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

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Project ID #
FC098

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Overview AMR 2015

Timeline

- Project start date: Oct 2011
- Project end date: Sept 2016
- Percent complete: 80%

Budget

- Total project funding
  - DOE share: 1.9M
  - Contractor share: n.a.
- FY15 DOE Funding: 270k
- Planned Funding for FY16: 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

Approach: Milestone AOP Tracking 2015

Qtr	Due Date	Type	Milestones, Deliverables, or Go/No-Go Decision	Decision Criteria
Q3	*6/30/2014*	*Regular*	*Literature/patent summary and functional specifications completed for SOFC systems in co-generation and stationary power.*	*Status: Done*
Q4	*9/30/2014*	*Go/No-Go*	*Go/No-Go project review meeting*	*Go Decision base on Go/No-Go Review Meeting 10/22/14*
Q1	12/31/2014	Regular	Balance of plant, bill of materials, and manufacturing process flows defined for SOFC systems stationary power and CHP systems	Done
Q2	3/31/2015	Regular	Manufacturing cost model completed for SOFC power and CHP systems	Done
Q3	6/30/2015	Regular	Policy and energy system scenario analysis completed for LT PEM total cost models for CHP and backup power systems	In Progress
Q4	9/30/2015	Go/No-Go	Total cost of ownership model and report completed for SOFC systems	Total cost of ownership model satisfactorily completed for SOFC systems in CHP and stationary power applications along with a report describing this work.

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

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

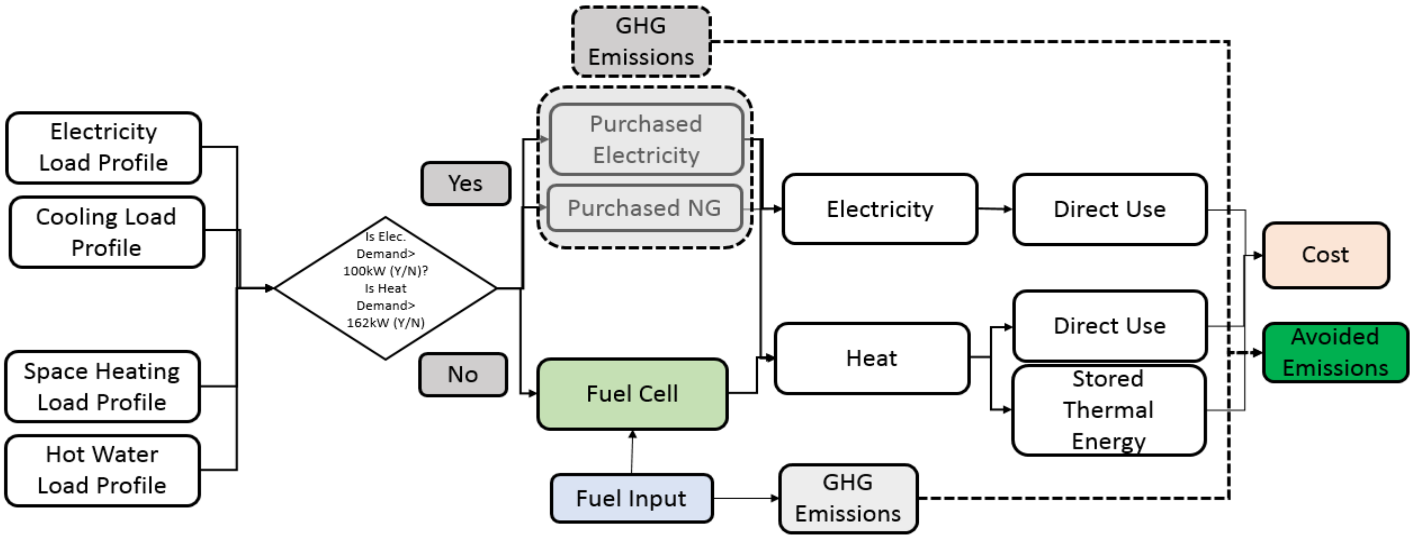
1 - Costing Approach

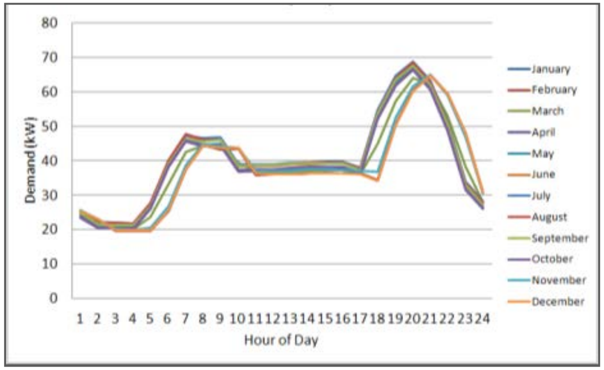
- **Direct Manufacturing Costs**
  - Capital costs
  - Labor costs
  - Materials costs
  - Consumables
  - Scrap/yield losses
  - Factory costs
- **Global Assumptions**
  - Discount rate, inflation rate
  - Tool lifetimes
  - Costs of energy, etc.
- **Other Costs:**
  - R&D costs, G&A, sales, marketing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

Source: Altergy Systems

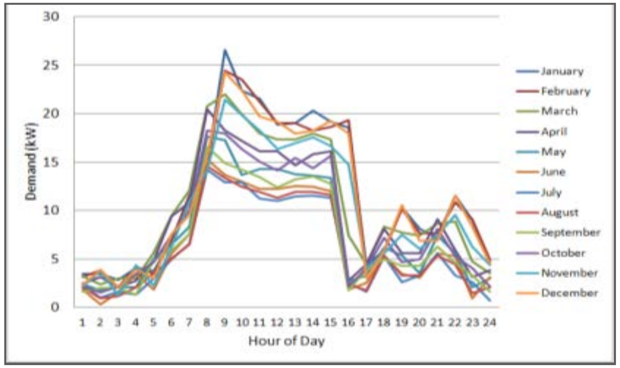
2 - Fuel Cell System Life Cycle Cost (Use Phase) Modeling

