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

Arlington, Virginia
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Lawrence Berkeley National Laboratory

Project ID #
FC098

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

Overview

Timeline

- Project start date: Oct 2011
- Project end date: Sept 2016
- Percent complete: 30%

Budget

- Total project funding
  - DOE share: $1.9M
  - Contractor share: n.a.
- Funding received in FY11: $100K
- Funding received in FY12: $500K
- Planned Funding for FY13: $560K

DOE Cost Targets

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

Barriers Addressed

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

Partners

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

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.
- Potential policy and incentive programs may not value fuel cell (FC) total benefits.

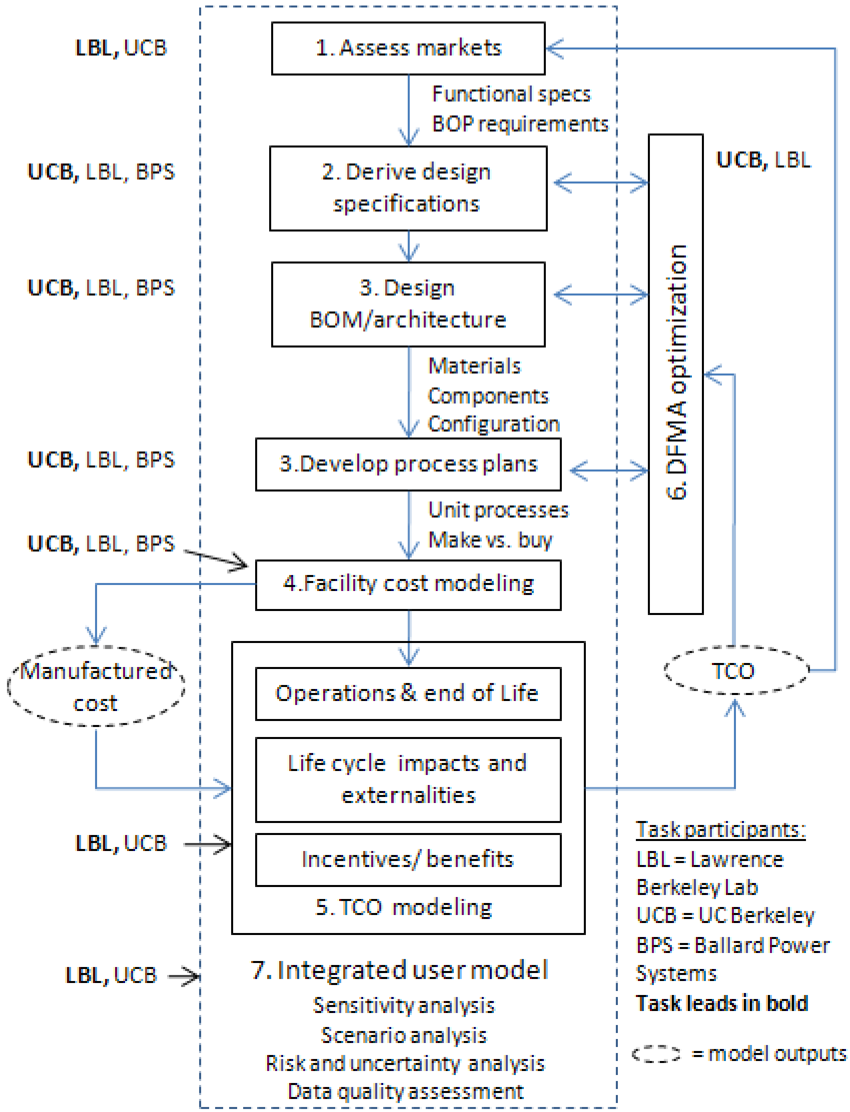
Overview: Chemistries and Applications

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

- **Application Space:**

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

Research and Modeling Approach: Task Flow



BOM: Bill of Materials

DFMA: Design for Manufacturing and Assembly

TCO: Total Cost of Ownership

Research and Modeling Approach: Inputs and Tools

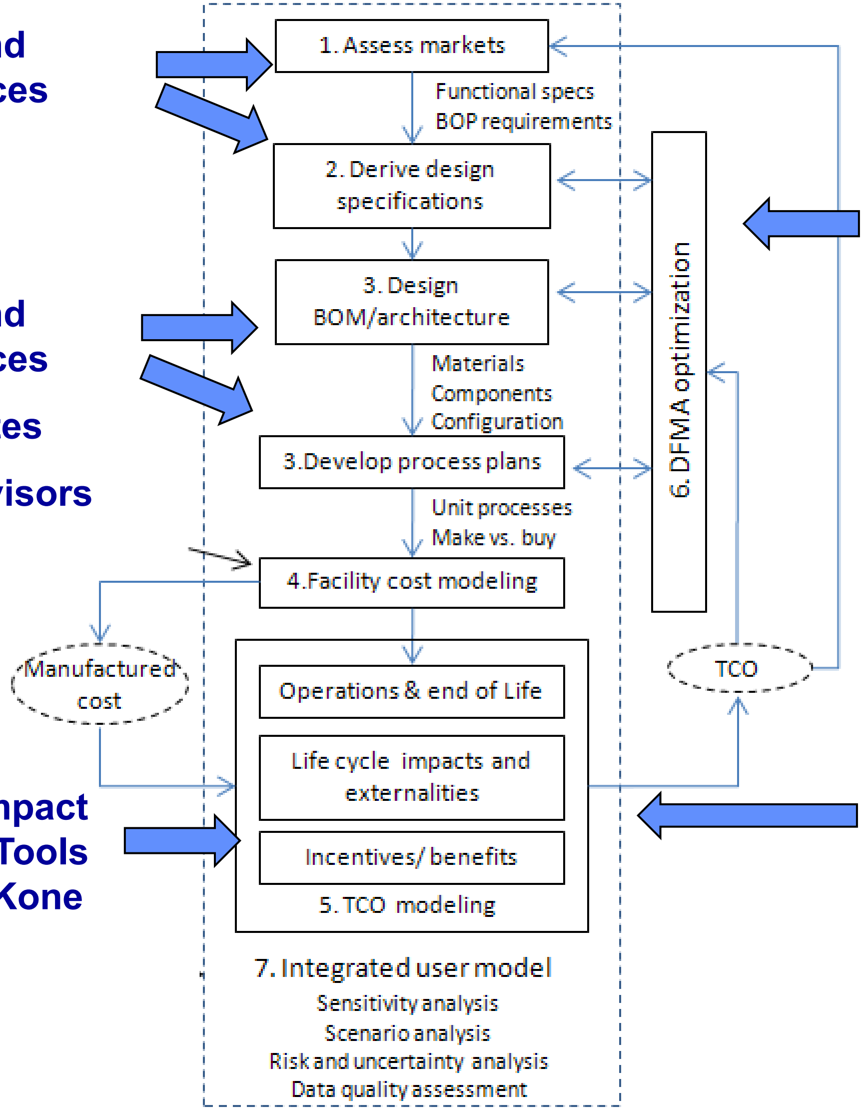
Literature and Patent Sources
DER-CAM
(CHP Apps)

Literature and Patent Sources

Vendor Quotes

Industry Advisors

Exposure /Impact Models and Tools e.g. Tom McKone Model



Boothroyd Dewhurst DFMA® Software

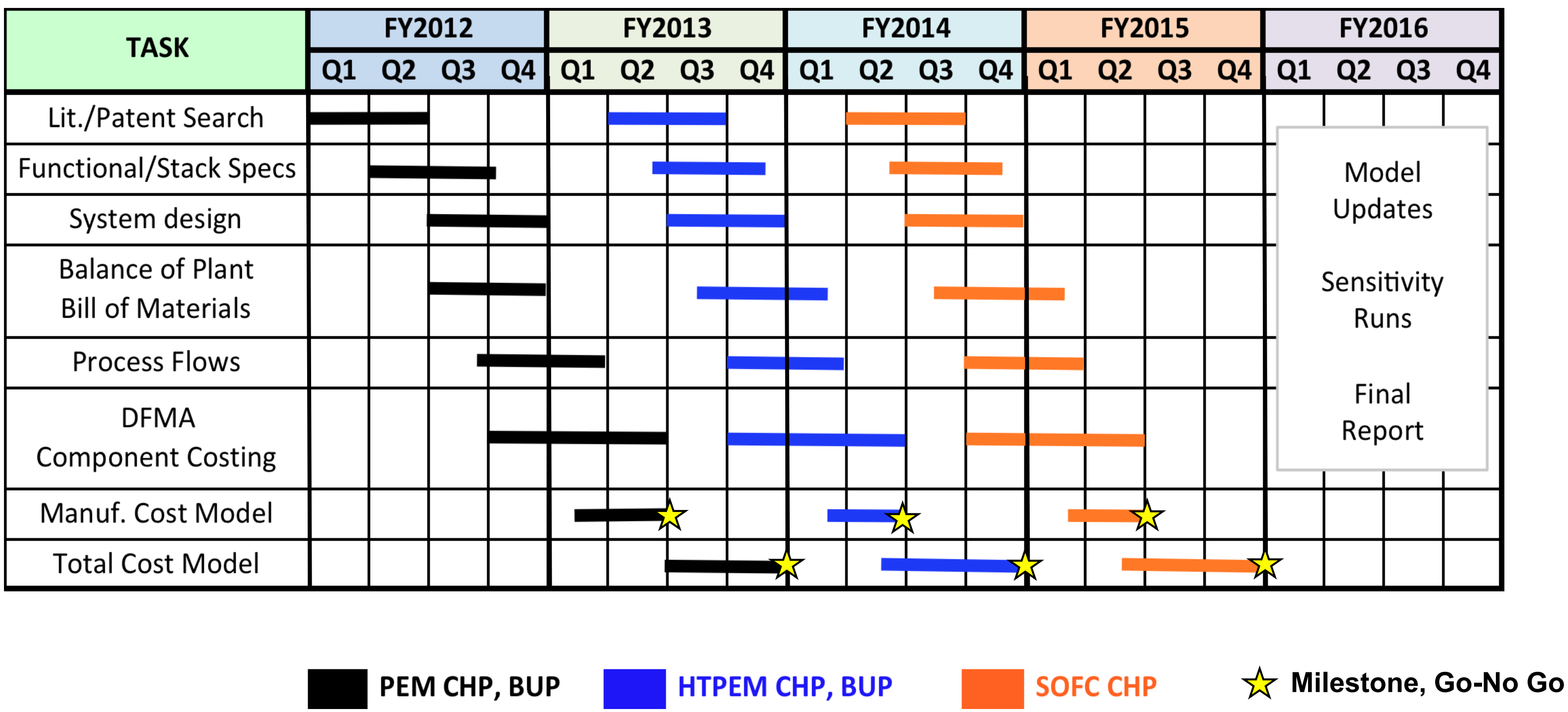
LCA database tools, Integrated Model in Analytica

