdown

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





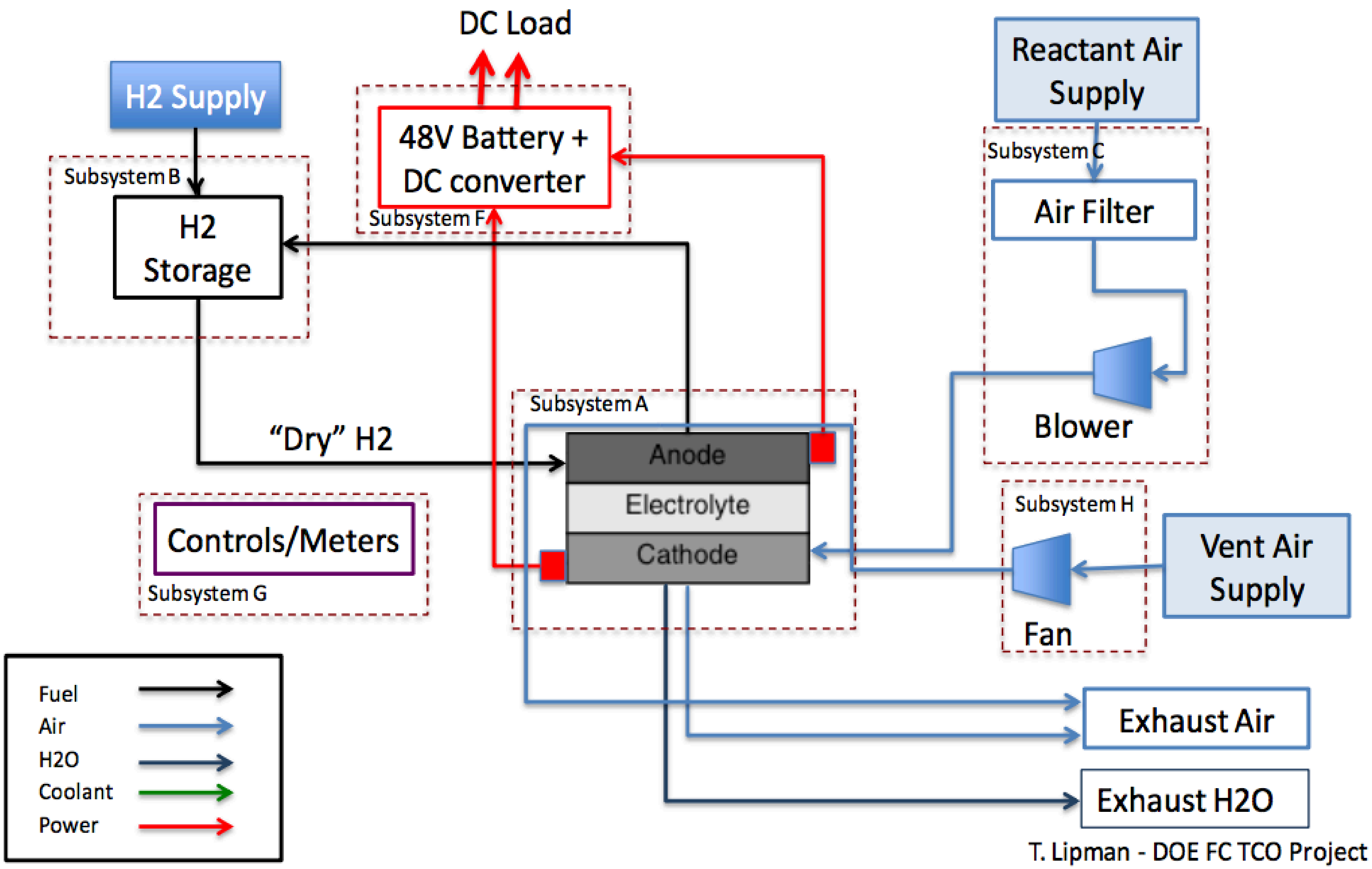


CHP System Equipment Cost Estimates vs. DOE Targets

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			
10kW CHP System	50,000	$1,700	$1,900	**$2,850**	$1,100	**$1650**
100kW CHP System	1000	$1000	$1,200	**$1,800**	$760	**$1140**

10 kW SOFC system meeting 2020 DOE target at high volume

PEM Backup System Design with H2 Fuel

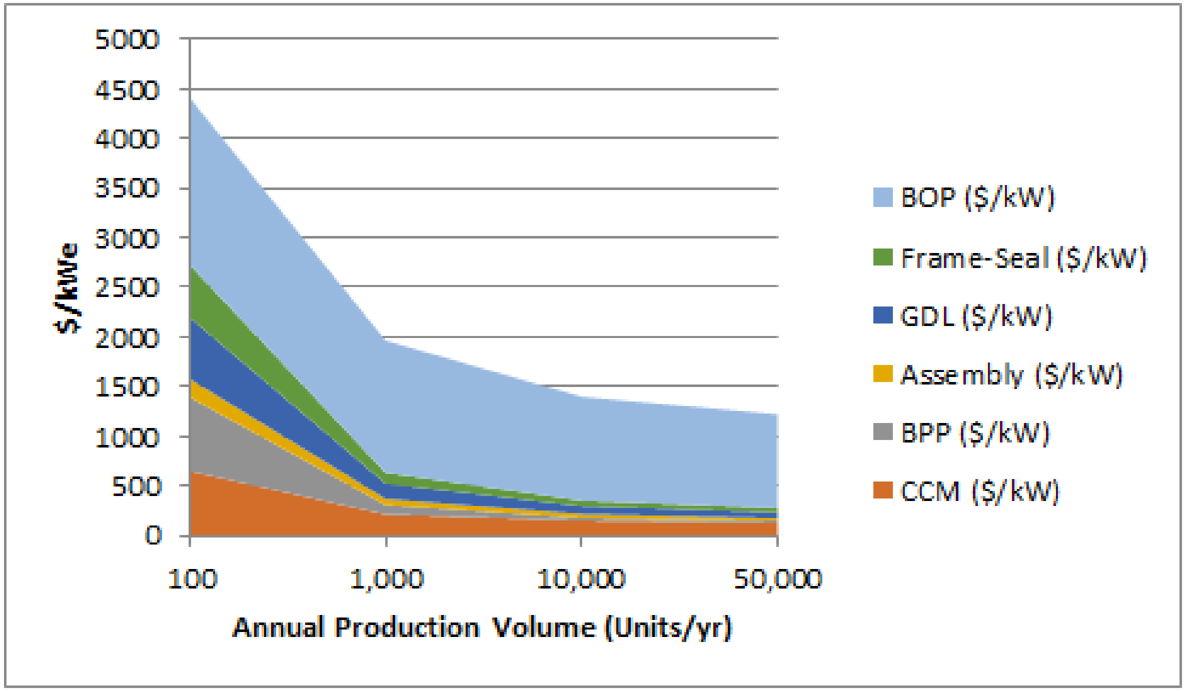


PEM Backup Function Specs and Direct Cost

Functional Specifications

5 kW		
Unique Properties:		Units:
Gross system power	5.20	kW
Net system power	5	kW (AC)
total plate area	360	cm^2
CCM coated area	306	cm^2
single cell active area	285	cm^2
gross cell inactive area	21	%
cell amps	116	A
current density	0.405	A/ cm^2
reference voltage	0.650	V
power density	0.263	W/ cm^2
single cell power	75.4	W
cells per stack	69	cells
percent active cells	100	%
stacks per system	1	stacks
Compressor/blower	0.025	kW
Other paras. loads	0.025	kW
Parasitic loss	0.05	kW

5kW System Direct Manufacturing Cost

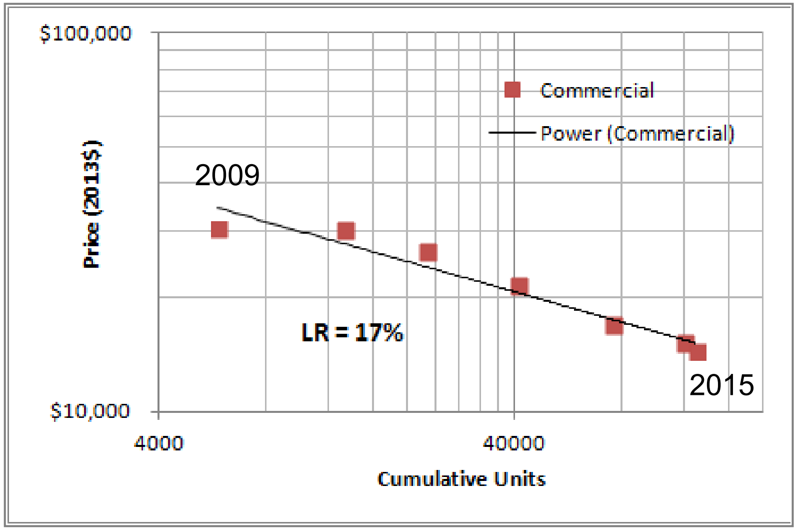


COST COMPARISONS TO MARKET DATA AND OTHER MODELS

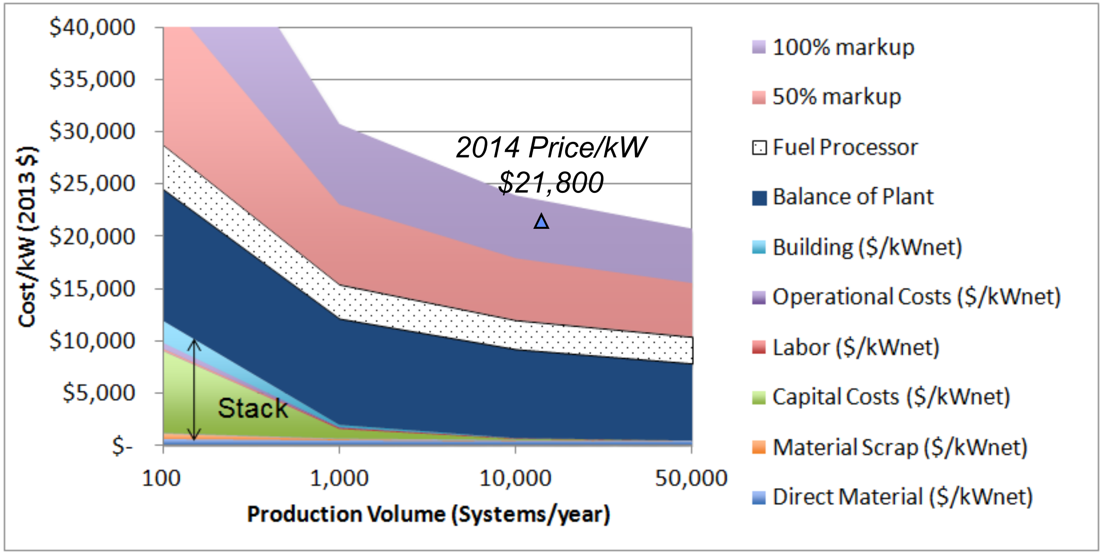
Japan Micro CHP (LT PEM) – LBNL cost modeling can help disaggregate cost reductions

- 17% Learning curve from 2009-2014, nominal 0.7kW system
- 50% cost reduction observed from 2009 to 2014

LEARNING CURVE (2009-2015)



LBNL DIRECT COST MODEL



- LBNL Cost model implies about 23% cost reduction from economies of scale (estimate ~1300 units/yr, 2009 to about 20,000 units/yr in 2014)
- About 19% cost reduction estimated based on publically announced design and performance improvements; about 20% cost reduction attributed to other factors.
- These three factors give the observed 50% cost reduction from 2009-2013.