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



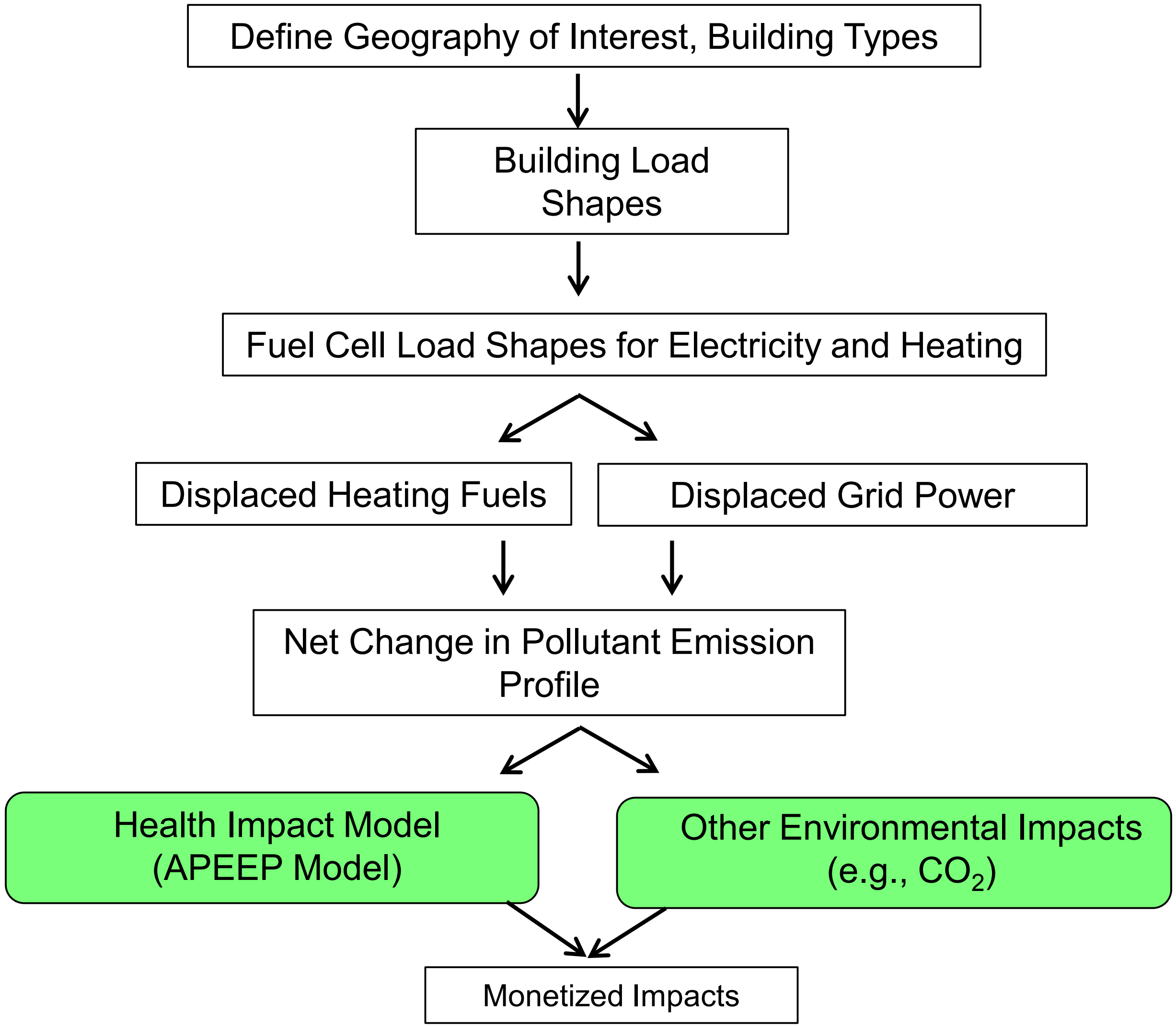


Daily electricity load profiles for small hotel in AZ



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: SOFC FC SYSTEM MANUFACTURING COST

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 – common properties

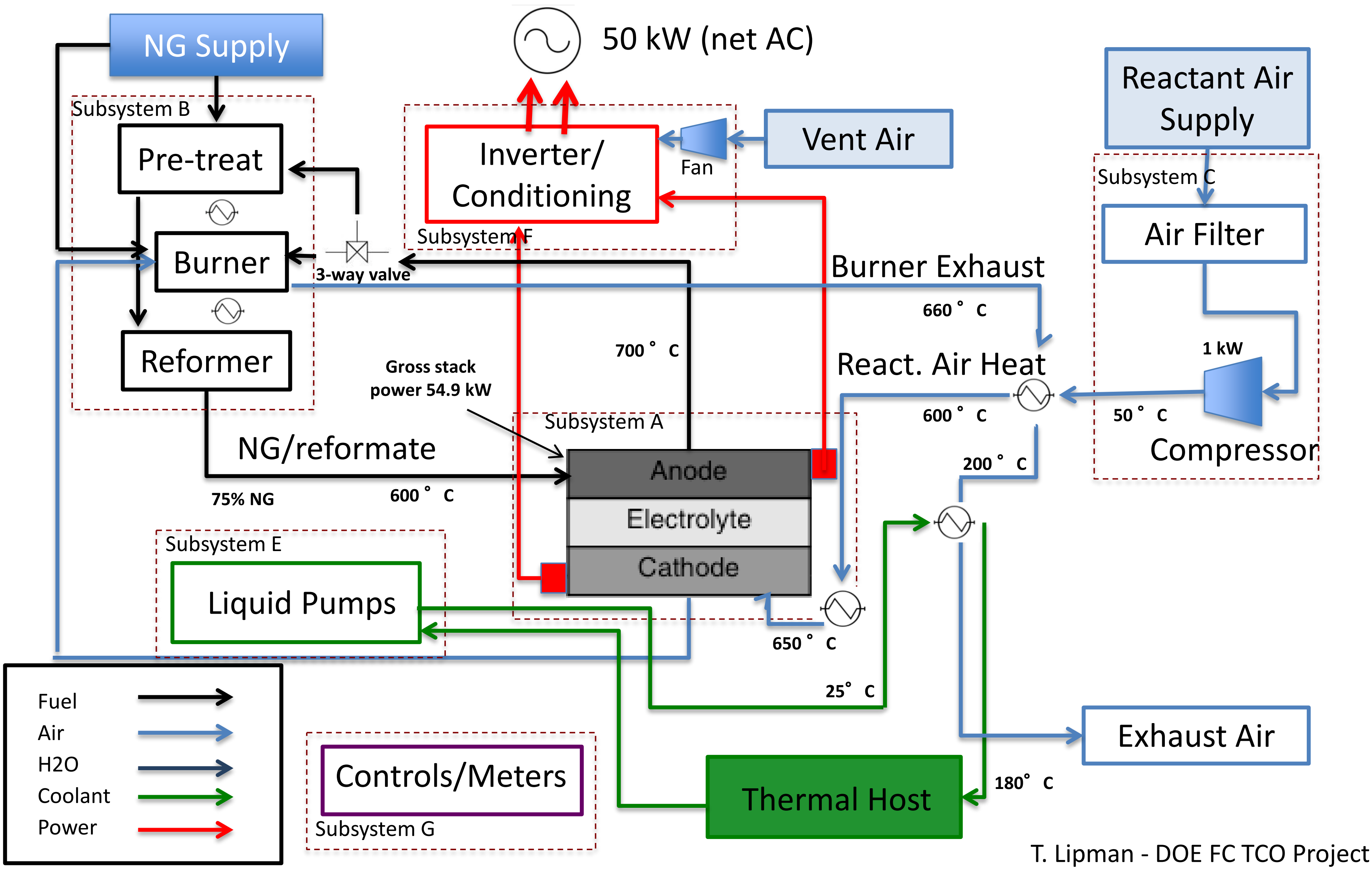
		Fuel Type:	Pipeline Natural Gas
Common properties:	**Near-Term**	**Future**	**Unit**
System life	15	20	years
Stack life	24000	40000	hours
Reformer life (if app.)	5	10	years
Compressor/blower life	7.5	10	years
WTM sub-system life	7.5	10	years
Battery/startup system life	7.5	10	years
Turndown % (>50 kW)	**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

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	

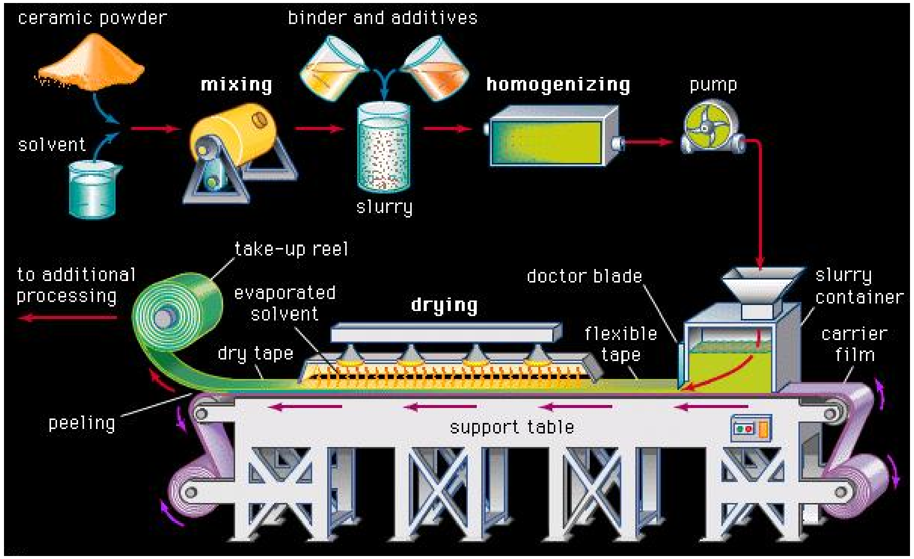
50 kW SOFC CHP System with Reformate Fuel