Milestones - AOP 2012 / 2013

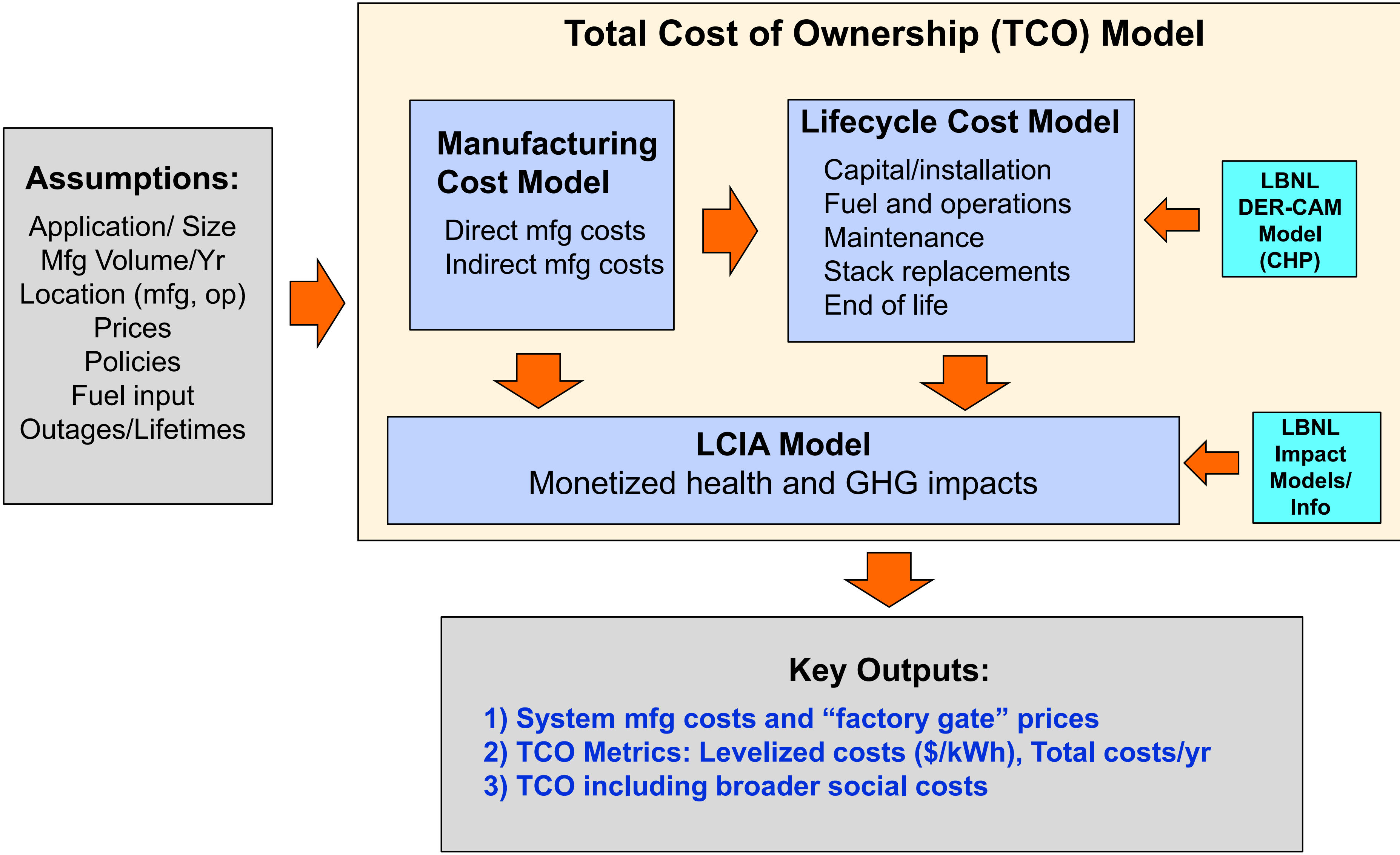
Task	Description	Status
Task 8.2 (6/12)	Meetings with project Advisory Partner groups	Done
Task 8.2 (6/12)	Develop technical and performance specifications for LTPEM fuel cells and initial applications (Stationary, CHP, and Backup Power)	Done
Task 8.3 (9/12)	Detailed LTPEM design plans and BOMs; including cell stack and balance of plant components plus materials and component requirements and cost estimates.	Done
3/13	Manufacturing cost model completed for LTPEM CHP and BU-Power systems.	Done
6/13	Literature search and functional specs defined for HTPEM CHP and BU-Power systems.	In Progress
9/13	DFMA and Total cost of ownership model completed for LTPEM CHP and BU-Power systems	In Progress

GANTT: 5-year Project Overview

- **LT-PEM CHP and BU-Power initial focus**
  - **Manufacturing Cost Model (PEM CHP, BU-Power) - March 2013**
  - **Total Cost Model (PEM CHP, BU-Power) - Sept 2013**
  - **HTPEM, SOFC to follow**