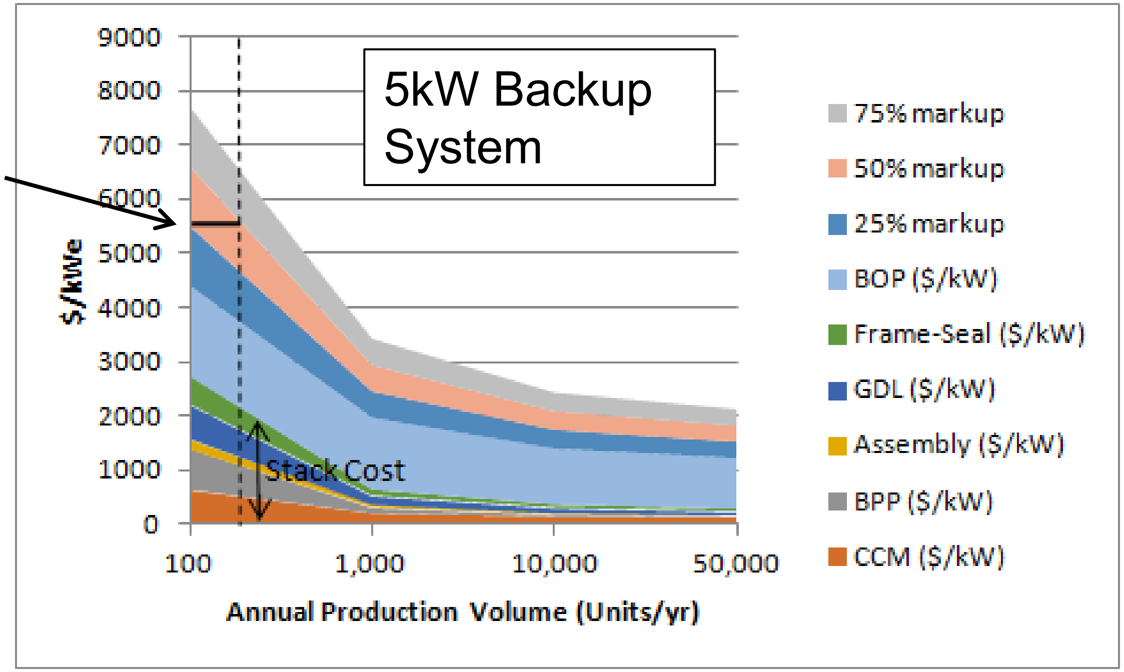
Cost Modeling Comparison –10kW Low Temp. PEM CHP

Source	Year	System Size and Annual Production Volume	Pt Loading (mg/cm^2)	Stack Direct Manufacturing Cost ($/kW)	Yield	CHP Direct System Cost ($/kW)
Manhattan Project	2011	10kW, 5000 units/yr.	0.5	$850 $480	60% 80%	Na
Strategic Analysis	2012	10kW, 5000 units/yr.	0.4	$370	99%	~$2100
This Work	2016	10kW, 5000 units/yr.	0.5	$860 $600 $450	60% 80% 99%	$2800 $2550 $2400

FC Backup Power Capital Cost vs. Price Quote in NREL 2014 Report

- **5kW system cost model ~$6000/kW at low production volume comparable to capital cost at $5700/kW in NREL 2014**
- **Increasing annual production volume to > 1000 units reduces price about 50%**

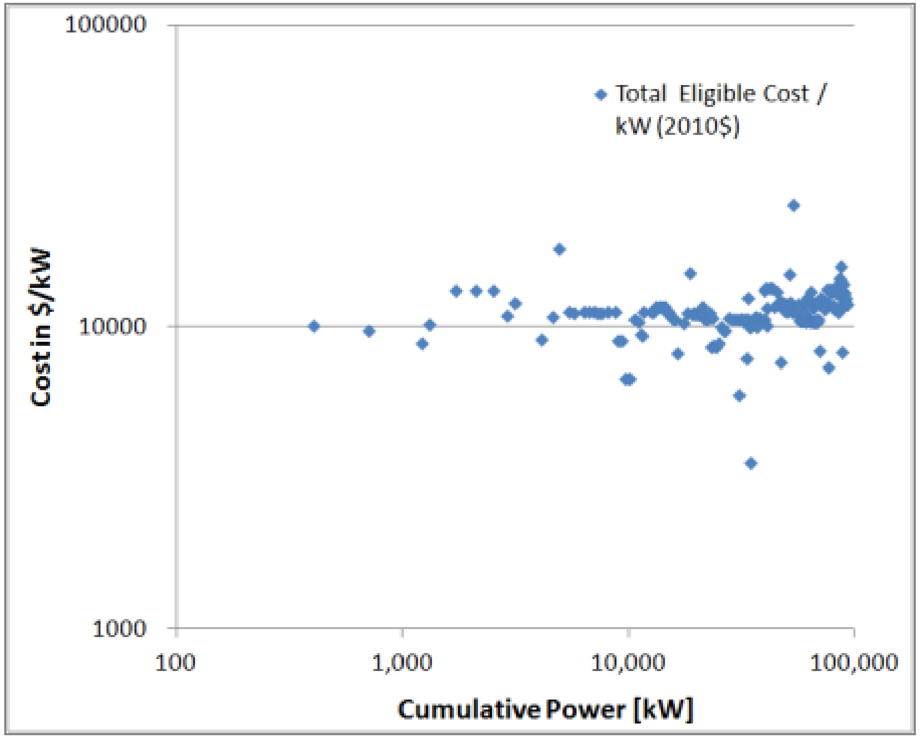
NREL 2014, $5700/kW
Cap. cost at low volume



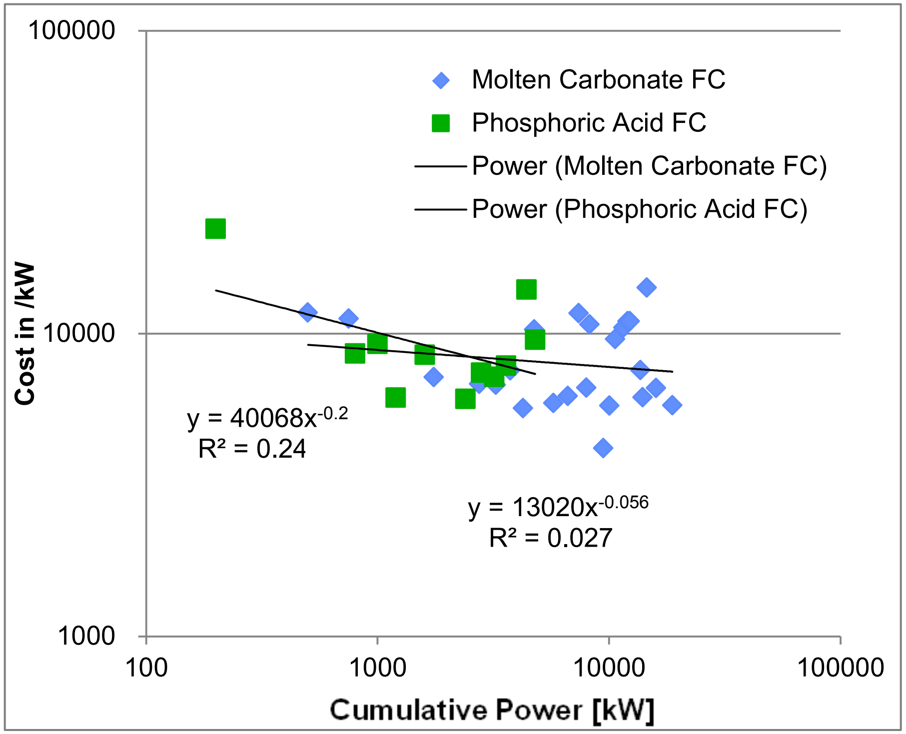
Total system cost data from California Self-Generation Incentive Program (SGIP)