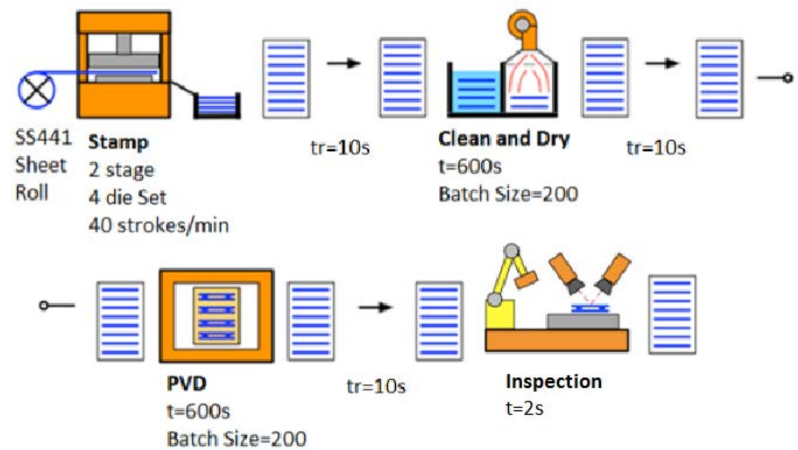
T. Lipman - DOE FC TCO Project

Manufacturing Cost Model – EEA, Metal Plates

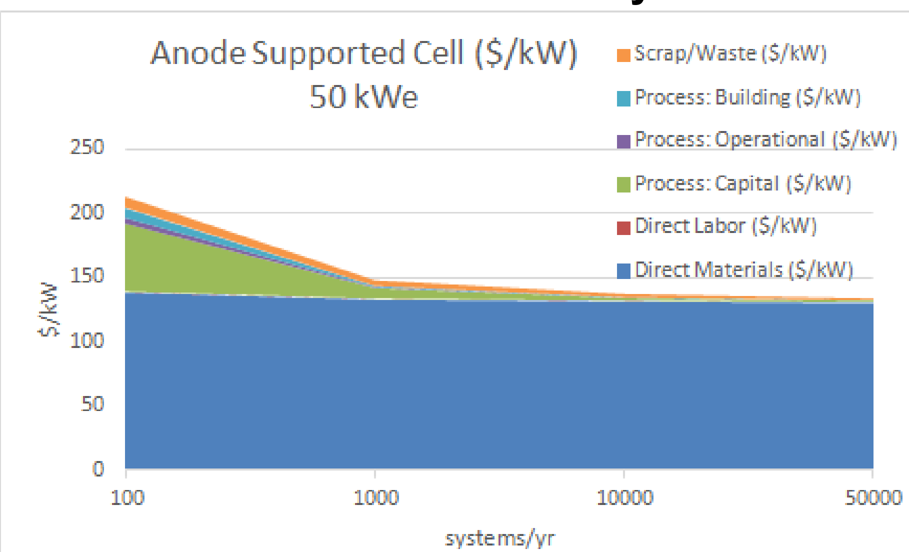
EEA Process Flow-Cathode Coating Line



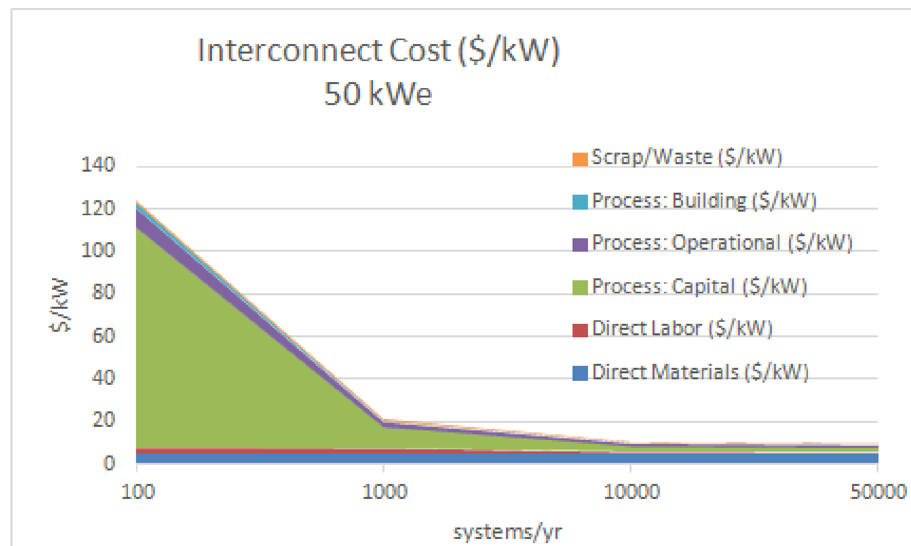
Metal Plate Process Flow



EEA Cost Plot - 50kW System

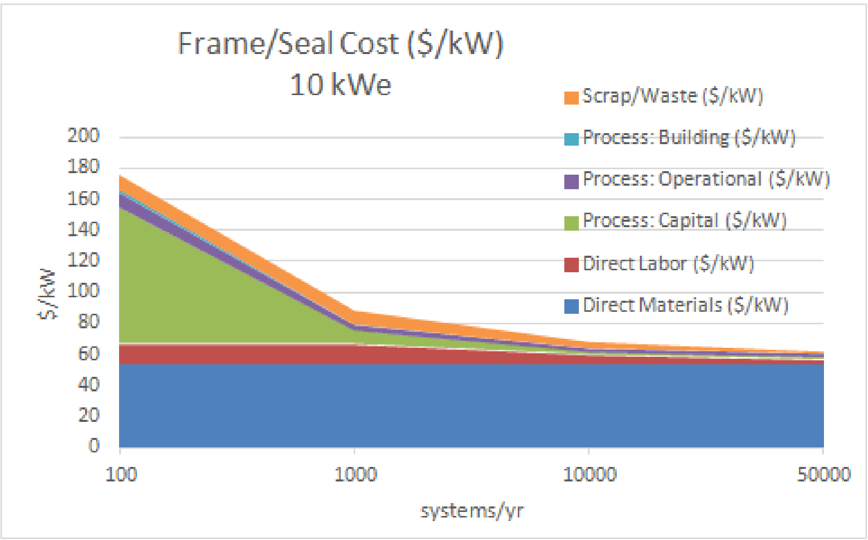


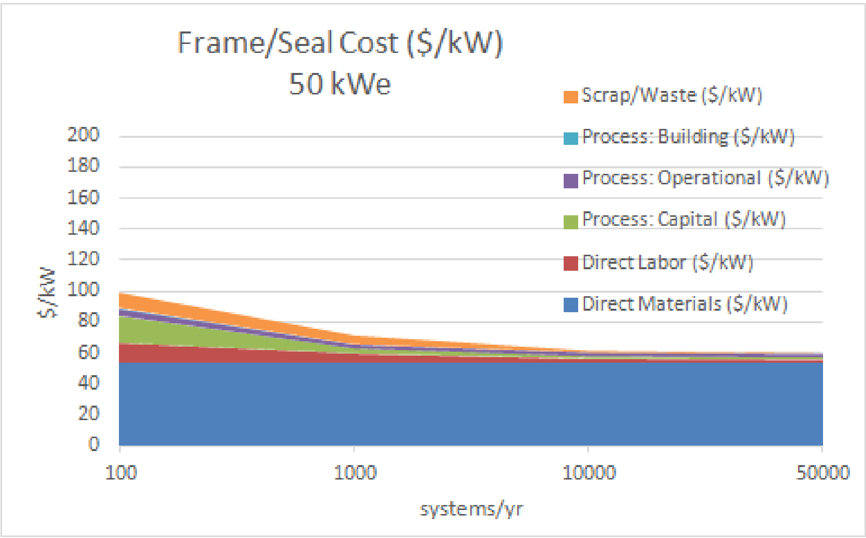
Plates Cost Plot - 50kW System

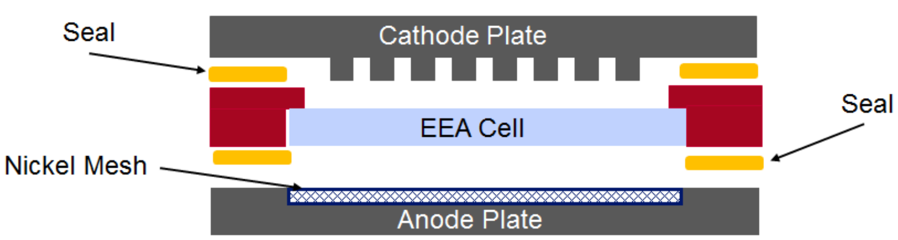


Seal/Frame Cost Analysis

- **Seal/frame cost ($/kW)**





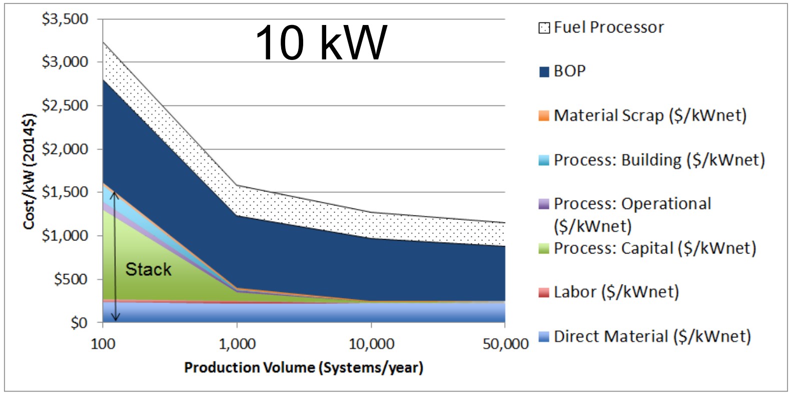


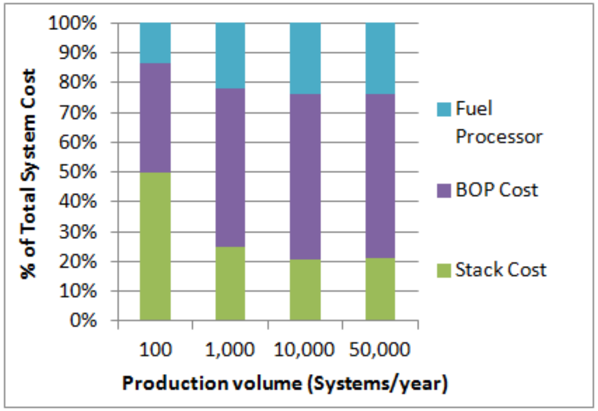
Cell to frame seal BOM
(US Patent 8,691,470 B2)