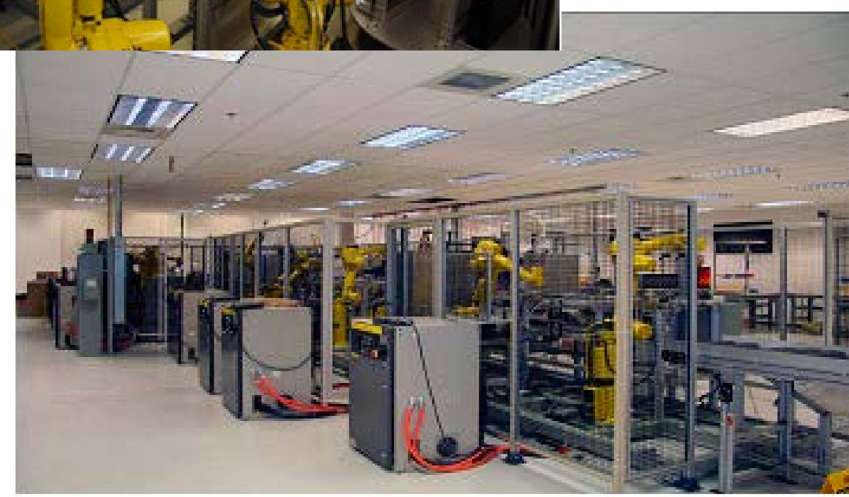


TCO Model Structure and Key Outputs



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

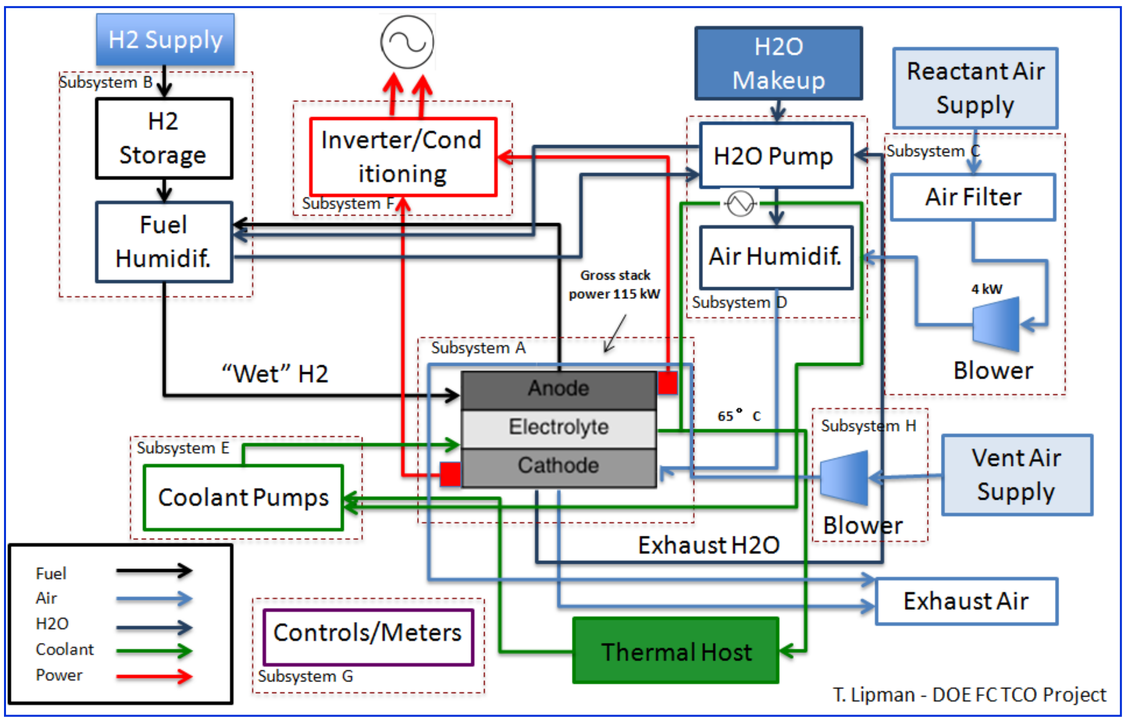


Source: Altergy Systems

CHP System Designs and Specs

- **Functional specifications completed for 1, 10, 50, 100, 250kW H2 fuel systems**

SYSTEM DESIGN



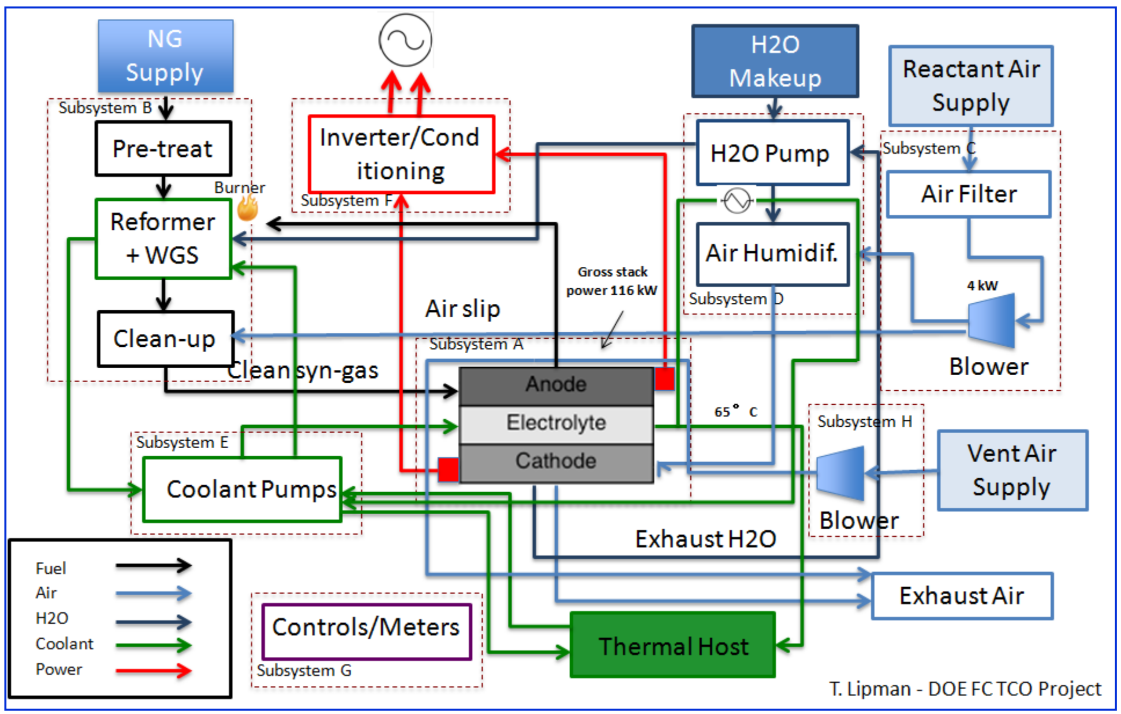
FUNCT. SPECS – 100kW

100 kW Size	Unique Properties:	Best. Ests.	Units:
System	Gross system power	115	kW
	Net system power	100	kW
	Physical size	2.9x4.8x9	meter x meter x meter
	Physical weight	~8,000 kg	kg
	Electrical output	480V AC	Volts AC or DC
	Peak ramp rate	12	kW/sec - size dep
	Waste heat recovery	188400	BTU/hr
	Waste heat grade	65	Temp. °C
	Fuel utilization	9.08	SLPM
also see fn->	Avg. electrical efficiency	38	% LHV
	Thermal efficiency	30	% LHV
	Total efficiency	68	Elect.+thermal (%)
Stack	stack power	8.85	kW
	total plate area	360	cm^2
	CCM coated area	232	cm^2
	single cell active area	198	cm^2
	gross cell inactive area	45	%
	cell amps	126	A
	current density	0.64	A/cm^2
	reference voltage	0.7	V
	power density	0.446	W/cm^2
	single cell power	88	W
	cells per stack	100	cells
	percent active cells	100	%
	stacks per system	13	stacks
Parasitics	Compressor/blower	4	kW
	Other paras. loads	11	kW
	Parasitic loss	15	%

CHP System Designs and Specs

- **Functional specifications** completed for 1, 10, 50, 100, 250kW **reformate fuel** systems