BERKELEY LAB

SOFC Installed Price



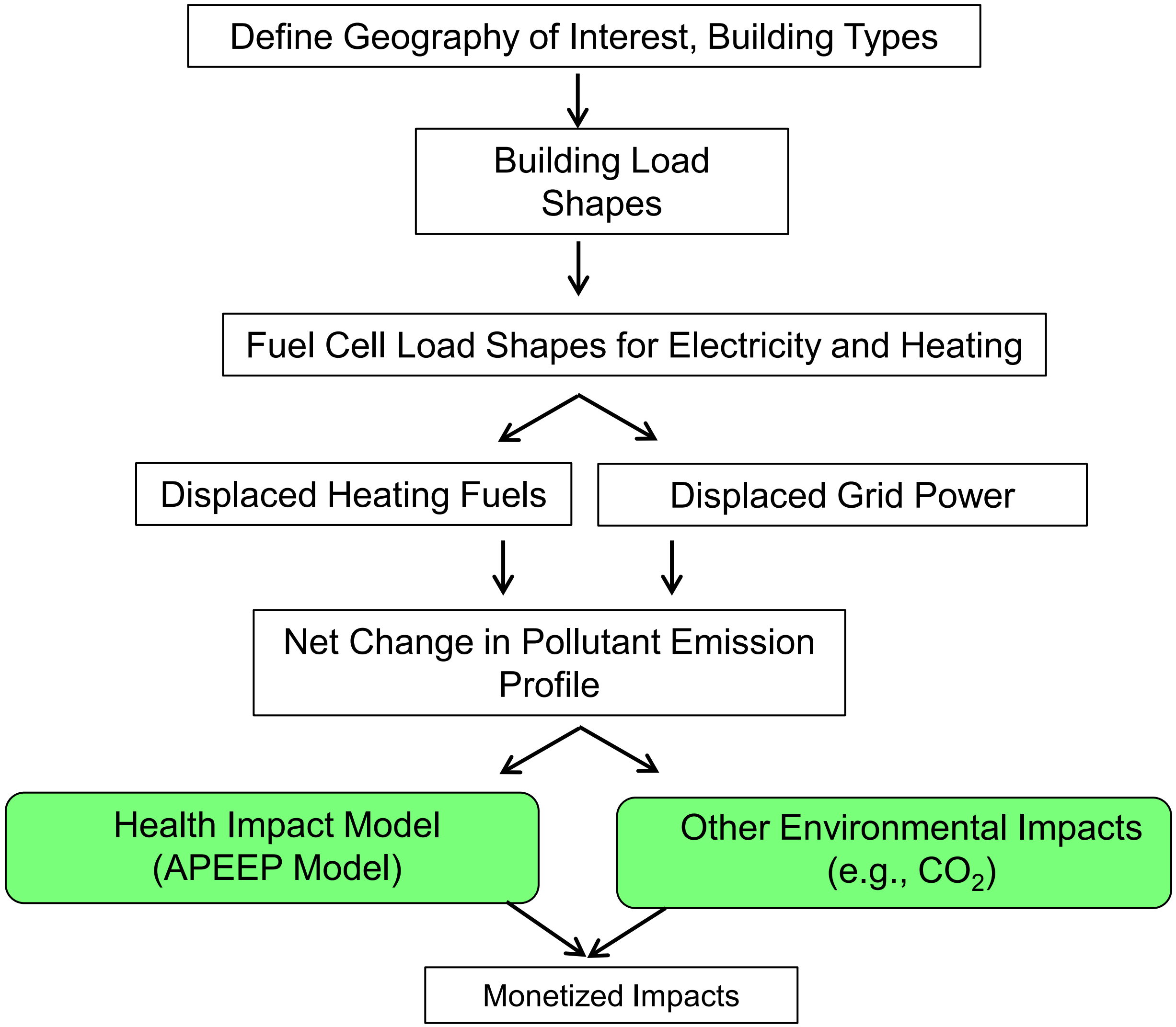
MCFC/ PAFC Installed Price



- Cost reduction not seen in CA SGIP database
- SOFC: Estimate annual volume of hundreds of units per year (40-50kW modules)
  - Difficult to estimate system manufacturing cost without further information
  - Possibly much higher cost than LBNL and other cost models
    - Due to lower automation, lower yield, material costs, “engineering” labor costs?

EXTERNAL VALUATION MODELING

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



Quantifying human health damages

Emissions

Ambient concentration

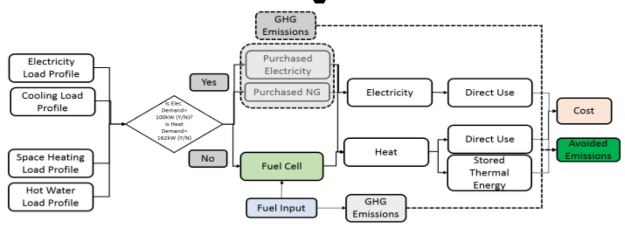
Exposure

Effect

Damages

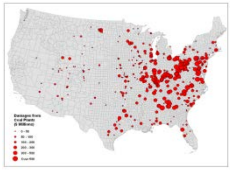
Define geographic boundary of interest

Fuel cell costs & application parameters

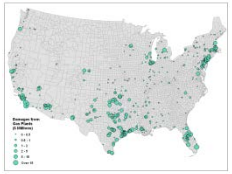


Baseline scenario

Fuel cell scenario



Map changes at power plant and building levels

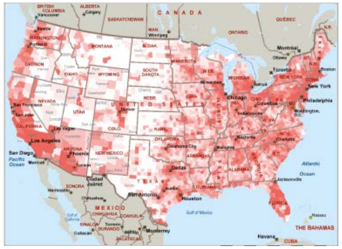


Net emissions = avoided emissions from power plants & building heating + fuel cell system emissions (Δtons/kWh)

Pollutant Emissions Modification

Air quality modeling

Intake fraction



Dose-response

Monetized damages ($/ton)

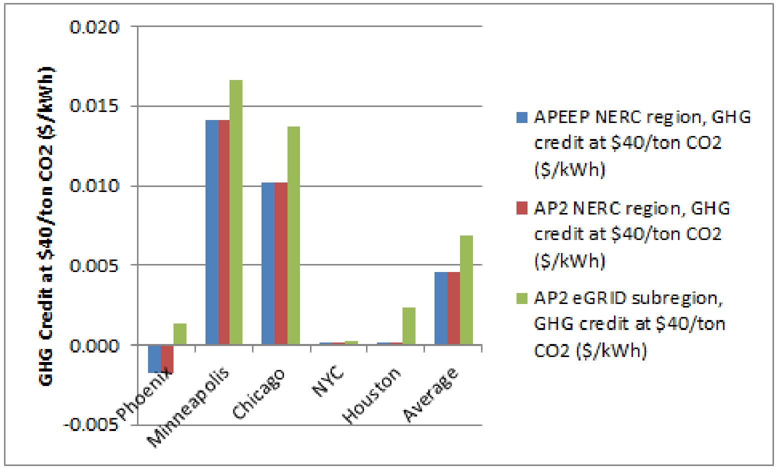
Δtons/kWh x $/ton

➔ $/kWh

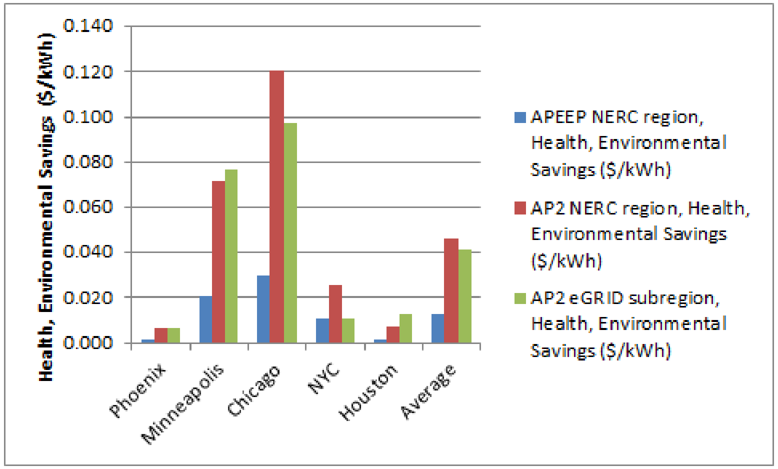
Marginal benefits of abatement valuation from AP2 model and updated eGRID subregion emission factors

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

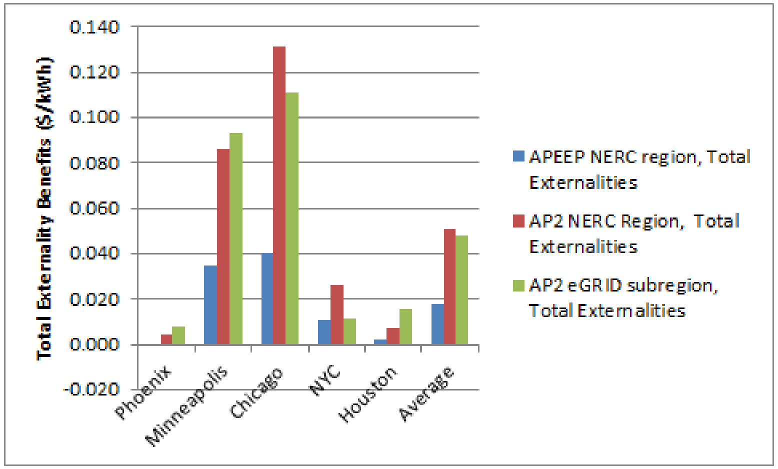
GHG benefits

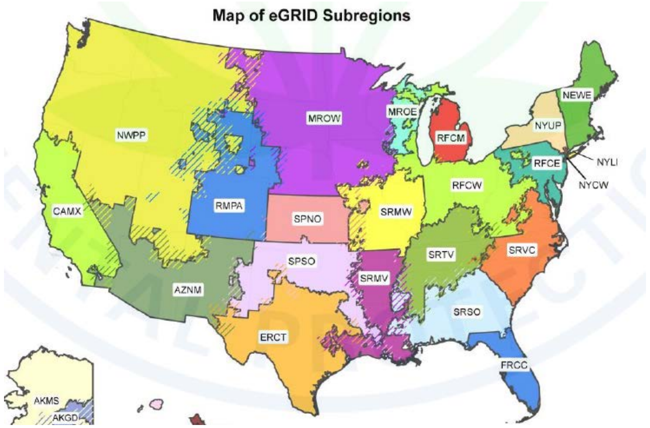


Health and Environmental Savings



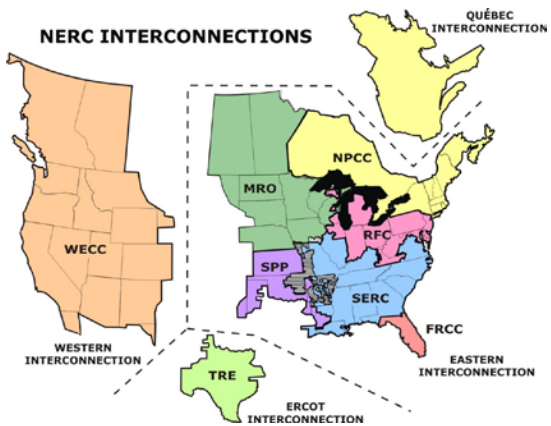
Overall externality benefits

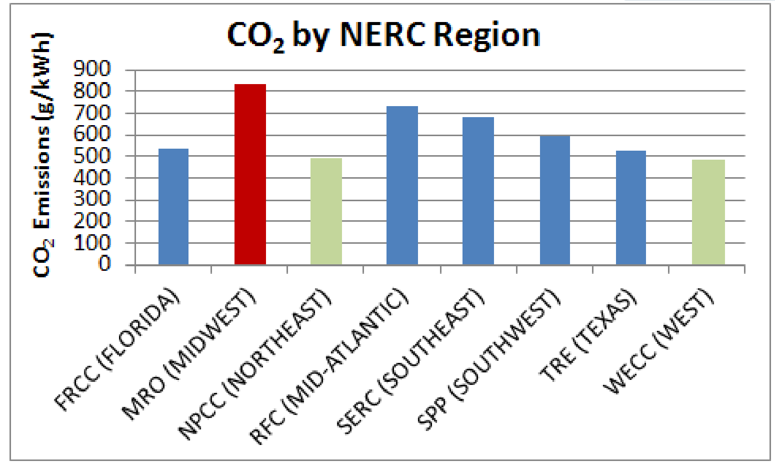




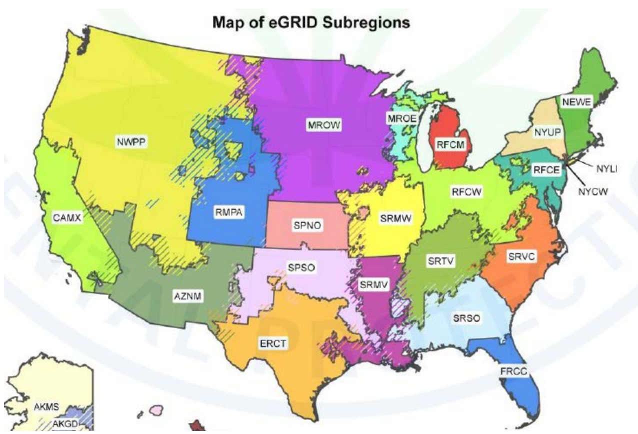
NERC region vs eGRID subregional CO2, criterion pollutant emission rates