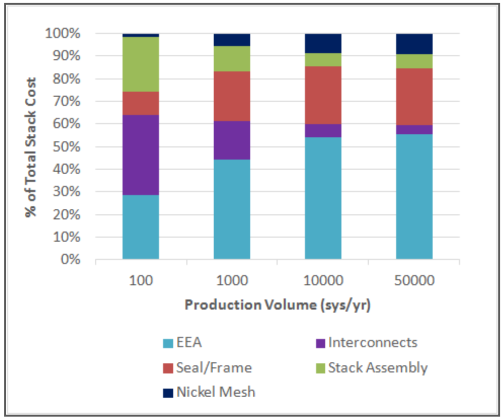
Material	Wt %	Cost ($/kg)
CaO	15.5	84
BaO	9	117
Al2O3	14.5	71
SiO2	56	112
K20	5	1.6

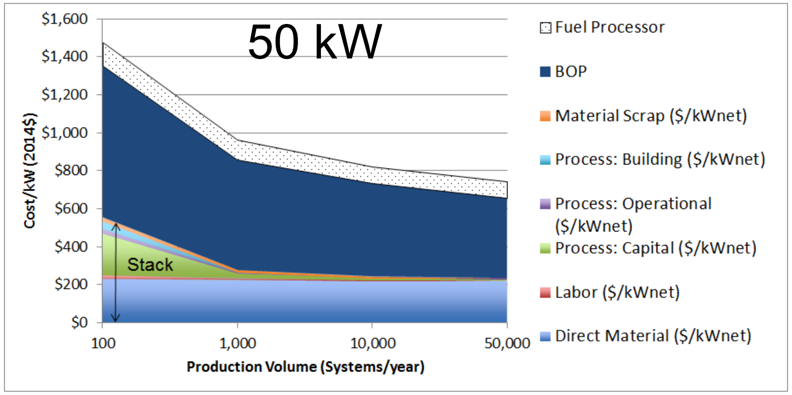
System Cost for 10/50kW CHP SOFC

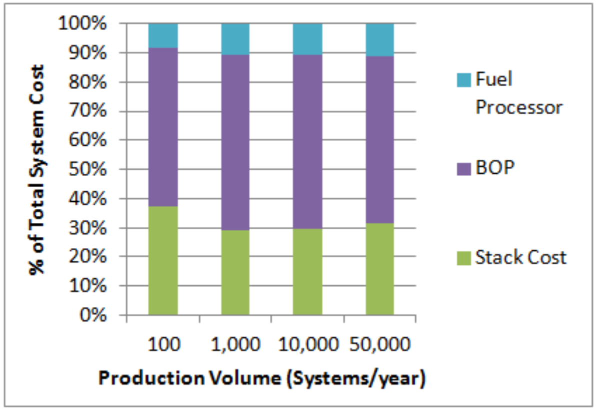
- Stack cost dominated by EEA then seal/frame at high volumes
- BOP_Non-FP and BOP_Fuel processor are 50%-80% of overall cost
- System direct cost < $800/kW at high volumes