SYSTEM DESIGN

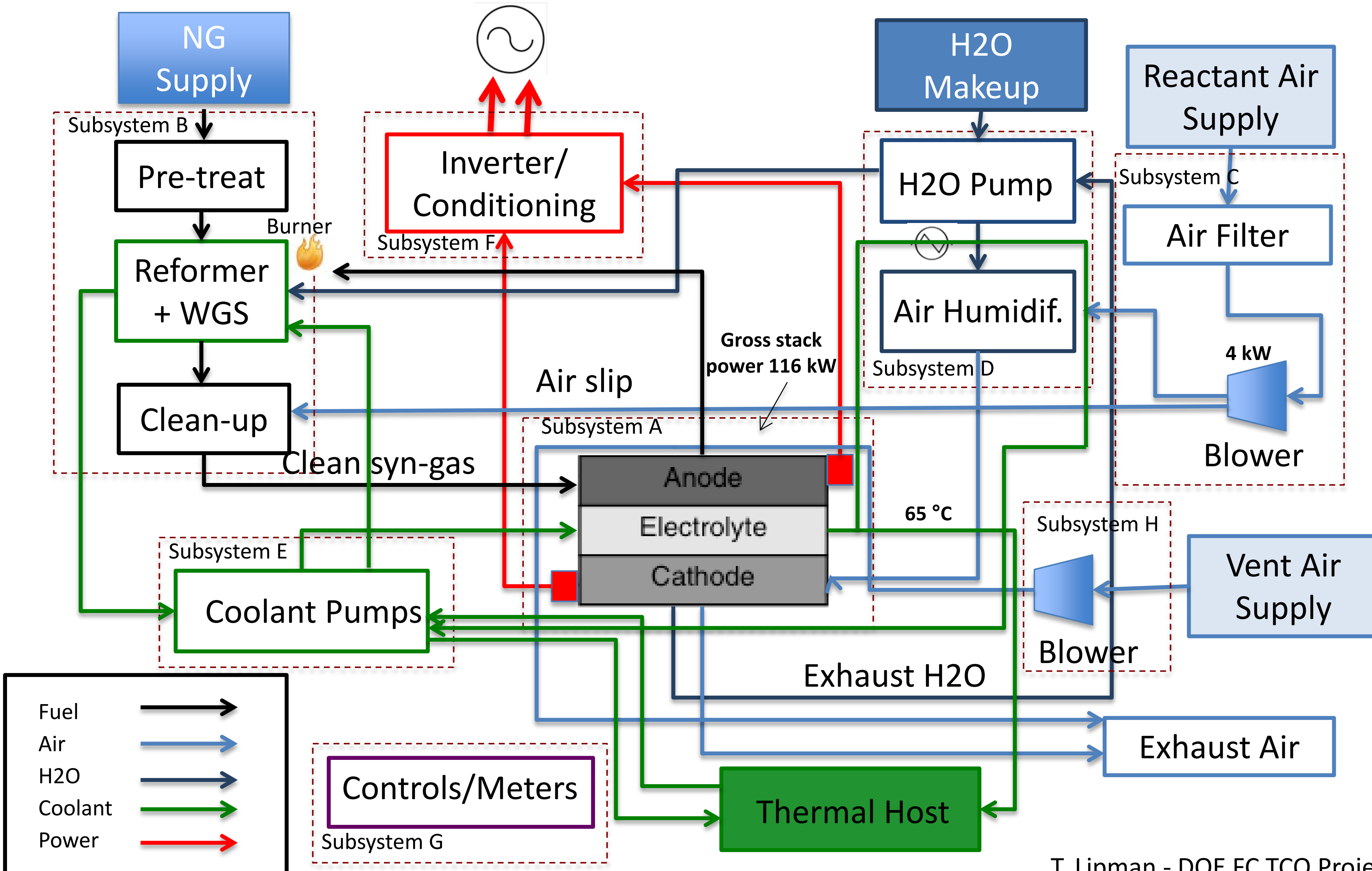


FUNCT. SPECS – 100kW

100 kW Size	Unique Properties:	Best. Ests.	Units:
System	Gross system power	116	kW
	Net system power	100	kW
	Physical size	2.9x4.8x9	meter x meter x meter
	Physical weight	~8,000 kg	kg
	Electrical output	480V AC	Volts AC or DC
	Peak ramp rate	12	kW/sec - size dep
	Waste heat recovery	188,400	BTU/hr
	Waste heat grade	65	Temp. °C
	Fuel utilization	9.08	SLPM
also see fn->	Avg. electrical efficiency	38	% LHV
	Thermal efficiency	30	% LHV
	Total efficiency	68	Elect.+thermal (%)
Stack	stack power	8.92	kW
	total plate area	360	cm^2
	CCM coated area	232.2	cm^2
	single cell active area	198	cm^2
	gross cell inactive area	45	%
	cell amps	116	A
	current density	0.58	A/cm^2
	reference voltage	0.7	V
	power density	0.409	W/cm^2
	single cell power	81	W
	cells per stack	110	cells
	percent active cells	100	%
	stacks per system	13	stacks
Parasitics	Compressor/blower	4	kW
	Other paras. loads	12	kW
	Parasitic loss	16	%

Technical Accomplishments

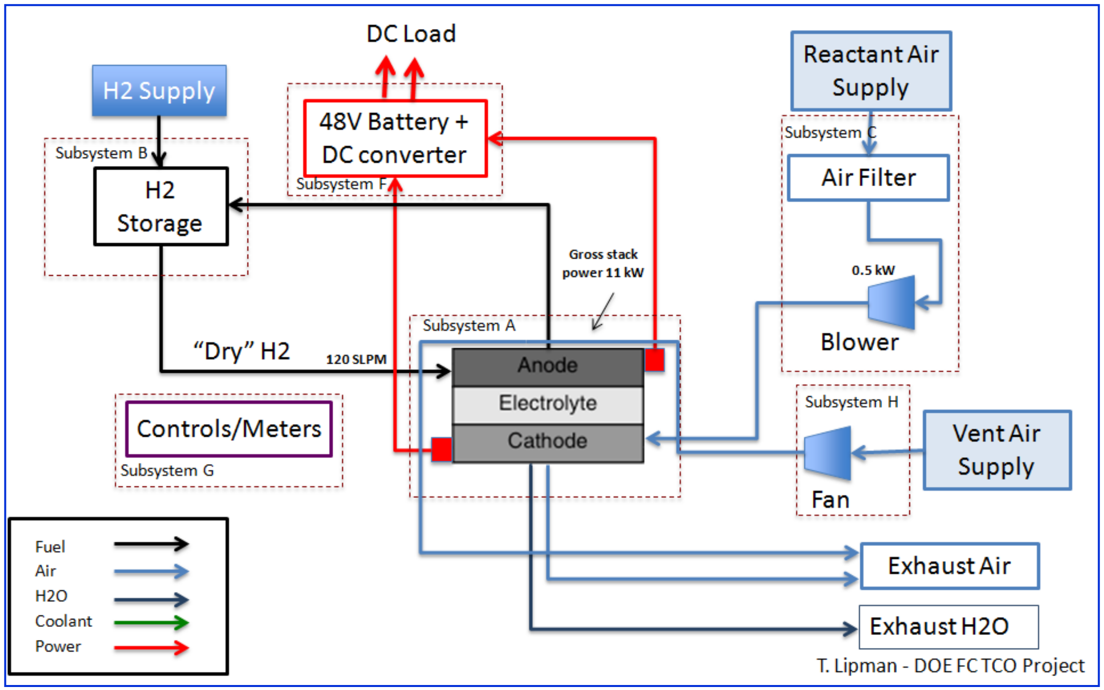
100 kW PEM Stationary (CHP) – Reformate Fuel



T. Lipman - DOE FC TCO Project

Back-up Power Designs and Specs

SYSTEM DESIGN



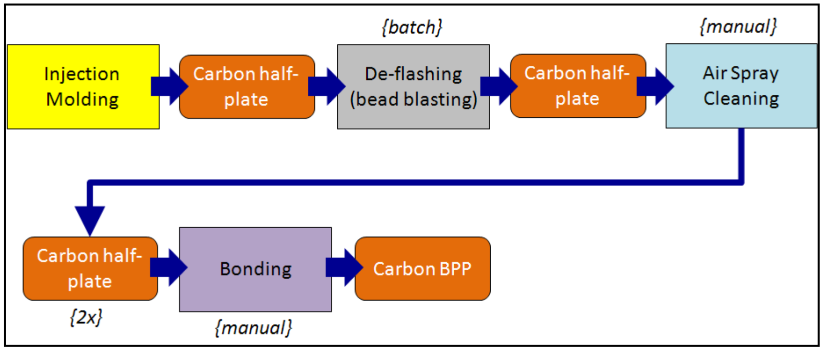
FUNCT. SPECS – 10kW

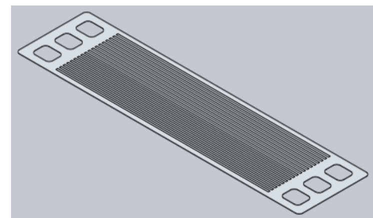
10 kW Size	Unique Properties:	Best. Ests.	Units:
System	Gross system power	11	kW
	Net system power	10	kW
	Physical size	0.53 x 0.83 x 1.3	meter x m x m
	Physical weight	172 kg	kg
	Electrical output	48V DC	Volts AC or DC
	Peak ramp rate	1.2	kW/sec
	Waste heat recovery		BTU/hr
	Waste heat grade		Temp. °C
	Fuel use rate	120	SLPM
also see fn->	Avg. electrical efficiency	46.5%	% LHV
	Thermal efficiency	0	% LHV
	Total efficiency	46.5%	Elect.+thermal (%)
Stack	stack power	11	kW
	total plate area	360	cm^2
	CCM coated area	232	cm^2
	single cell active area	198	cm^2
	gross cell inactive area	45	%
	cell amps	112	A
	current density	0.57	A/cm^2
	reference voltage	0.70	V/cell
	power density	0.40	W/cm^2
	single cell power	79	W
	cells per stack	140	cells
	percent active cells	100	%
	stacks per system	1	stacks
Parasitics	Blower	0.5	kW
	Other paras. loads	0.5	kW
	Parasitic loss	9.1	%