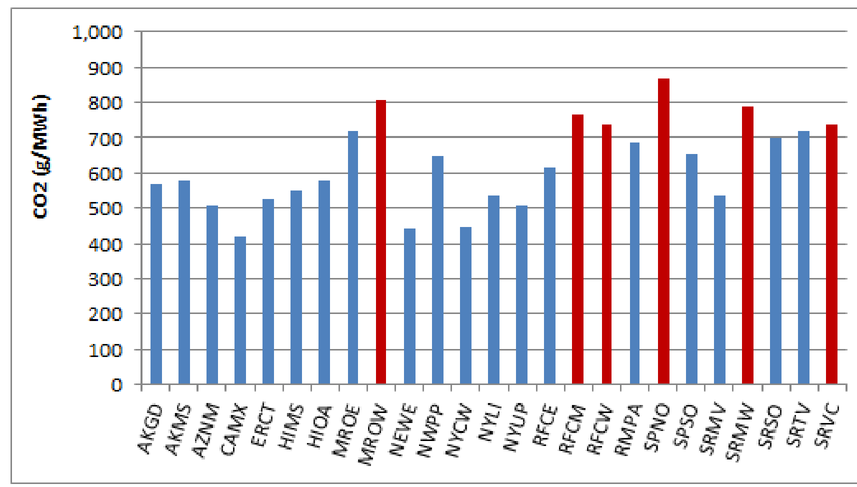
Previous Years:





This year:



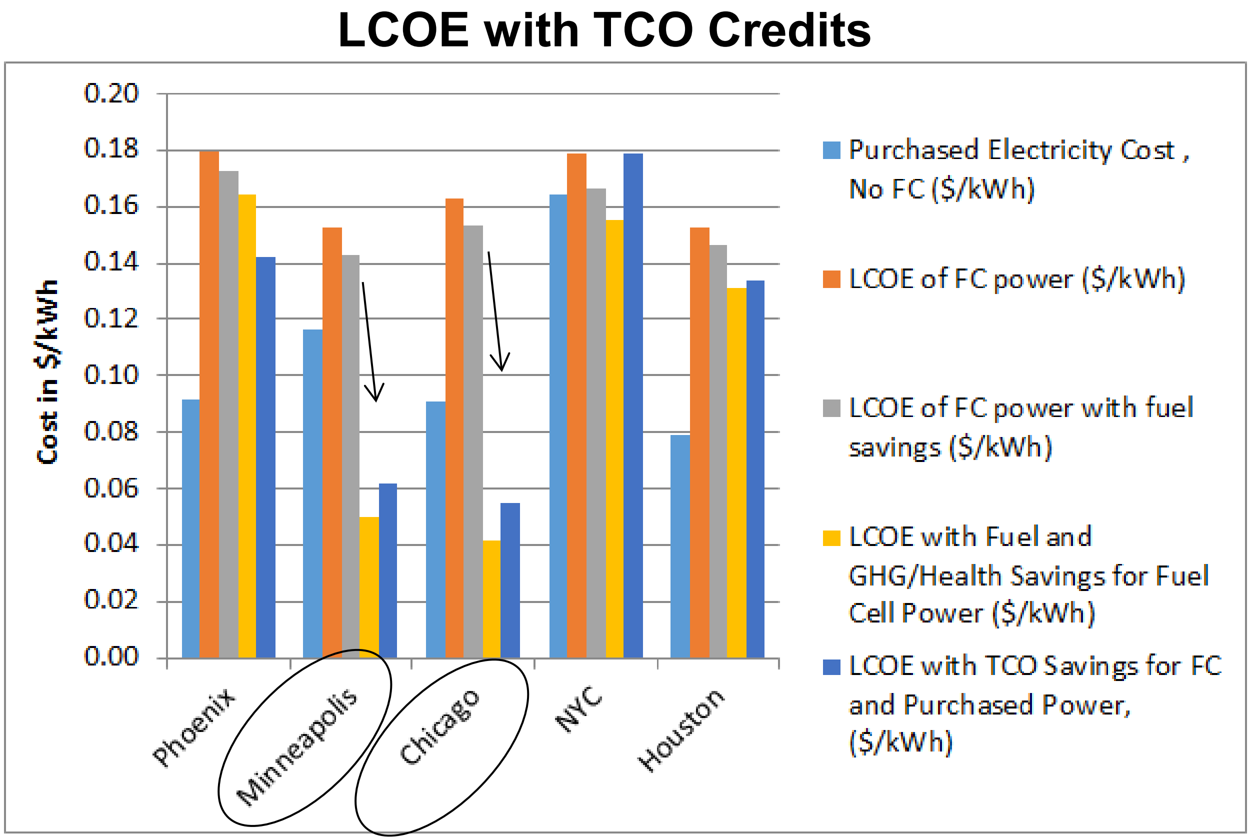


Earlier work used marginal emission factors by NERC region. This year, eGRID subregional emission rates are utilized for improved spatial resolution

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

Levelized cost of electricity with TCO credits

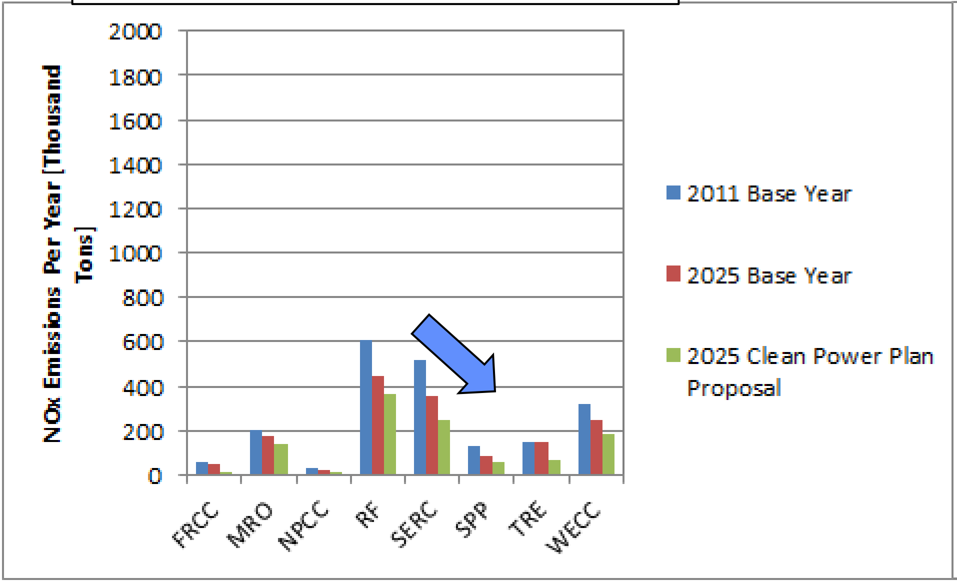
- Example of 50kW LT PEM CHP in hotel at \$2900/kWe installed cost (2000 units annual production)



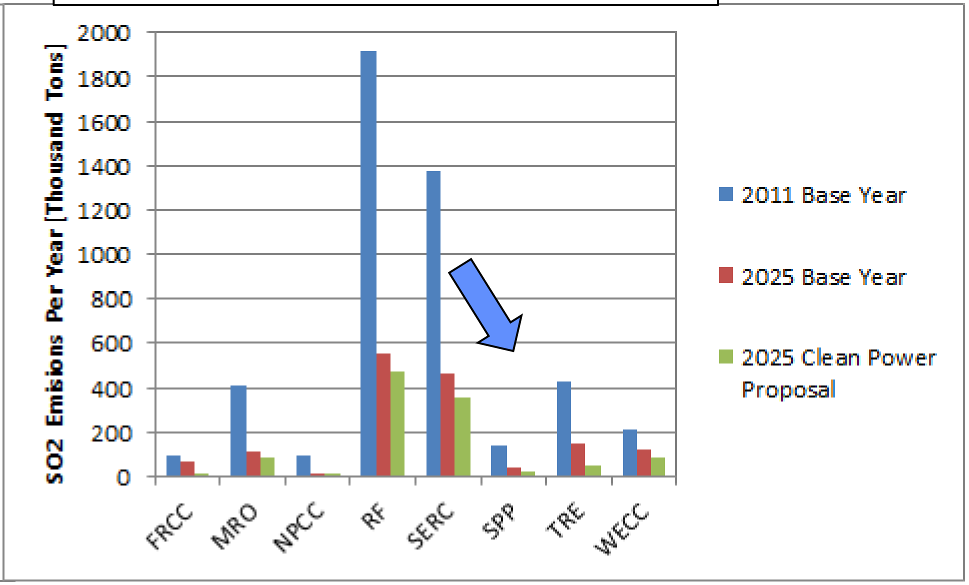
EPA Clean Power Plan to 2030 – Cleaner grid electricity will reduce benefits from fuel cell CHP

- CPP: Improve emissions from coal plants and shift from coal to natural gas
  Build more renewable sources of electricity
- How will these changes impact the externality benefits of fuel cell CHP?
  (Previous slide was for 2012 base year)