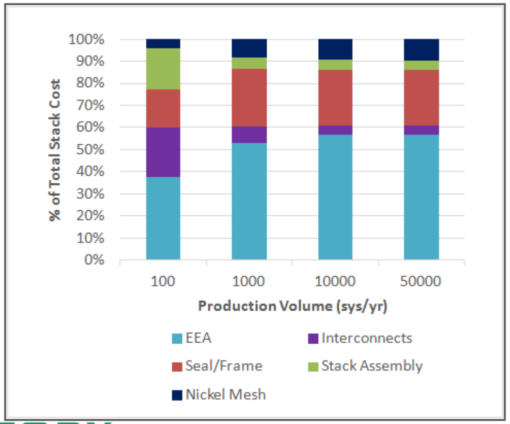






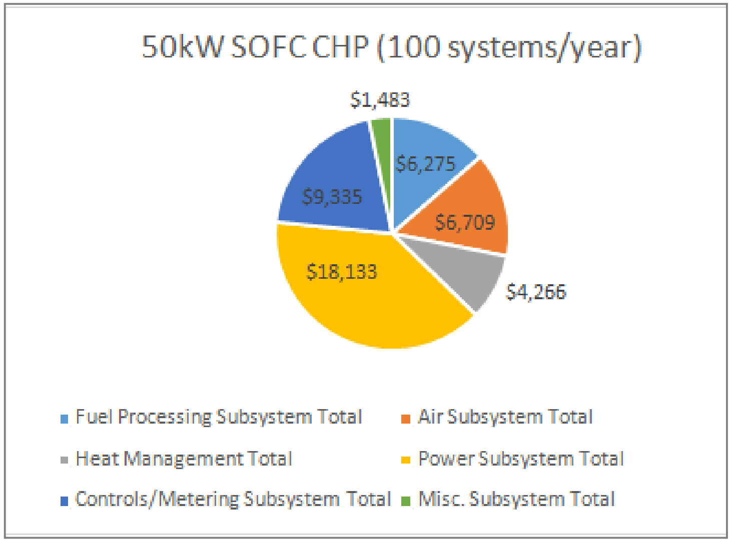


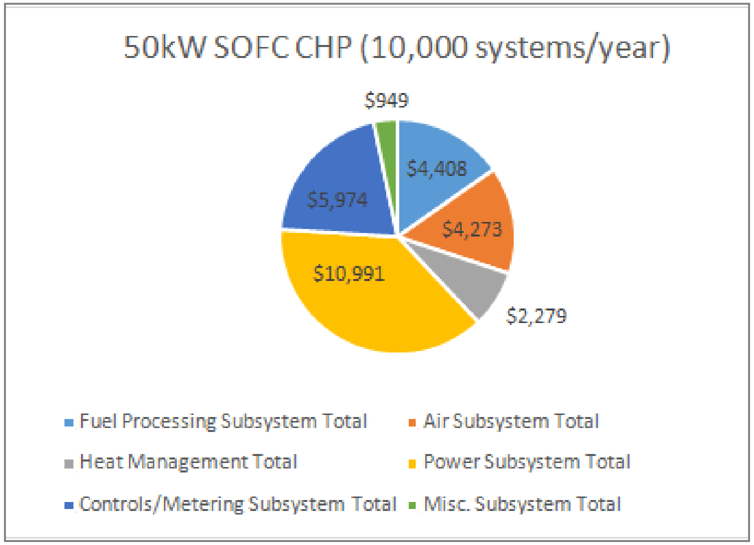


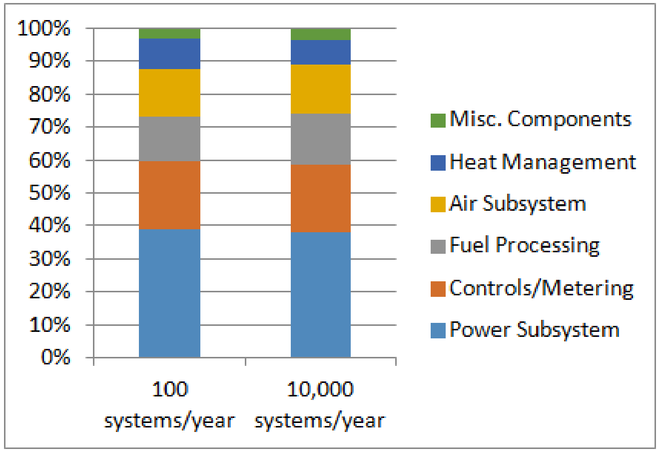


BOP Components Cost Breakdown

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







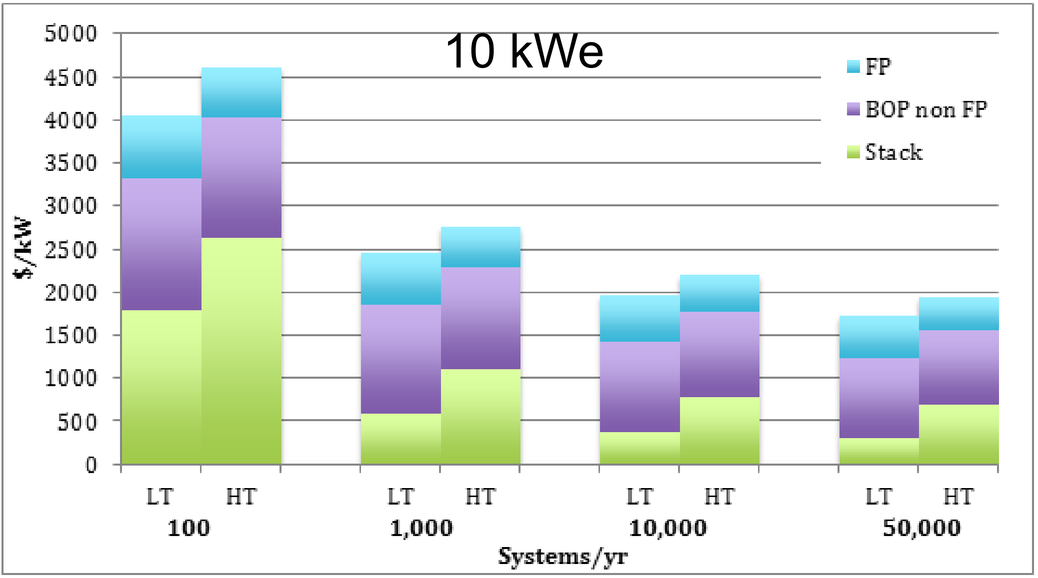
Equipment Cost Estimates vs. DOE Targets

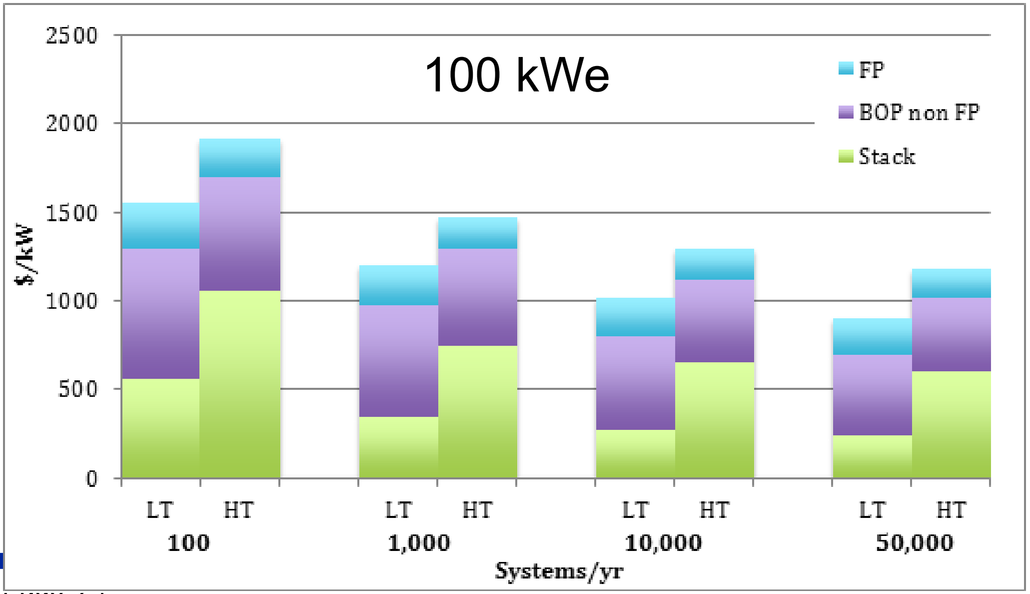
System	Units/yr	2020 DOE Target w/ Markup ($/kW)	LT PEM direct cost ($/kW)	LT PEM cost with 50% markup ($/kW)	SOFC direct cost ($/kW)	SOFC cost with 50% markup ($/kW)
		DOE Targets	This Work			
10kW CHP System	50,000	$1,700	$1,724	**$2,586**	$1,170	**$1755**
100kW CHP System	1000	$1000	$1,200	**$1,800**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

10 kW SOFC system close to 2020 DOE target

TECHNICAL PROGRESS: HT PEM SYSTEM AND TCO COST MODELING

HT PEM vs LT PEM



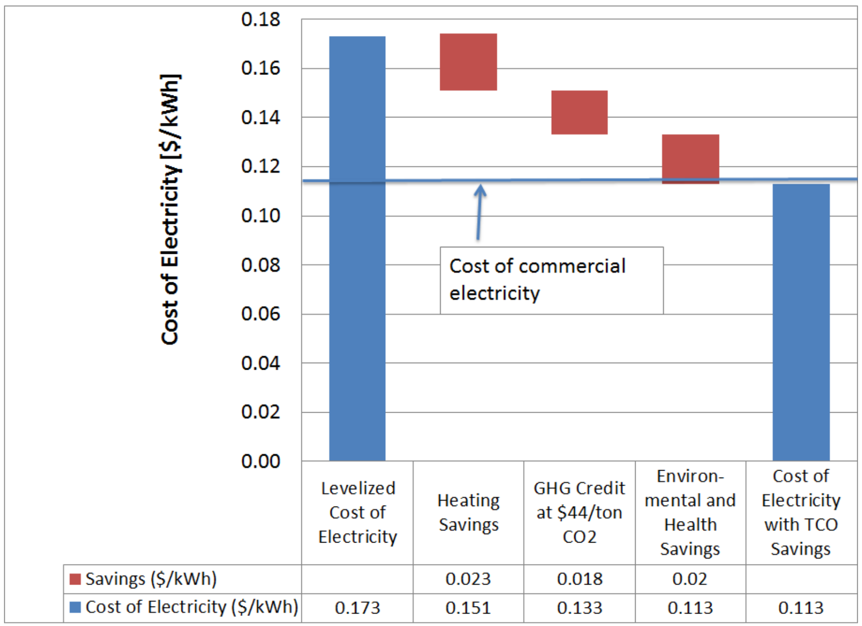


- Higher stack cost for HT PEM because of lower power density and larger plate size, higher Pt loading, and different design
- Somewhat lower BOP/FP cost for HT PEM (simpler system), and a lower fraction of system costs
- Overall HT PEM: 10-15% higher system costs at low volume than LT PTEM, up to 30% higher cost at 100kW, high volume
- LT PEM: Non-stack costs dominate

HT PEM Total cost of ownership

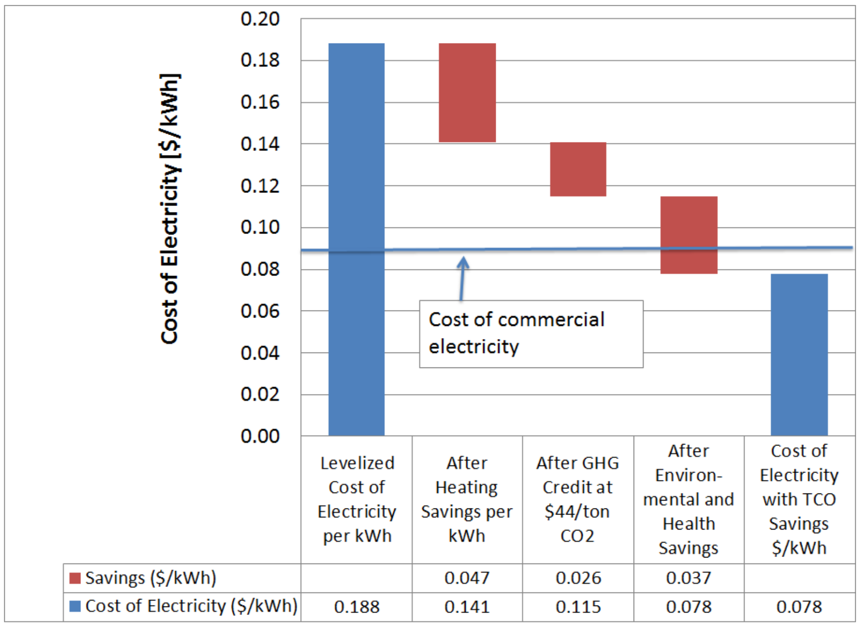
TCO model includes New York, Chicago, Minneapolis, Phoenix, Houston, and San Diego settings with various commercial buildings