Technical Accomplishments

Manufacturing Cost Model - Plates

Process Flow



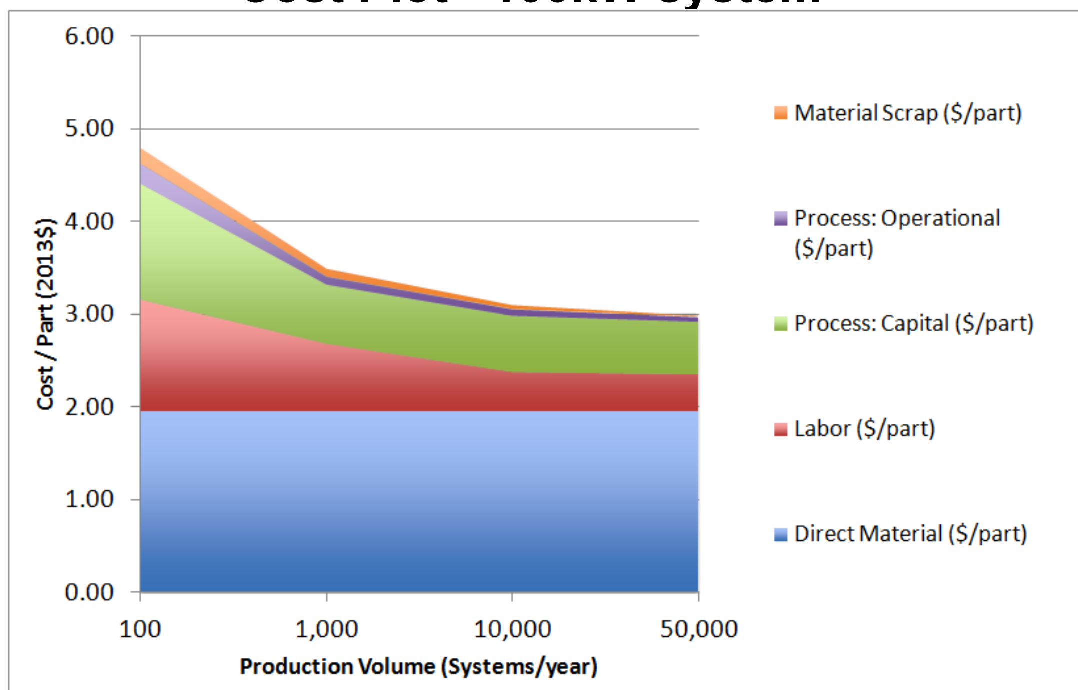


L = 360mm, W = 100mm,
T_{max} = 3mm

Key Materials

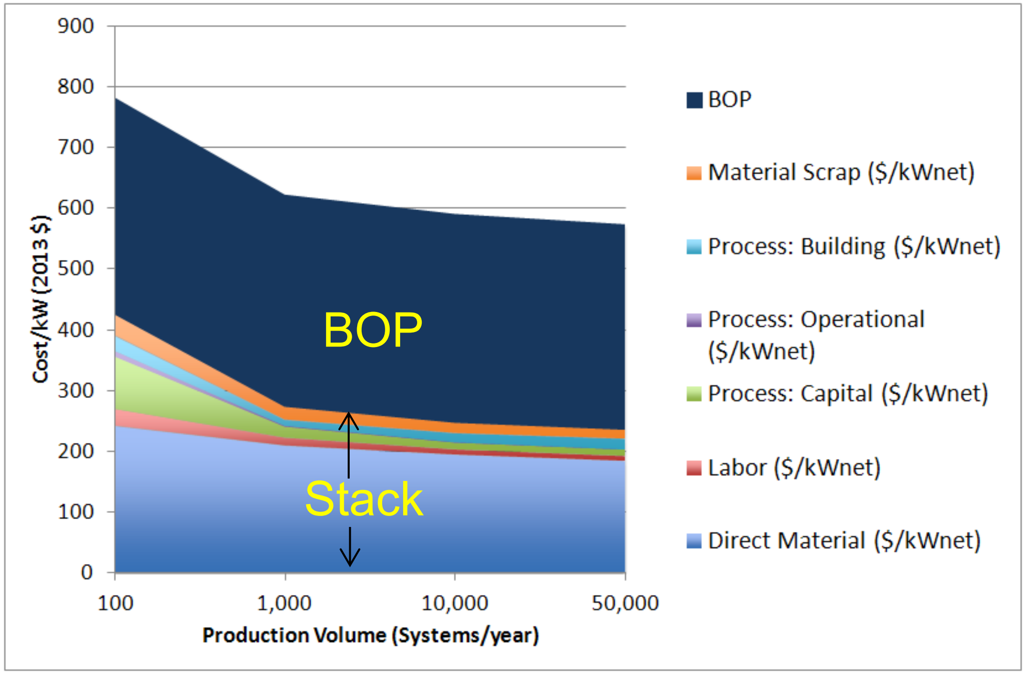
- **Binder (polymer): Polypropylene**
- **Filler (carbon):**
  Graphite + Carbon Black
- **Composition:**
  30wt% PP, 66.5wt% Graphite, 3.5wt% Carbon Black
- **Composite density:**
  1.585 g/cm^3
- **Composite cost: $10.259/kg**

Cost Plot - 100kW system

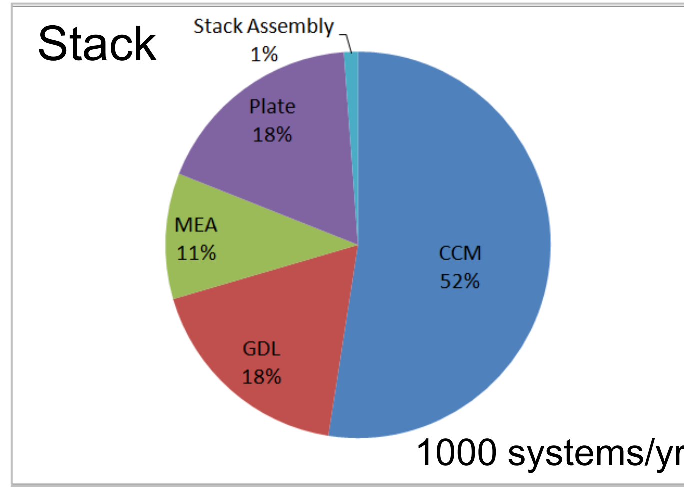


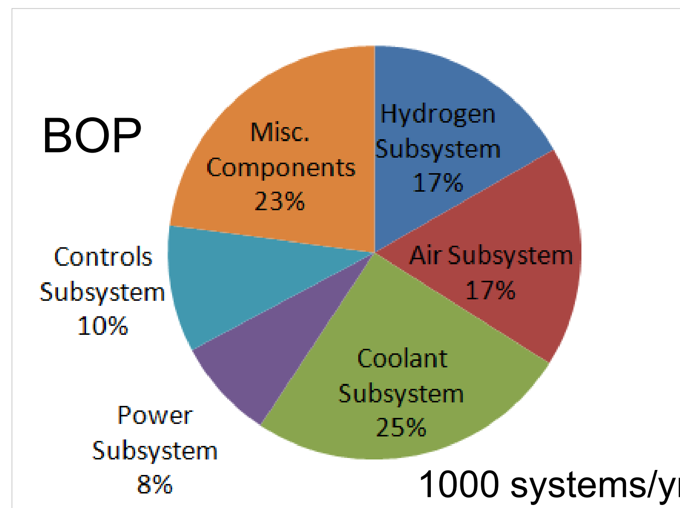
Manufacturing Cost Model – CHP H2

100kW CHP System (H2)



Stack Size (kW)	100			
Production Volume (Systems/yr)	100	1,000	10,000	50,000
Stack Cost ($/kWnet)	$ 426	$ 274	$ 248	$ 236
BOP ($/kWnet)	$ 357	$ 349	$ 343	$ 338
Total ($/kW$_{net}$)	$ 782	$ 622	$ 591	$ 574

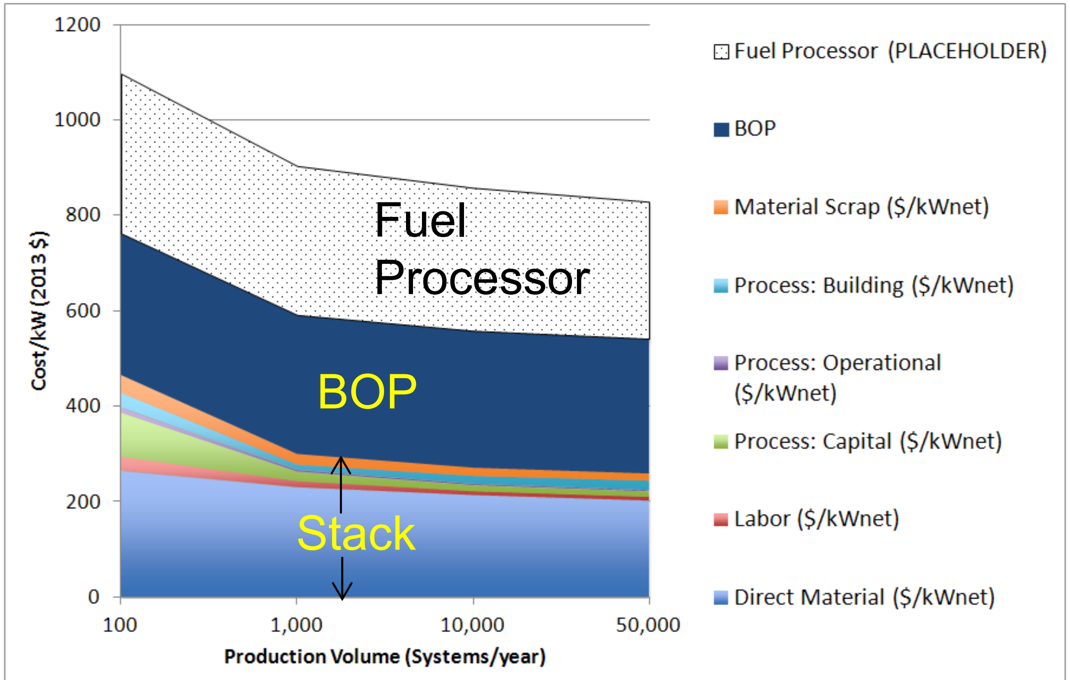




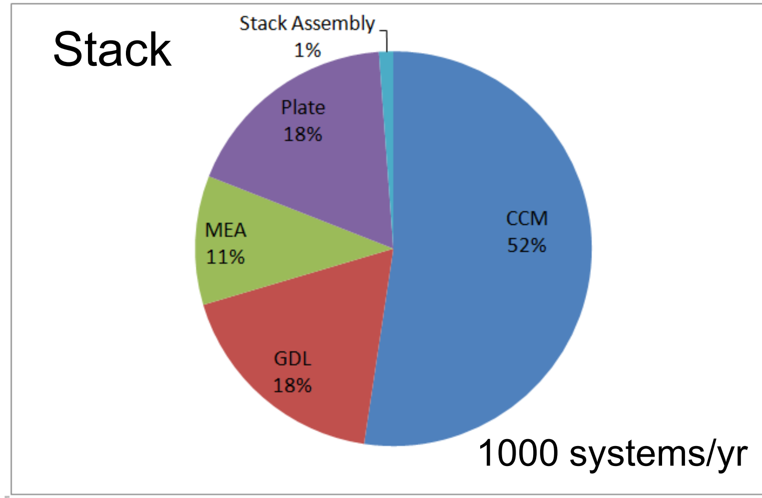
Note: Cost refers to direct manuf. cost and excludes profit, R&D costs, and other corporate costs (sales and marketing, general/admin., warranty, etc.).