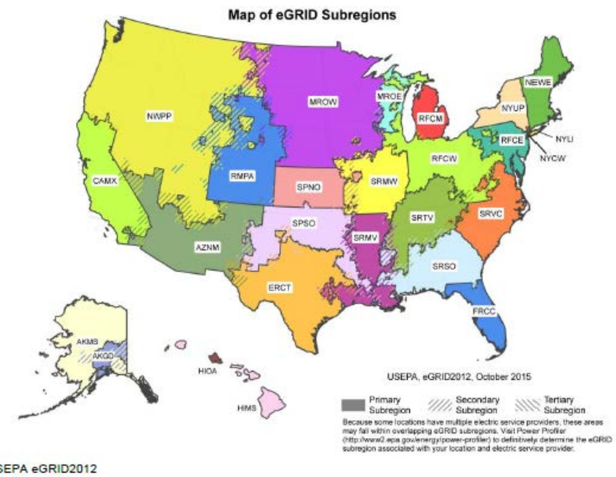
NOX average reduction 50% 2011-2025 in Criteria Pollutant regulations



SO2 average reduction 80% 2011-2025 in Criteria Pollutant regulations



Estimated Clean Power Plan impacts for six representative regions



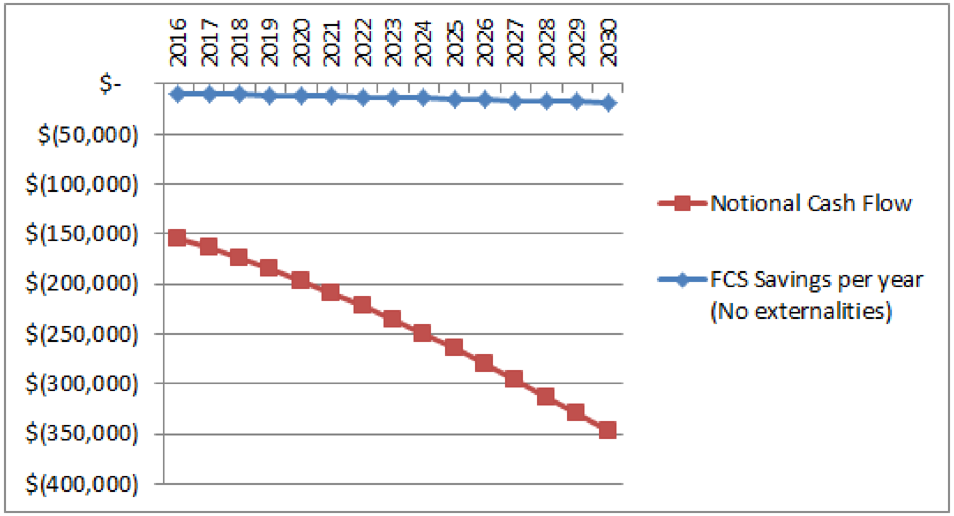
		kg/MWH			kg/MWh			% Reduction 2030 from 2012		
City	EGRID subregion	EGRID for 2012, released 10/15			2030 Projection with Clean Power Plan					
		CO2 AEF eGRID	SO2 AEF eGRID	NOx AEF eGRID	CO2 AEF	SO2 AEF	NOx AEF	CO2	SO2	NOx
Minneap.	MROW	646	1.33	0.73	489	0.25	0.45	24%	81%	38%
NYC	NYCW	316	0.03	0.15	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

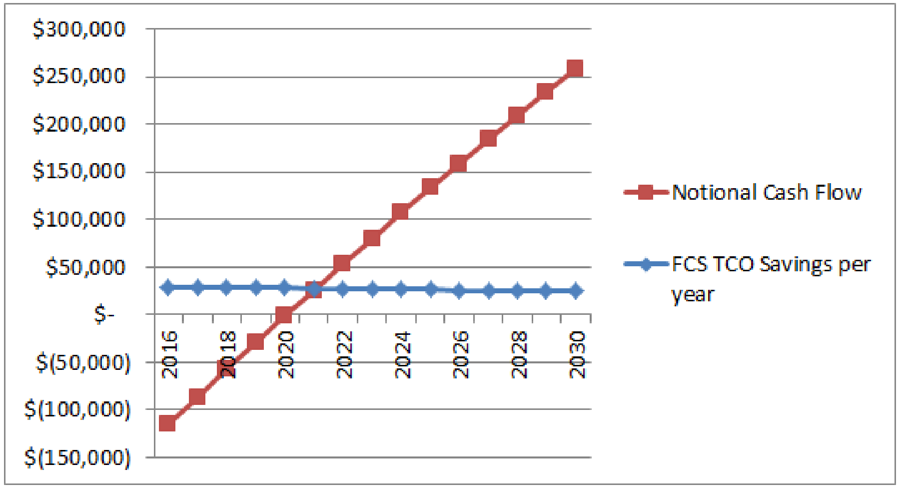
Notational Cash Flow example – Fixed marginal emission factors, escalating social cost of CO2

- **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



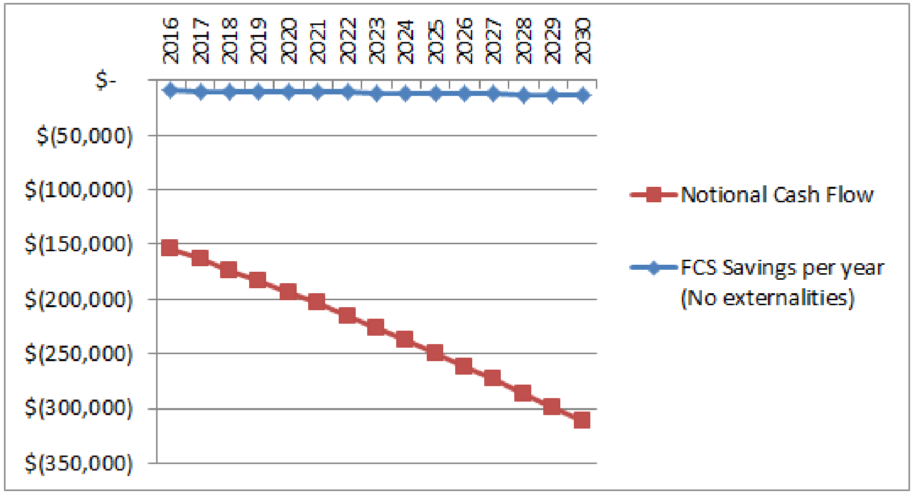
Private costs: Not favorable to owner

For society, cash positive investment

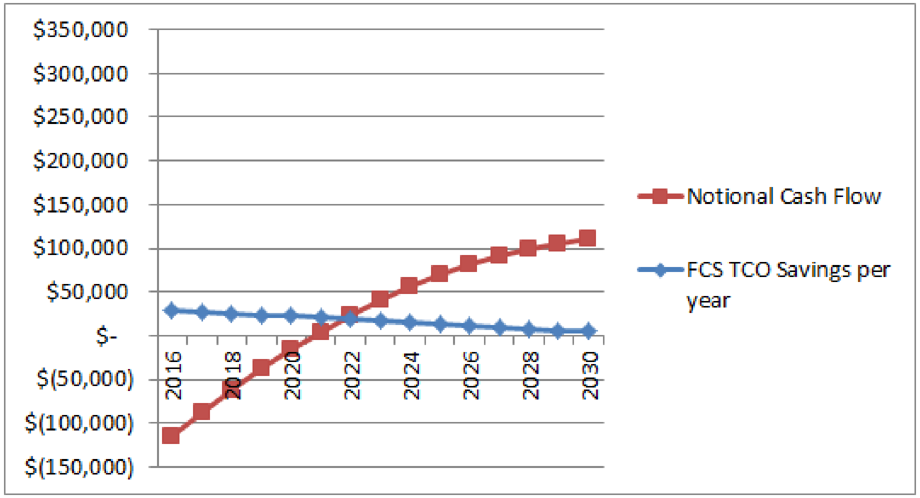
Notional Cash Flow example – reduction in marginal emission factors, escalating social cost of CO2

- **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

Conclusions

- Stack, system costs for PEM to \$220/kW, \$900/kW at hi-volume
- Stack, system costs for SOFC to \$170/kW, \$600/kW at hi-volume
- For CHP systems, BOP costs higher than stack costs for the manufacturing assumptions here
- Modeled price comparisons within range to PEM prices for Japan micro-CHP and backup power, but SOFC harder to compare
- Including externalities, FC CHP economic applicability identified for a subset of commercial buildings in some regions of country with high carbon intensity electricity from grid
- Spatial dependency of externality benefits suggests regional incentives tied to grid electricity and heating fuel type may be appropriate

LT PEM and SOFC Reports online

LT PEM Report (updated report to be posted soon):

- https://eetd.lbl.gov/publications/a-total-cost-of-ownership-model-for-l

SOFC Report:

- http://energy.gov/sites/prod/files/2016/06/f32/fcto_lbnl_total_cost_ownership_sofc_systems.pdf

Acknowledgments

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Thanks also to:

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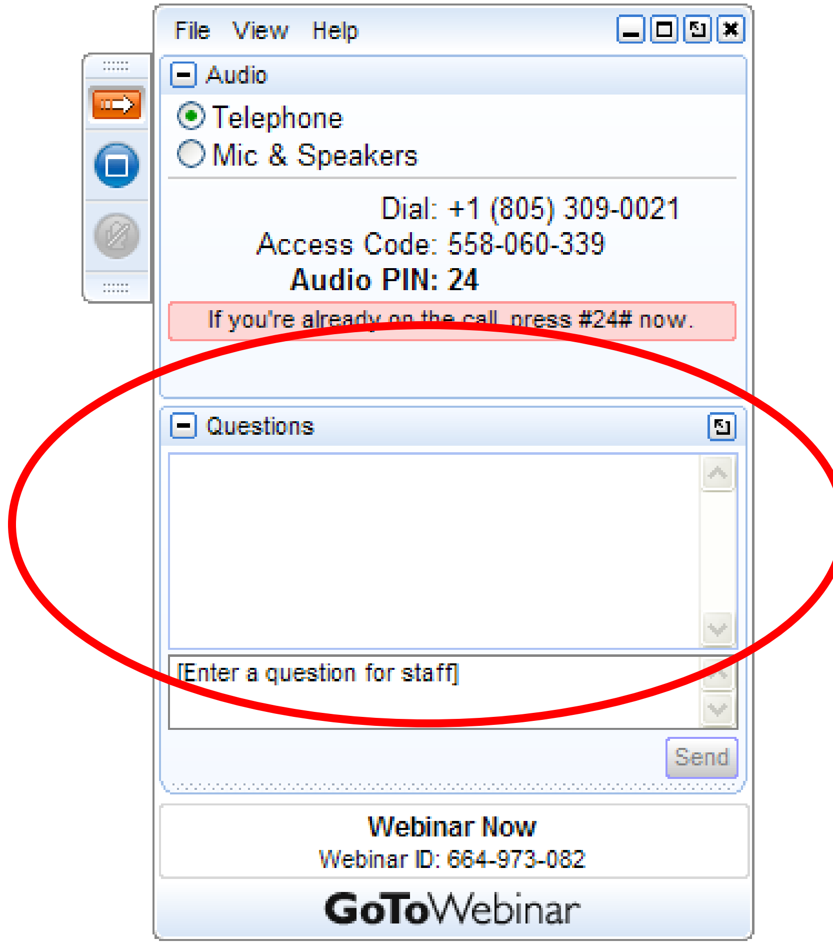
Question and Answer