FC CHP is most favorable in regions with higher carbon intensity electricity (Chicago and Minneapolis)



	Levelized Cost of Electricity	Heating Savings	GHG Credit at $44/ton CO2	Environ-mental and Health Savings	Cost of Electricity with TCO Savings
Savings ($/kWh)		0.023	0.018	0.02	
Cost of Electricity ($/kWh)	0.173	0.151	0.133	0.113	0.113

50kW Small Hotel in Minneapolis
HT PEM system with WH+ SH
Installed cost $3,400/kWe



	Levelized Cost of Electricity per kWh	After Heating Savings per kWh	After GHG Credit at $44/ton CO2	After Environ-mental and Health Savings	Cost of Electricity with TCO Savings $/kWh
Savings ($/kWh)		0.047	0.026	0.037	
Cost of Electricity ($/kWh)	0.188	0.141	0.115	0.078	0.078

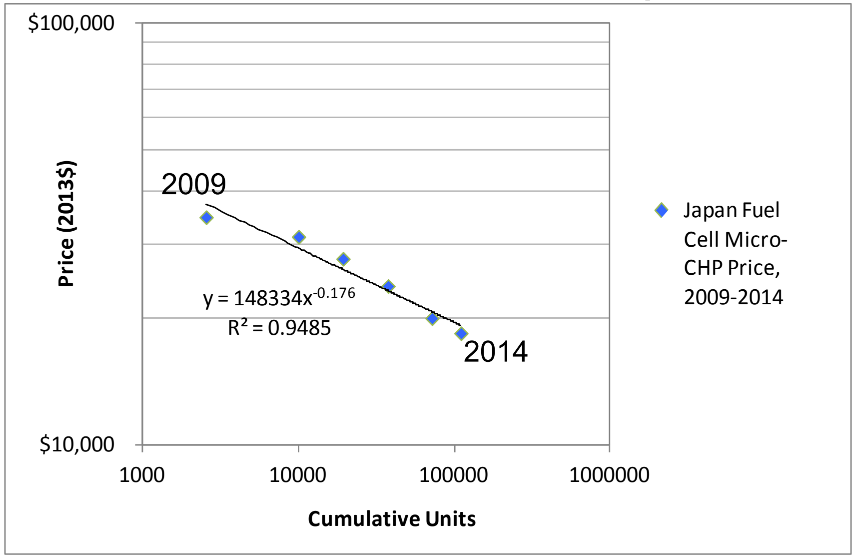
10kW Small Hotel in Chicago
HT PEM system with WH+SH
Installed cost $4,400/kWe

TECHNICAL PROGRESS: COMPARISONS TO MARKET DATA AND OTHER MODELED COSTS

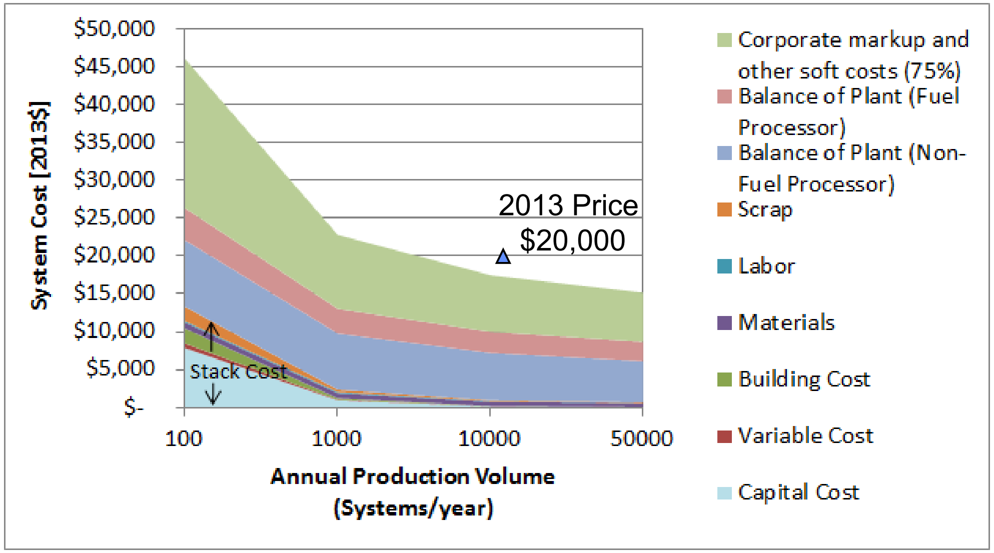
Japan Micro CHP (LT PEM) – LBNL cost modeling can help disaggregate cost reductions

- 12% Learning curve from 2009-2014, nominal 0.7-1kW
- 42% cost reduction observed from 2009 to 2013

LEARNING CURVE, PRICES (2009-2014)



LBNL DIRECT COST MODEL



- LBNL Cost model implies about 23% cost reduction from economies of scale (estimate ~1300 units/yr, 2009 to about 15,000 units/yr, 2013 per vendor)
- About 19% cost reduction estimated based on publically announced design and performance improvements; about 7% cost reduction attributed to other factors.
- These three factors give the observed 42% cost reduction from 2009-2013.

LT PEM: LBNL 2014 vs SA 2012 cost comparison

Comparison between SA and LBNL studies for stationary fuel cell applications (100 kWe FC system)					
	Annual Production Volume (sys/yr)				
Trial No.	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr	Changed Variables
	Stack Cost in $/kWe				
SA Study (2012)	351	272	161	123	Pt loading= 0.4mg/cm2; Pt cost=$36/g (based on $1,100/tr.oz); Power density= 0.408W/m2; Yield assumptions >99.5% for all stack modules.
0 (Actual Assumptions of LBNL Study)	556	346	273	238	Discount Rate=15%; Pt price $57.6/g; and Pt loading= 0.5mg/cm2; power density=0.354W/cm2; Yield (see Table on right)
1	467	276	210	178	Pt loading=0.4mg/cm2 &pt price $36/g and yield=99.5% for all FC stack modules
2	509	299	226	192	Pt price $36/g only
3	472	291	221	187	Discount Rate=10% and Pt price $36/g
4	494	284	211.4	177	Pt loading= 0.5 mg/cm2
5	457	276	207	173	Discount Rate=10%; Pt price $36/g; and Pt loading= 0.4mg/cm2
6	386	239	181	152	Discount Rate=10%; Pt price $36/g; and Pt loading= 0.4mg/m2; power density=0.408W/cm2; Yield=99.5% for all stack modules
Trial 6 Delta from SA, matched conditions	10%	-12%	12%	24%	
Trial 2 vs Trial 0 (Pt impact only of LBNL cost)	15%	16%	19%	21%	

- **Different assumptions: Pt price, Disc. Rate, yield, power density**
  - **SA's 2014 AMR update increased Pt cost to $1500/tr. oz (or $49/g) from $1100/tr. oz above. This is much closer to LBNL's assumed Pt price of $57.60/g**
- **LBNL / SA within 20% of each other with matched assumptions**
  - **LBNL estimates are higher cost; possibly more detailed in process flows**

Responses to 2014 AMR Reviewer Comments

1. **"De-prioritize" HT PEM –** An initial HT PEM cost analysis report was completed in Q4'14, but the focus of the team's efforts have been on SOFC systems.
2. **Increase industry inputs/collaborators –** The team has increased the number of industry inputs and reviewers, including VersaPower(FCE), SOFCpower, Minh Nguyen of University of California, San Diego (formerly of GE fuel cells), Jack Brouwer of University of California, Irvine, and Massimo Santarelli of Polytechnic University of Turin. Strategic Analysis is also a collaborator on the project.
3. **Compare with known cost numbers and cost modeling –** This update contains several slides describing LBNL cost estimates vs. SA and known price data on Japanese micro-CHP and stationary fuel cell systems in California.
4. **Clarify value of work vis a vis SA's previous DFMA, etc. -** This work is part of a complimentary portfolio of DOE analysis projects. Other projects have focused on different applications (e.g., MHE, passenger vehicles). This project also expands the direct cost modeling approach to include life-cycle costing and ancillary financial benefits (GHG credits, health and environmental impacts).
5. **BOP 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). 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.
6. **Include Incentives –** Both federal and state incentive programs and scenarios will be included in the SOFC life-cycle cost modeling Q3'15.