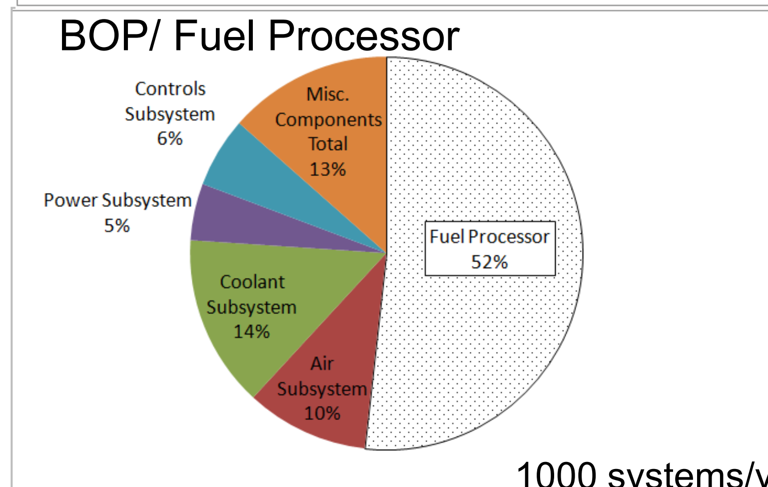
Manufacturing Cost Model – CHP reformate

100kW CHP System (Reformate)



Stack Size (kW)	100			
Production Volume (Systems/yr)	100	1,000	10,000	50,000
Stack Cost ($/kWnet)	$ 466	$ 301	$ 272	$ 260
BOP ($/kWnet)	$ 297	$ 291	$ 287	$ 282
Fuel Processor ($/kWnet)	$ 335	$ 313	$ 300	$ 288
Total ($/$kW_{net}$)	$ 1,098	$ 905	$ 859	$ 830



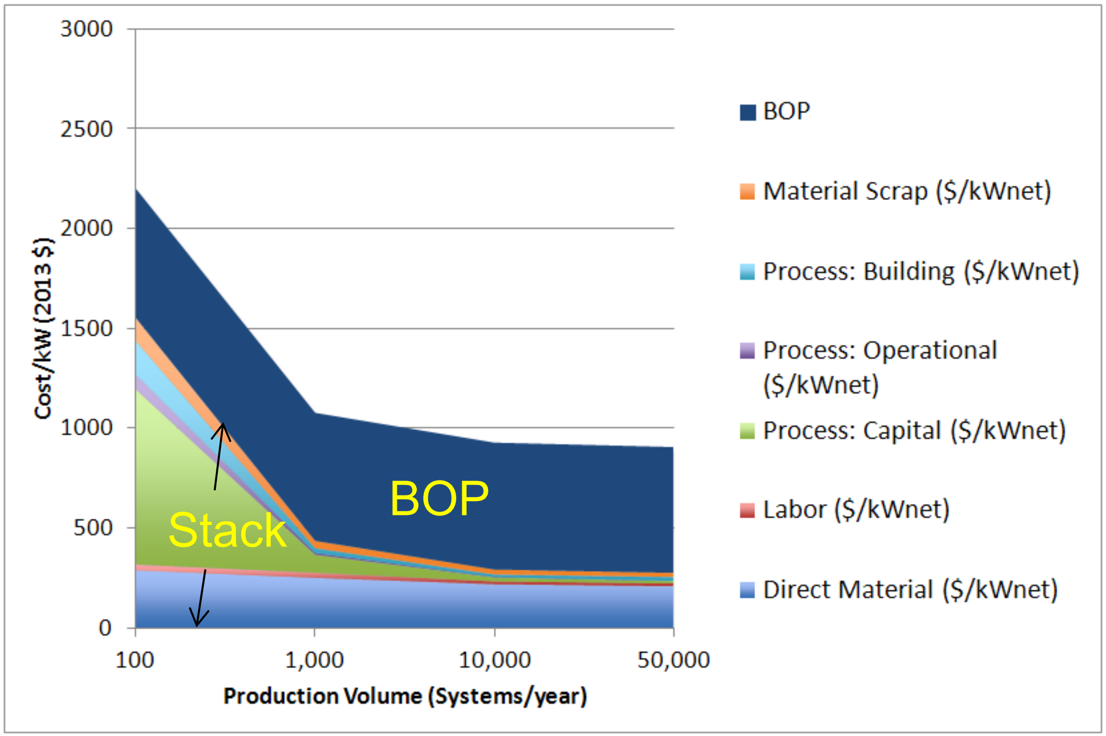


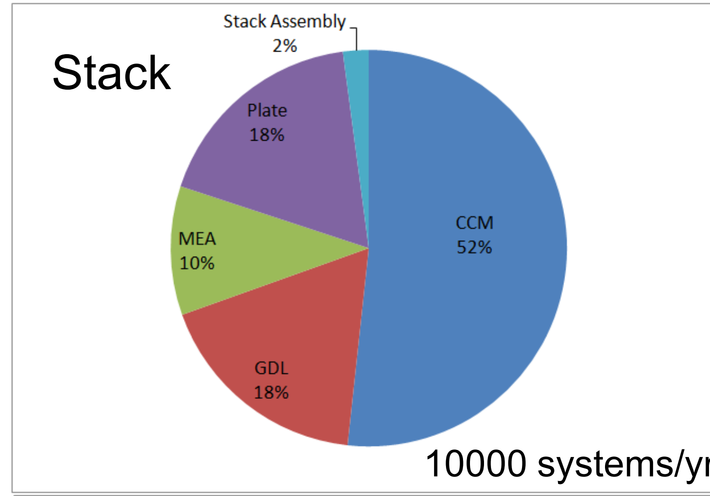
Note: Cost refers to direct manuf. cost and excludes profit, R&D costs, and other corporate costs (sales and marketing, general/admin., warranty, etc.).

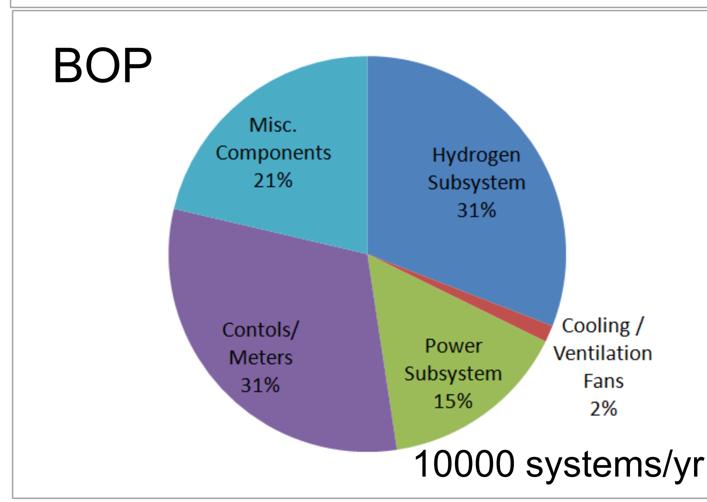
Technical Accomplishments

Manufacturing Cost Model – Backup Power

10kW BU-Power System (H2)