- **Please type your questions into the question box**



Thank you

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Total Cost of Ownership Modeling for Stationary Fuel Cell Systems

Department of Energy
Fuel Cell Technologies Office Webinar

Washington, D.C.
December 13, 2016

Max Wei (mwei@lbl.gov)

Lawrence Berkeley National Laboratory

Back-Up Slides

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

LABORATORY

SOFC 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

SOFC 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)

SOFC Binders, platicizers, pore formers and solvent prices

Table 4.5. Binders, plasticizers, pore formers and solvents prices

Vendor/Country	Material	Order quantity (kg)	Price ($/kg)	Comments
Jiangsu Xiangcanghongrun Trade Co.,Ltd (China)	N-butyl acetate 99,5%	100	4.34	CIF USA by sea
		1000	1.516	CIF USA by sea
		10000	1.29	CIF USA by sea
ChemPoint Inc (USA)	Methocel A4M	1-45400	18,5-29,6	CIF price
Dowd & Guild, Inc. (CA)	Butvar B-76	63.5	23.37	by rail or truck
		200	21.42	by rail or truck
		500	19.47	by rail or truck
		1000	18.36	by rail or truck
		2000	17.14	by rail or truck
		5000	16.07	by rail or truck
Univar USA	Santicizer 160	Contact Univar USA for a current price quote		
Cancarb Limited (USA)	Thermax® N990 Thermal Carbon Black	Contact Cancarb for a current price quote		
Jinan Shijitongda Chemical Co., Ltd. (China)	2-Butoxyethanol	1000	3.07	CIF USA
		10000	3.07	CIF USA
		100000	2.53	CIF USA
		1000000	2.32	CIF USA
		10000000	2.29	CIF USA

CIF = price including cost, insurance and freight

SOFC Yield Assumptions Updated from 2015

Process Yield assumptions for 2015 AMR

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

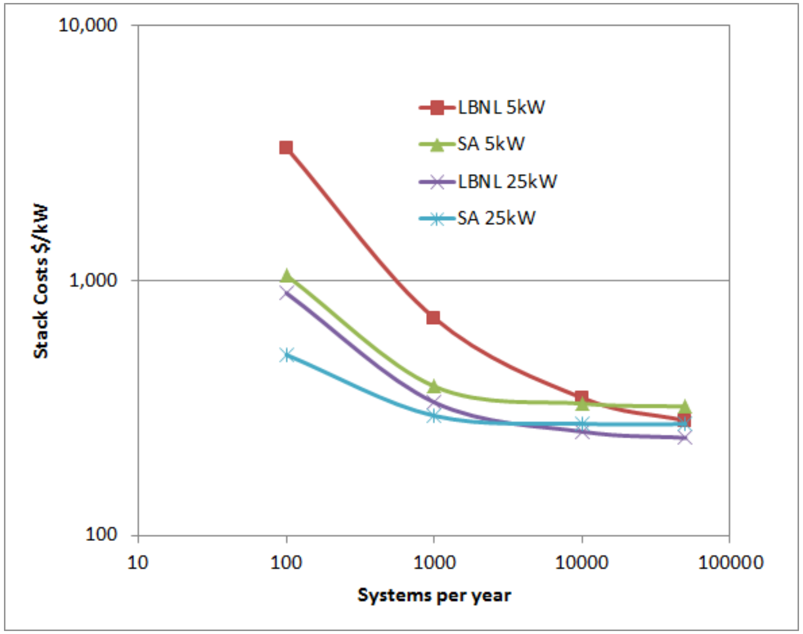
Power	Systems/year	Process Yield (%)	Availability (%)	Line Performance (%)
1	100	85.00%	80.00%	89.00%
	1,000	88.00%	80.00%	89.00%
	10,000	91.00%	80.79%	95.00%
	50,000	92.00%	85.79%	95.00%
10	100	88.00%	80.00%	89.00%
	1,000	91.00%	80.79%	95.00%
	10,000	92.00%	88.04%	95.00%
	50,000	93.00%	93.49%	95.00%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

- Versa power reported yield numbers >95% for EEA‡

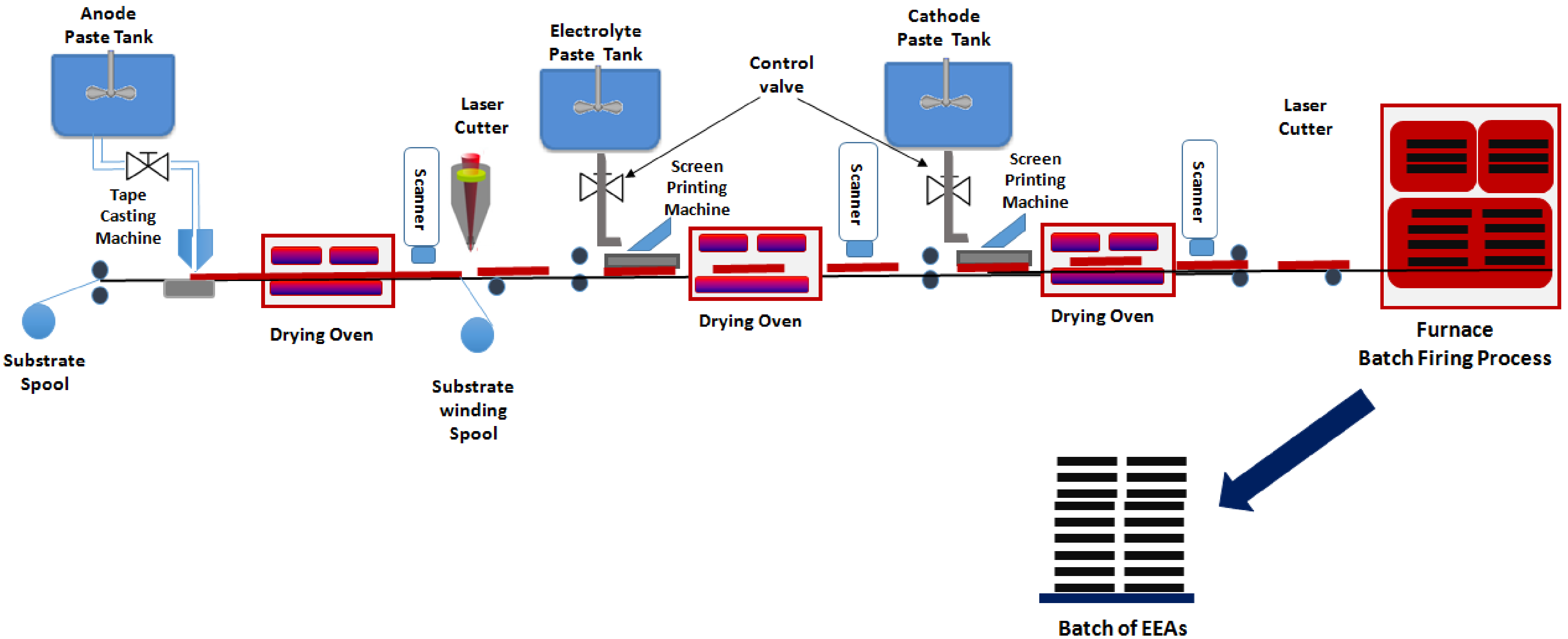
‡ B. P. Borglum. Development of Solid Oxide Fuel Cells at Versa Power Systems. ECS Transactions, 17 (1) 9-13 (2009)

SOFC – LBNL 2015 vs SA 2012

- At higher volume and power levels ≥ 25kW, and annual volume ≥ 1000 units/yr, agreement within 20% and within ~10% at very high volume
- At lower volume LBNL is 2-3X more - due to higher capital costs



Schematic Diagram of EEA Casting Line (SOFC)



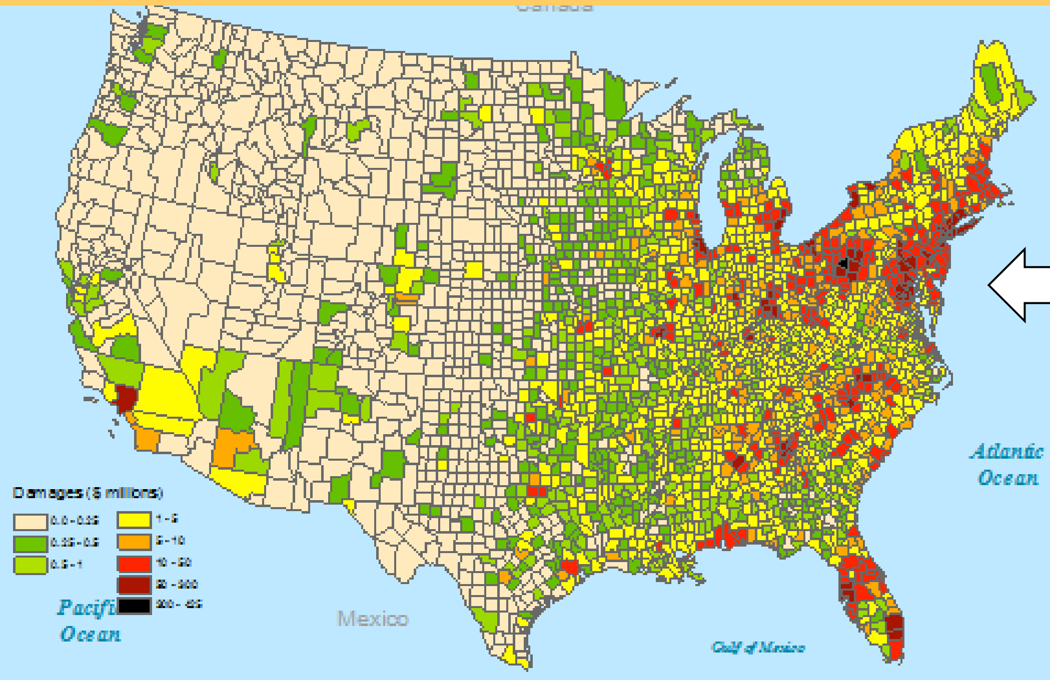
Air Pollution Emissions Experiments and Policy Analysis Model (APEEP and AP2)