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.

Industry/expert inputs and reviews conducted below and will continue

Functional specs and system design:

- Strategic Analysis (sub-con)
- Brian Borglum, Versa Power/FCE

General system and manufacturing:

- SOFCpower, Mezzolombardo, Italy visit, 18 October 2014
- Minh Nguyen, University of California, San Diego (formerly of GE)
- Prof. Massimo Santarelli of Polytechnic University of Turin, Italy

Balance of plant:

- Jack Brouwer, University of California, Irvine

Remaining Challenges

- System and stack data availability for electrolyte-supported SOFC stack
- Low volume costing and yield modeling
- Modeling the transition from manual to automated automation
- Lack of data for system availability – will add as a sensitivity factor to LCC model

Proposed Future Work

- LCC and TCO model for SOFC systems including absorption cooling option (Q3-Q4’15)
- Scenario modeling of stationary FC systems: incentives, future gas and electricity prices, future H_2 supply (Q3-Q4’15)
- Updating LT PEM TCO model, material prices, balance of plant costs (Q1-Q2’16)
- Automating SOFC TCO model for user enabled interface in Analytica (Q1-Q2’16)
- Case study analysis of key cost reduction opportunities in BOP, e.g., power conditioning and inverters (Q2’16)
- Updated SOFC TCO model, material prices, BOP costs, and scenario/sensitivity analysis (Q2-Q3’16)
- Final updated reports for LT PEM and SOFC TCO modeling (Q3-Q4’16)

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 and electric power systems; Total cost of ownership model for HT PEM CHP systems (manufacturing cost model, LCC model and externality valuation);***

Collaboration: ***Partnerships with UC-Berkeley manufacturing analysis and transportation sustainability research groups and collaboration with Strategic Analysis***

Proposed Next-Year Research: ***Total cost of ownership model for SOFC CHP/Power systems and updating of PEM manufacturing cost and TCO models***

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Thank you

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Technical Back-Up Slides

Global DFMA Costing assumptions

Parameter	Symbol	Value	Units	Comments
Operating hours	t_{hs}	varies	Hours	8 hours base shift; [1,1.5,2] shifts
Annual Operating Days	t_{dy}	250	Days	52wks*5days/wk-10 vacation days
Production Availability	A_m	0.85		Typical value in practice
Avg. Inflation Rate	j	0.026		US avg. for past 10 years‡
Avg. Mortgage Rate	j_m	0.05		See following reference ‡‡‡‡
Discount Rate	j_d	0.10		Typical value
Energy Inflation Rate	j_e	0.056		US avg of last 3 years‡‡‡
Income Tax	i_i	0		No net income
Property Tax	i_p	0.014		US avg from 2007†
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	Typical U.S. value
Floor space Cost	c_{fs}	1291	\$/m^2	US average for factory††
Building Depreciation	j_{br}	0.031		BEA rates† ††
Building Recovery	T_{br}	31	Years	BEA rates† ††
Building Footprint	a_{br}	Varies	m^2	
Line Speed	v_l	Varies	m/min	Approximation from DTI2010 (James et al., 2010)
Web Width	W	Varies	M	Lower widths at low volume
Hourly Labor Cost	c_{labor}	28.08	\$/hr	Hourly wage per worker

Materials Prices

	Vendor/Country	Material	Price	Application
Electrode-Electrolyte Assembly (EEA)	AIICHI JITSUGYO (Japan)	Nickel Oxide	$65-70/kg for 1,000kg order $40-45/kg for 5,000kg order $35-40/kg for 10,000kg order $32-37/kg for 20,000kg order	Anode backing layer
	AIICHI JITSUGYO (Japan)	8YSZ (8mol%YSZ)	$75-80/kg for 100kg order $65-70/kg for 1,000kg order $60-65/kg for 5,000kg order	Electrolyte layer
	Daiichi (Japan)	8YSZ (8mol%YSZ)	100kg by sea shipment: $95/kg 1,000kg by sea shipment: $83/kg 100kg by air shipment: $97/kg	Electrolyte layer
	Daiichi (Japan)	Scandia Stabilized Zirconia(10ScSZ):	100kg by sea shipment: $524/kg 1,000kg by sea shipment: $515/kg 100kg by air shipment: $526/kg	Electrolyte layer (Electolyte-supported cell)
	Inframat Advanced Materials (USA)	8mol%YSZ powder	$150 per kg; if order>100kg	Electrolyte layer
	Inframat Advanced Materials (USA)	LSM powder	$150 per kg; if order>100kg	Cathode layer
	Qingdao Terio Corporation (China)	LSM powder	$250 per kg	Cathode layer
	Hebei Baicheng (China)	Cerium Oxide (Doped Ceria)	$13.5 per kg	Inter-layers (Electolyte-supported cell)
	Changsha Asian Light Economic Trade Co. (China)	Cerium Oxide (Doped Ceria); purity:99.95%	$2,667 per ton	Inter-layers (Electolyte-supported cell)
Stamped Interconnect		SS 441	$2.30/kg	Base material
	Qingdao Terio Corpora	MnCO	$300/kg for 1 kg $250/kg for 10 kg	Coating material
Glass Seal	Spectrum Chemical Ma	CaO	$84/kg	Alkaline-earth based silicate glass
	Fisher Scientific (USA)	BaO	$117/kg	Alkaline-earth based silicate glass
	Fisher Scientific (USA)	Al2O3	$71/kg	Alkaline-earth based silicate glass
	Alibaba (China)/Shijiaz	SiO2	$112/kg	Silicate glass
		K2O	$1550/metric ton	Alkaline-earth based silicate glass
Metal Seal		Ag	$19.73/troy ounce	Brazing alloy
	Infomine.com	Cu	$3.06/lb	
	Infomine.com	TiH2	$0.025/g	Promotes wetting brazing of Ag-based alloys and enhances the sealing properties

Yield Assumptions

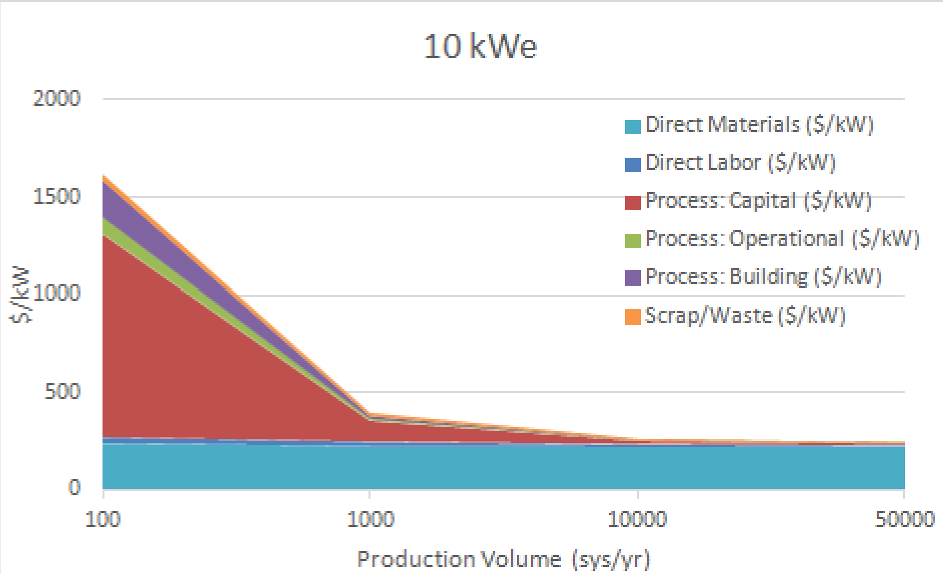
FC Size (kW)	10	10	10	10
Annual Production Volume	100	1,000	10,000	50,000
EEA Yield	95.00%	96.00%	97.00%	98.00%
Interconnect & Frame	85.00%	85.65%	92.67%	97.91%
Seal	85.00%	85.77%	92.79%	98.04%
Assembly	99.5%	99.5%	99.5%	99.5%
Stack Average Yield	89.8%	90.3%	95.0%	98.5%