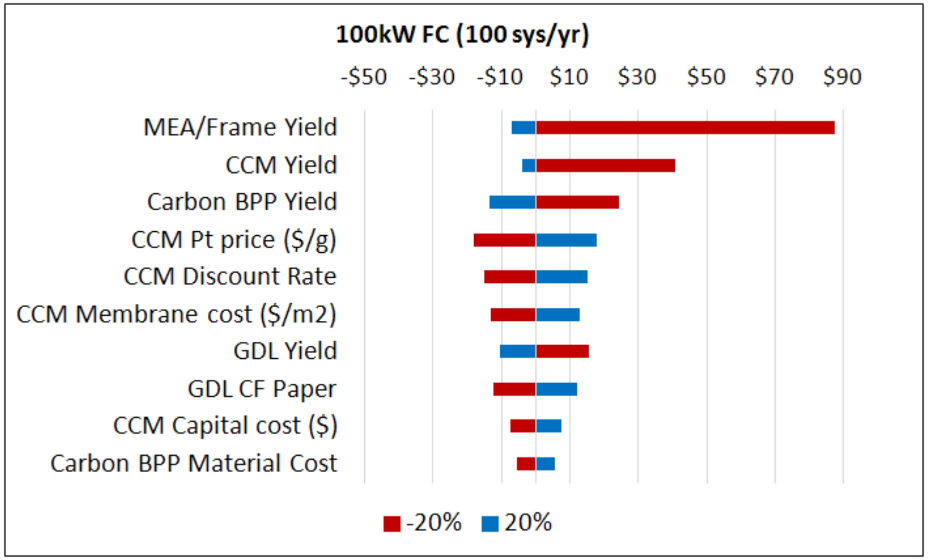


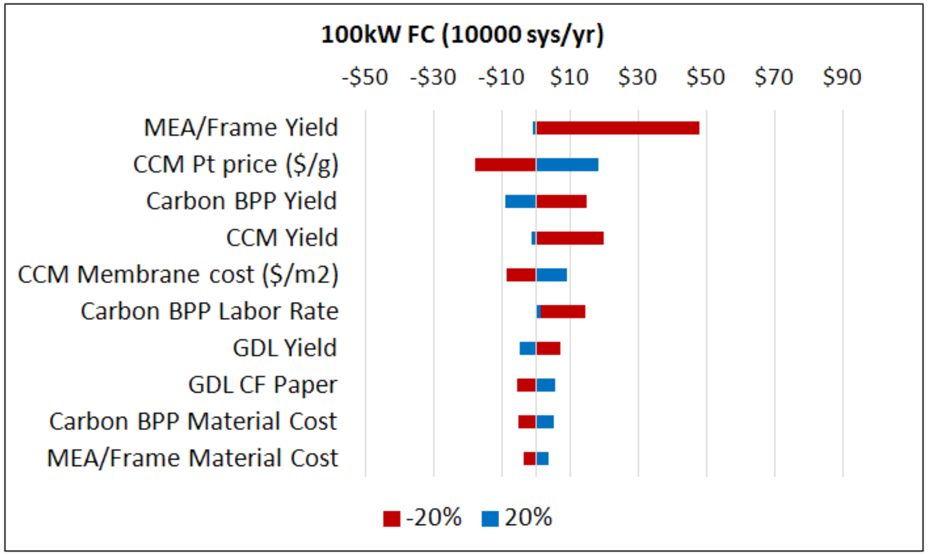


Stack Size (kW)	10			
Production Volume (Systems/yr)	100	1,000	10,000	50,000
Stack Cost ($/kWnet)	$ 1,549	$ 433	$ 290	$ 273
BOP ($/kWnet)	$ 647	$ 641	$ 636	$ 631
Total ($/$kW_{net}$)	$ 2,196	$ 1,074	$ 926	$ 903

Note: Cost refers to direct manuf. cost and excludes profit, R&D costs, and other corporate costs (sales and marketing, general/admin., warranty, etc.).

Manufacturing Cost Model – Sensitivity ($/kW)





Note: Yield is limited to 100% for "+20% case"

Yield of MEA/Frame, CCM, BPP and Pt price are key factors

LCC Use Phase: DER CAM / Bldg Modeling

DER-CAM Tool for Realistic FC Duty Cycles in CHP Mode:

- LBNL Distributed Energy Resources Customer Adoption Model (DER-CAM) optimization of distributed generation (DG) resource economics in micro-grid context
- Incorporates building load shapes for electricity and heating for given climate zone
- Includes utility tariff structures, demand charges, and electricity marginal carbon intensity
- Allows comparison of fuel cell CHP case vs. conventional "no DG" reference case
- Includes: Capital amortization, natural gas fuel costs, O&M costs, stack replacement costs, avoided utility costs

Life Cycle Cost Example

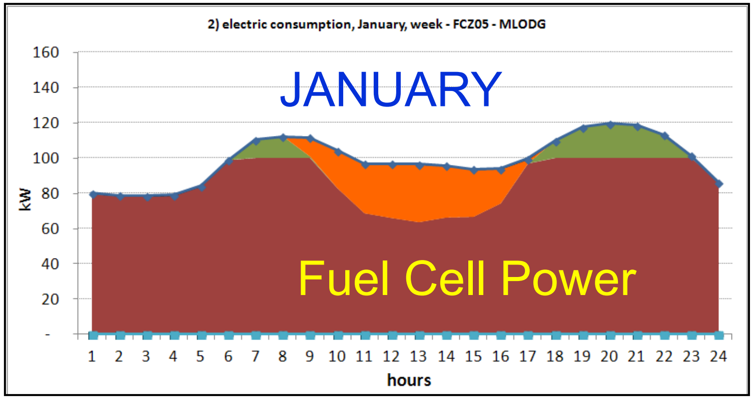
Climate Zone05 MED-LODGING (San Francisco)

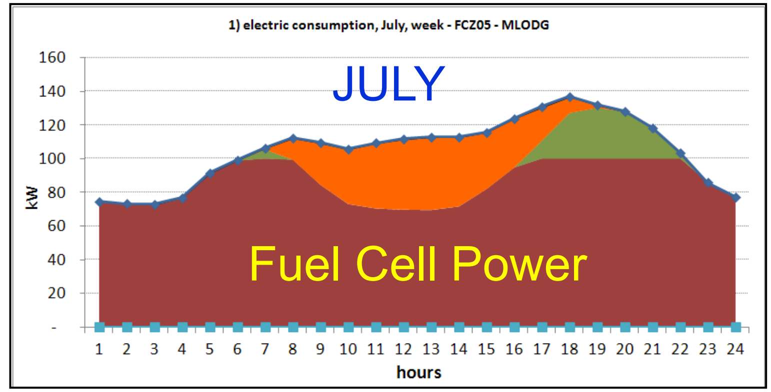
- 100kW Fuel Cell System
- Annual costs
  - — Cap amort $16.8K
  - — O&M $22.2K
  - — Fuel $48.6K
- Annual Savings vs No DG Case
  - 34% CO_2 Emissions
  - 37% Energy Costs

Climate Zone13 MED-LODGING (San Diego)

- 100kW Fuel Cell System
- Annual costs
  - — Cap amort $16.8K
  - — O&M $26.2K
  - — Fuel $48.8K
- Annual Savings vs No DG Case
  - 23% CO_2 Emissions
  - 20% Energy Costs
  - 59% lower demand charges