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

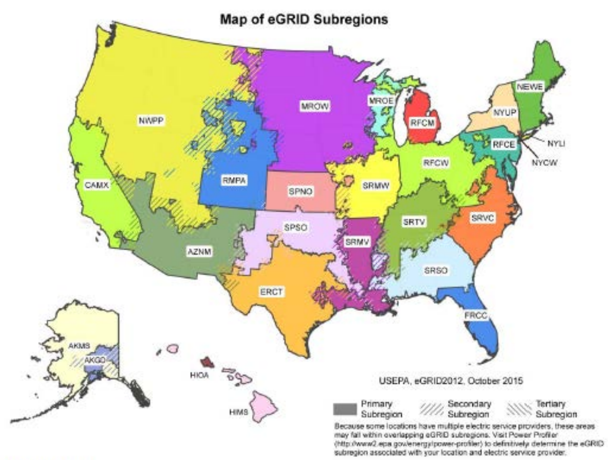


Nicholas Muller

- **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)**

Emission factors, damage functions differ over geographical region

- **From state, subregion, NERC region, to EPA region**



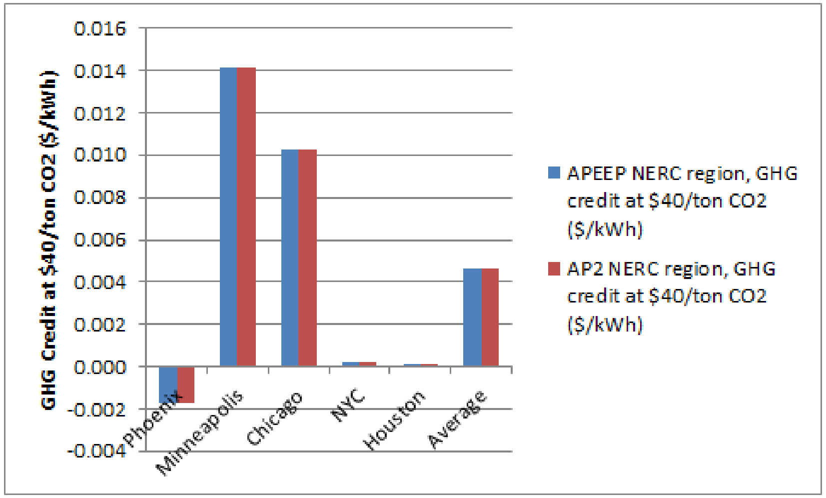
USEPA eGRID2012

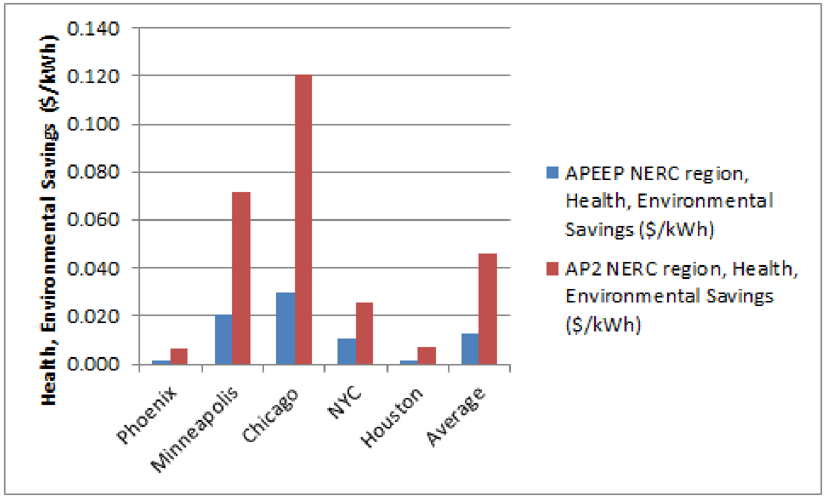
Figure 4A-1. Regional Breakdown

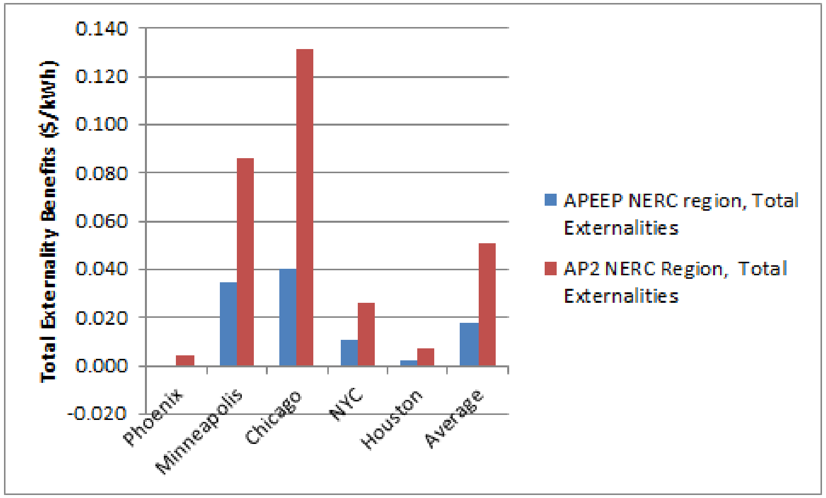
Three Large Regions for damages in EPA Clean Power Plan Analysis, 2015

Marginal benefits of abatement valuation for APEEP and AP2 (APEEP2) model

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



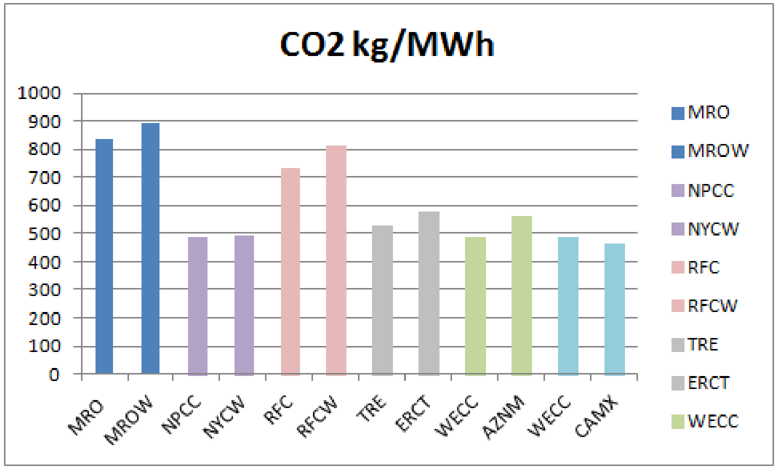


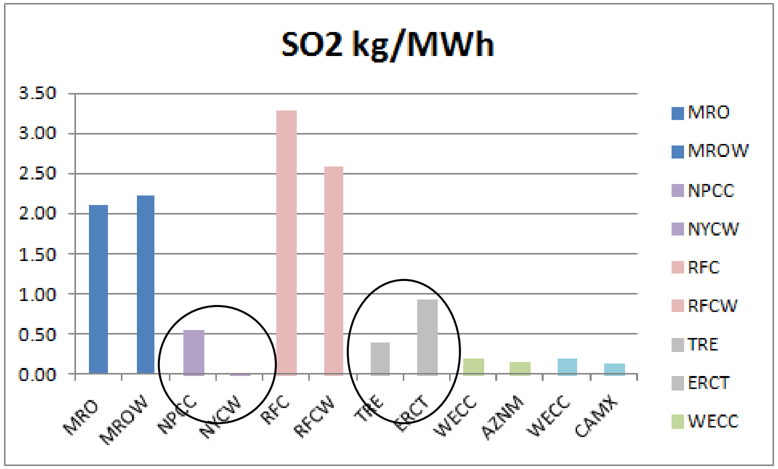


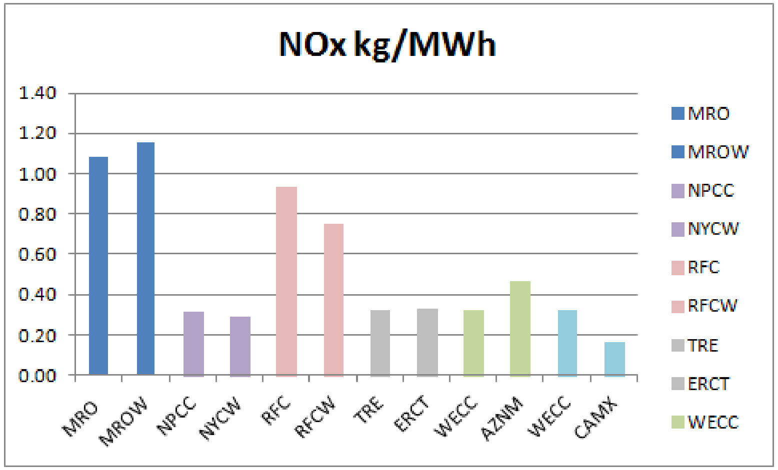
AP2: Health, Environmental benefits are increased by a factor of 3-5X over previous APEEP estimates