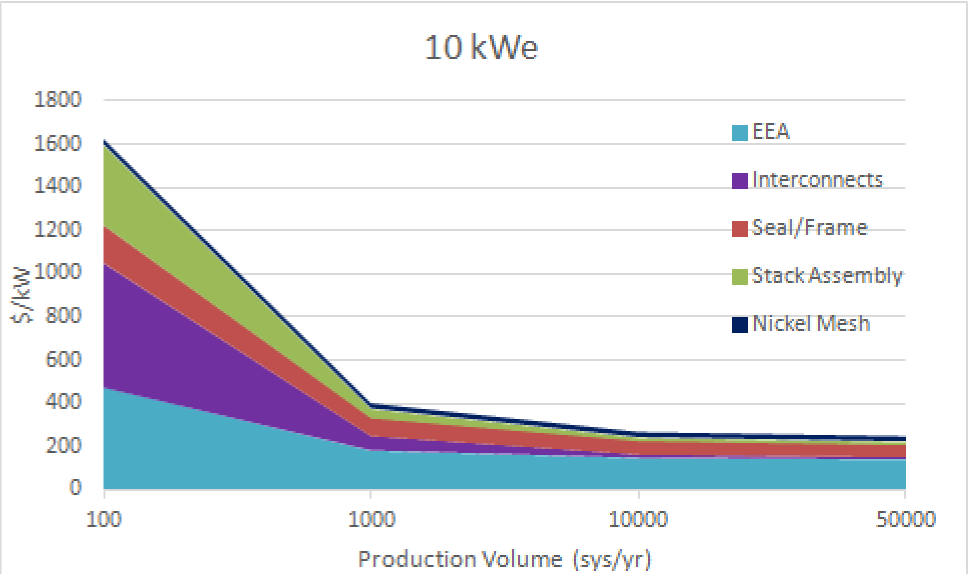
FC Size (kW)	50	50	50	50
Annual Production Volume	100	1,000	10,000	50,000
EEA Yield	96.00%	97.00%	98.00%	99.00%
Interconnect & Frame	85.00%	90.50%	97.91%	99.50%
Seal	85.00%	90.62%	98.04%	99.50%
Assembly	99.5%	99.5%	99.5%	99.5%
Stack Average Yield	89.8%	93.5%	98.5%	99.5%

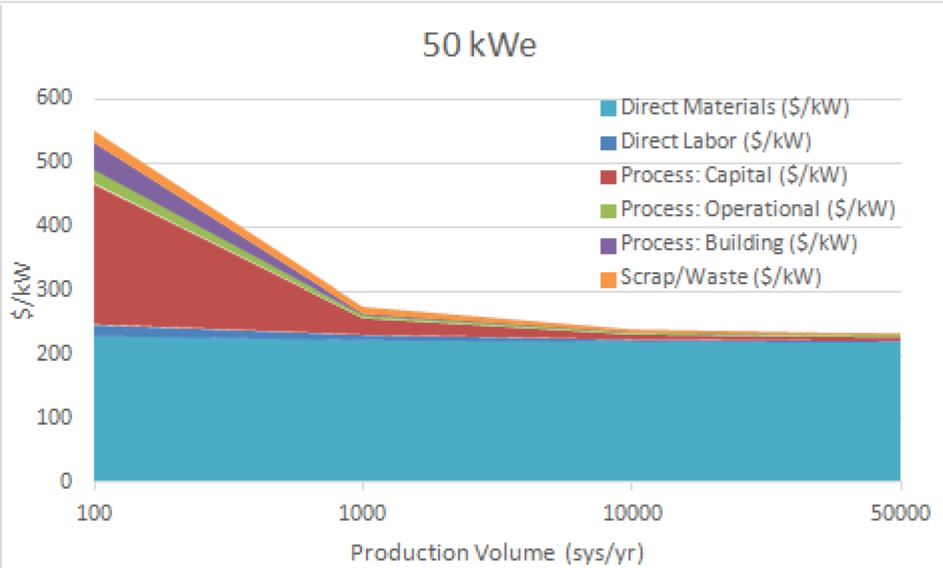
- Versa power reported yield numbers >95% for EEA‡

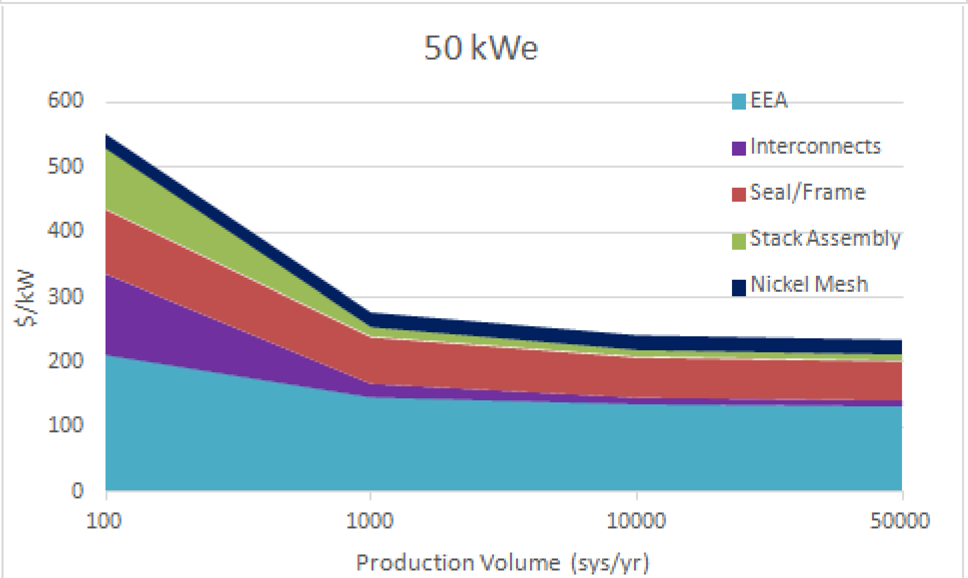
‡ B. P. Borglum. Development of Solid Oxide Fuel Cells at Versa Power Systems. ECS Transactions, 17 (1) 9-13 (2009)

SOFC Stack cost in ($/kW)





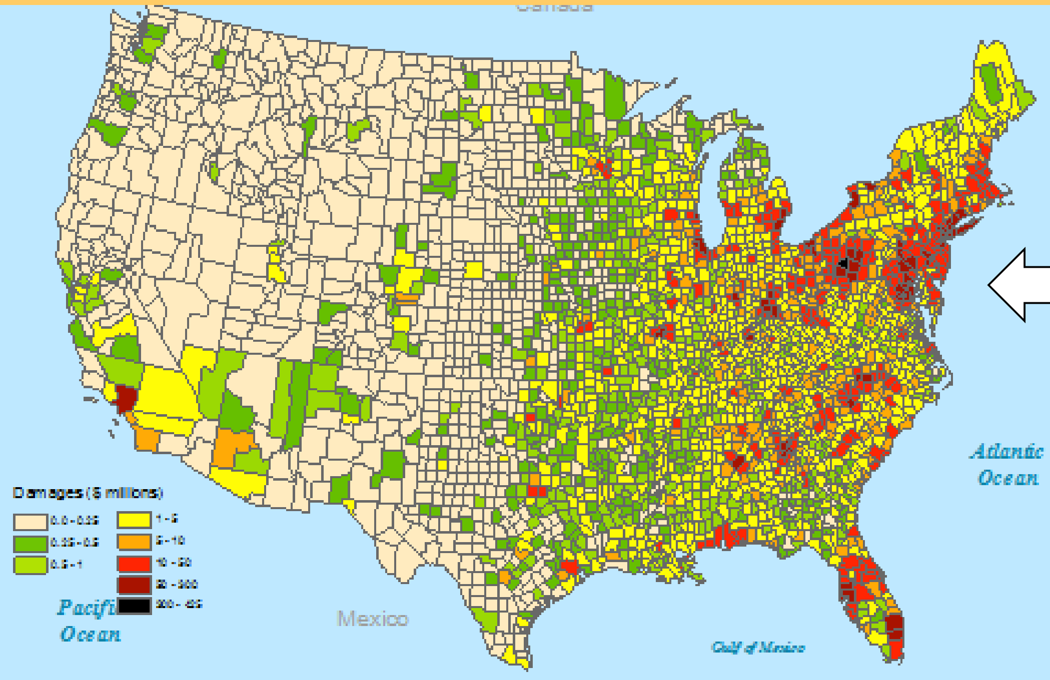




Air Pollution Emissions Experiments and Policy Analysis Model (APEEP)

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)**