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

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

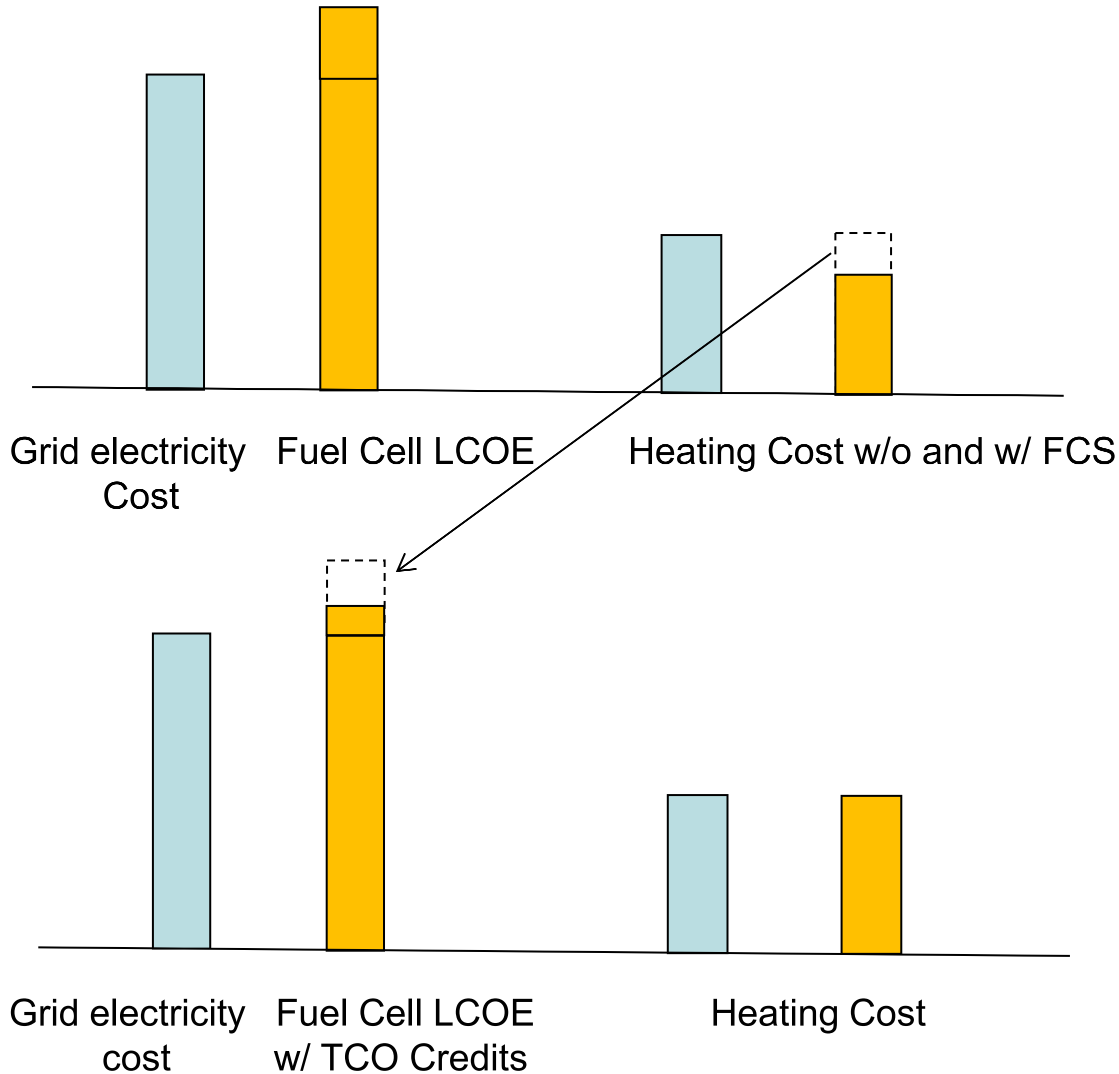






- For each pair- first bar is larger NERC region (Old value); 2nd bar eGRID sub-region (updated value)
- Reasonably matched except: SOX much lower in NYC; SOX much higher in Texas (ERCT)

Cost of Energy Service with FC CHP



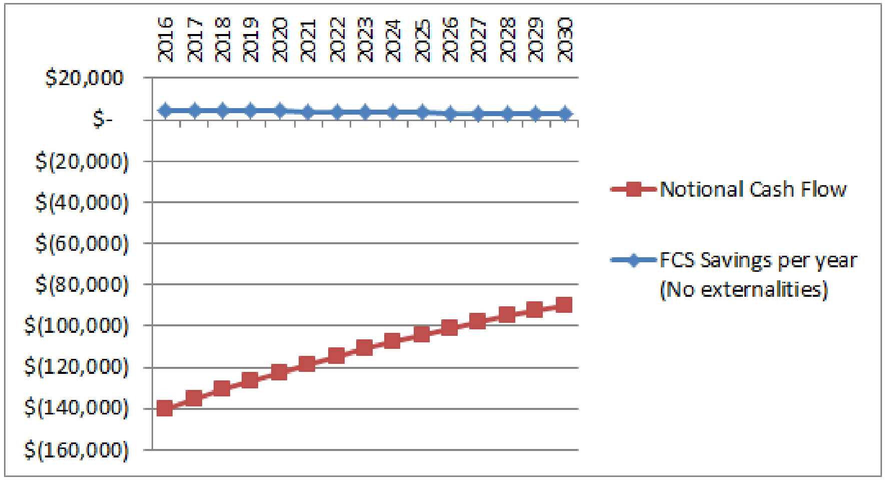
Take heat savings as a credit to FC cost of electricity, and similarly with other TCO credits.

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

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

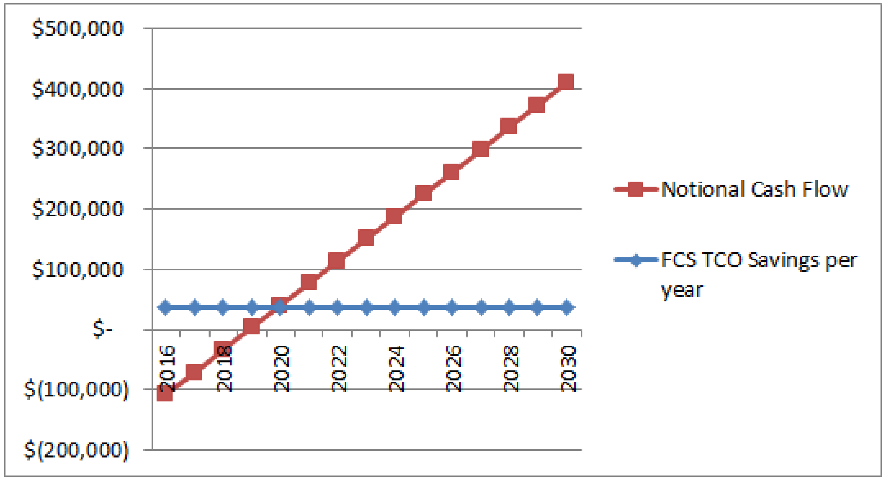
- **50kW LT PEM CHP in small hotel in Minneapolis 2016-2030**, with
  (1) No reduction in MEFs assumed
  (2) escalating social cost of carbon at 3% discount rate
- Not a real cash flow, but including private costs and public benefits
- Installed cost of $2900/kWe assumed; NPV(societal)=0 at $7200/kWe installed cost

FCS vs Grid, No Externalities



Private costs: Not favorable to owner

FCS vs Grid, Including Externalities

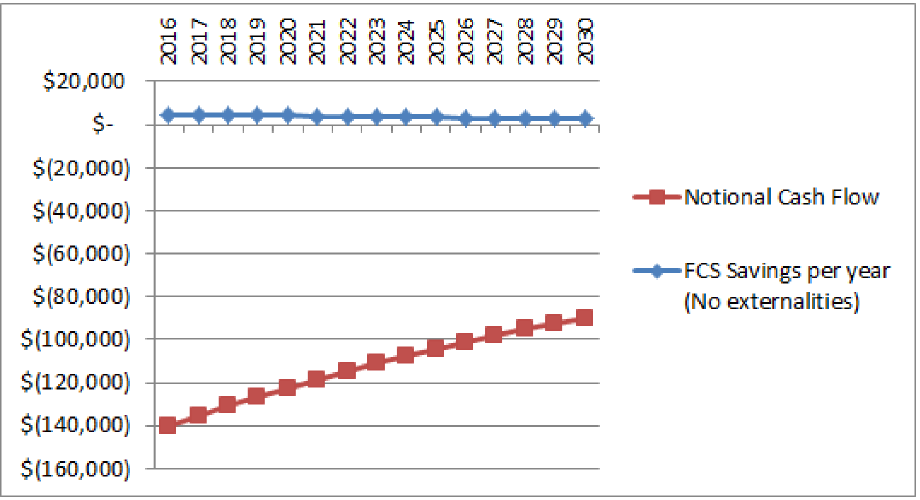


For society, cash positive investment

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

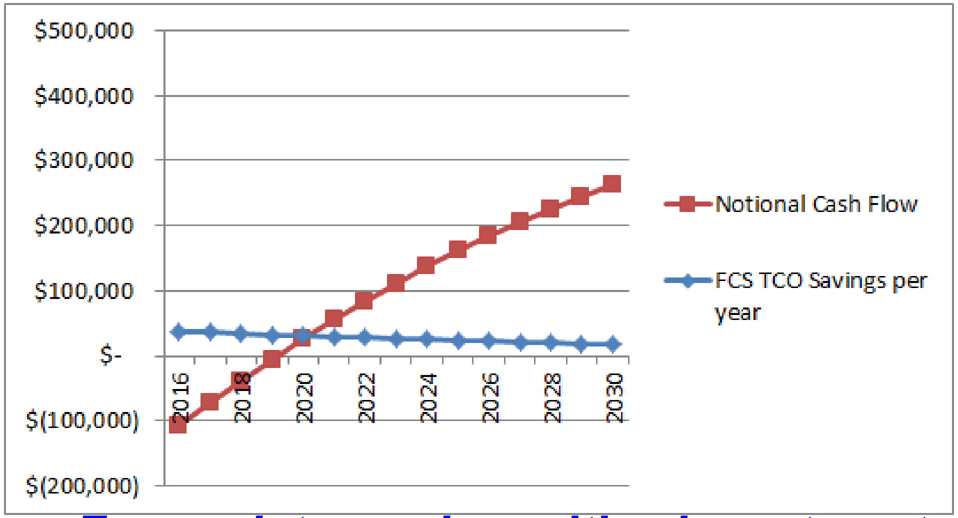
- **50kW LT PEM CHP in small hotel in Minneapolis 2016-2030**, with
  (1) Reduction in MEFs tracking estimated reduction in AEF assumed
  (2) escalating social cost of carbon at 3% discount rate
- Not a real cash flow, but including private costs and public benefits
- Installed cost of $2900/kWe assumed; NPV(societal)=0 at $5900/kWe installed cost

FCS vs Grid, No Externalities



Private costs: Not favorable to owner

FCS vs Grid, Including Externalities



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

Social Cost of carbon, EPA Clean Power Plan

- **Clean Power Plan Regulatory Impact Analysis, Oct. 2015 – we take 3% DR values for 2015, 2025, 2030**

Social Cost of CO2, 2015-2050 (2014$ per tonne)

Disc. Rate=>	5% avg	3% avg	2.5% avg	3% (95th %-tile)
2015	$13	**$41**	$63	$116
2020	$14	$46	$70	$139
2025	$15	**$51**	$75	$151
2030	$17	**$56**	$81	$174
2035	$20	$61	$87	$186
2040	$23	$67	$94	$209
2045	$26	$72	$100	$220
2050	$29	$77	$106	$232