Technical Accomplishments
San Francisco, Medium Lodging Building



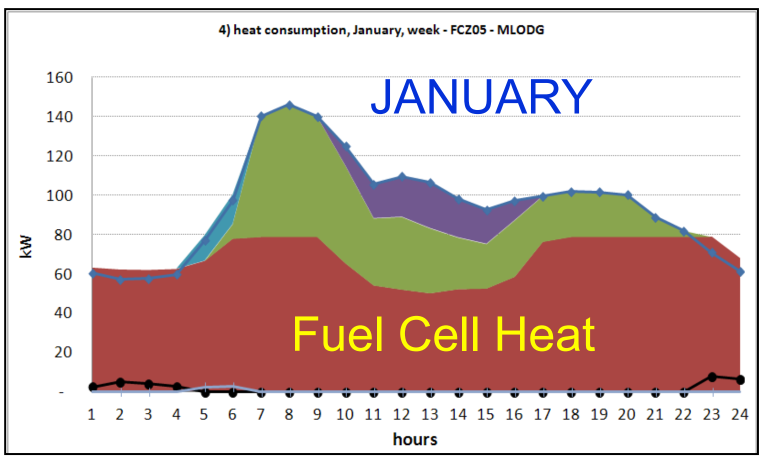


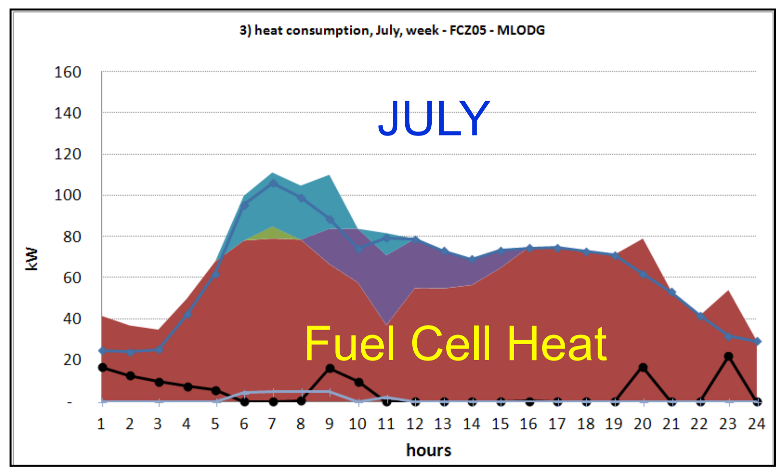
electricity generation from DG

electricity generation from PV

utility electricity consumption

electricity provided by battery





heat collected from DG

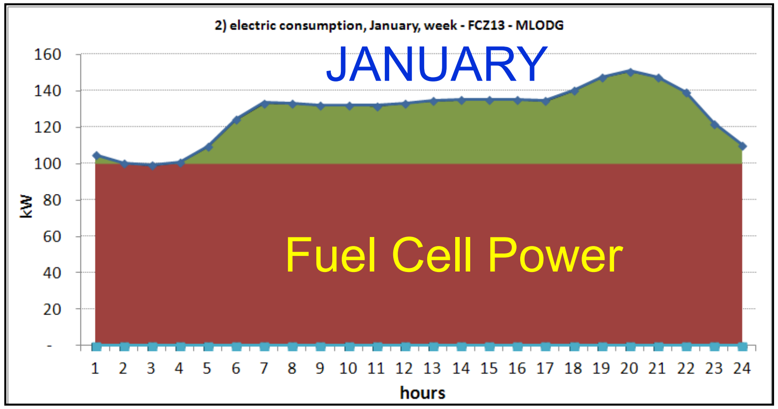
heat collected from solar thermal

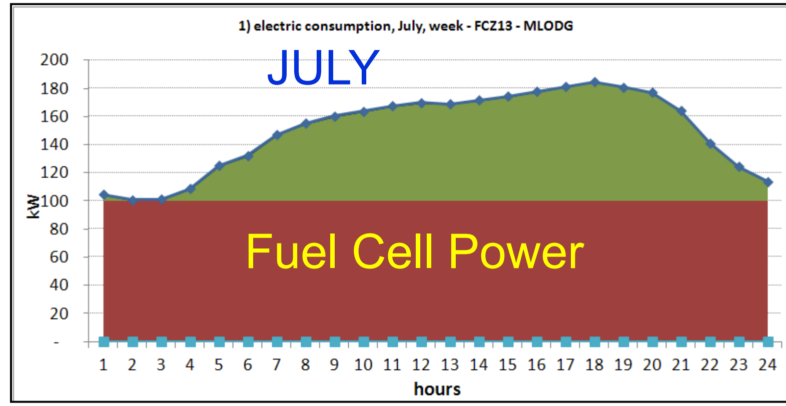
heat collected from NG

heat taken from storage

Technical Accomplishments

San Diego, Medium Lodging Building



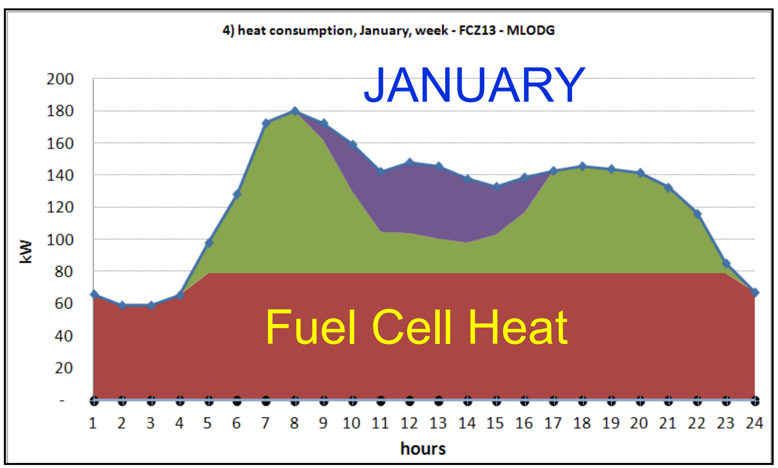


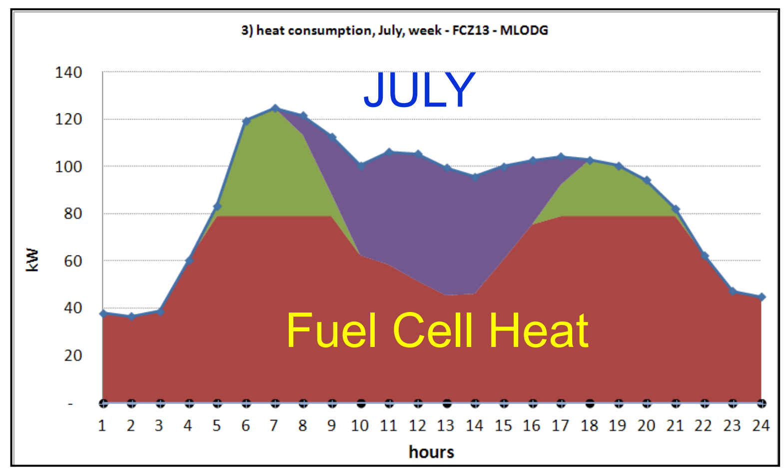
electricity generation from DG

electricity generation from PV

utility electricity consumption

electricity provided by battery





heat collected from DG

heat collected from solar thermal

heat collected from NG

heat taken from storage

High Temp-PEM Membrane Lit./Patent Review

BERKELEY LAB

- **Patent search conducted for HT-PEM membrane**
- **PBI Membrane manufacturing review completed**

Relevant Patents:

— **Modified Polybenzimidazole (PBI) Membranes for Enhanced Polymer Electrochemical Cells** (US Patent 6,987,163 B2 (2006))

— **Proton- Conducting Electrolyte Membrane Method for Production and use thereof in a Fuel Cell** (US Patent 7,655,334 B2 (2010))

— **High Temperature Membrane Electrode Assembly with High Power Density and Corresponding Method of Making** (US Patent 2011/0244364 A1 (2011))

— **Proton Conductive Polymer Electrolyte and Fuel Cell Including the Same** (US Patent 8,017,659 B2 (2011))

— **Polymer Electrolyte Membrane for Fuel Cell, Method of Manufacturing the Same, and Fuel Cell Employing the Same** (US Patent 8,039,166 B2 (2011))

Processing Step	Primary Process Input	Primary Process Outputs
1. Casting	Dimethylacetamide solution, and equilibrated with 11M $H3PO4$	Cast films
2. Solvent Evaporation	At 60C- 140C	Polymerized cast film
2. Boiling	Water, cast films	Films
3. Doping	Film, phosphoric acid	Acid doped PBI membrane

Processing Step	Primary Process Input	Primary Process Outputs
1. Knife-edge or slot die dep. on sacrificial carrier	PBI powder and DMAc on glass plate	Film formation
2. IR heating 140C	Deposited film	PBI membrane; Multiple passes of 1, 2.
3. Doping	Film, phosphoric acid	Acid doped PBI membrane

Collaborations

- **Partners**

  University of California Berkeley

  Laboratory for Manufacturing and Sustainability, Dept. of Mechanical Engineering:
  - — Manufacturing process analysis, DFMA analysis

  Transportation Sustainability Research Center and DOE Pacific Region Clean Energy Application Center:
  - — System and BOP design, funct. specs, BOM definition, parametric relationships
  - — CHP applications and functional requirements

  Ballard Power Systems
  - — Consultation on fuel cell system design and manufacturing processes

  Strategic Analysis:
  - — Fuel processor systems and DFMA costing

- **Other Collaborators**
  - — **Altergy:** Consultation on backup power system

Future Work

FY13-14 Specific Plans :

- LT-PEM CHP, BUP applications: Total Cost of Ownership Model -- Sept 2013
  - Manufacturing cost model enhancements (CCM, metal plates, fuel processor)
  - Life cycle cost profiles for buildings in different geographies
  - End-of-life Pt recovery
  - Environmental/health impact valuation

- HT-PEM CHP, BUP applications: Manufacturing Cost model -- March 2014
  - Literature review
  - Functional and stack specifications
  - System design
  - Process flows
  - Component costing / DFMA

Building Modeling – Other U.S. Regions

- Extension of DER-CAM model to other climate zone in U.S.
  - 16 climates zones
  - 16 building types x 3 vintages
  - Comprehend utility tariff structure
- Northwest/Midwest U.S. Simulation of FCS adoption
  - Output: displaced grid electricity and displaced utility fossil fuel (natural gas, heating oil) + CO_2 reduction
  - DER-CAM Output + Criteria pollutant impact ➔Input to Lifecycle Impact Assessment Model (LCIA)

Quantifying human health damages

Emissions

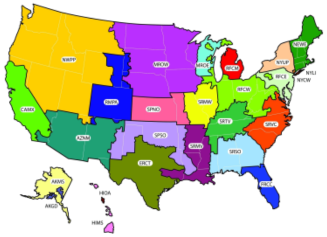
Ambient concentration

Exposure

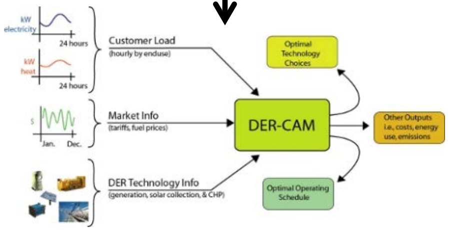
Effect

Damages

Define geographic boundary of interest

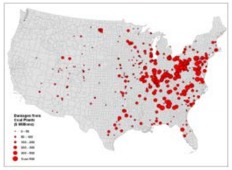


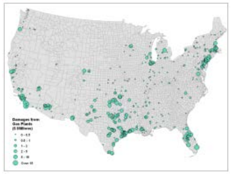
Fuel cell cost & technology parameters



Baseline scenario

Fuel cell scenario





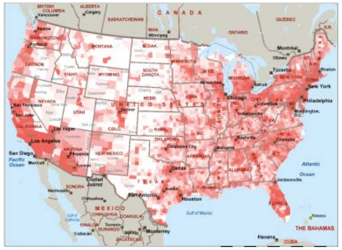
Map changes at power plant and building levels

Net emissions = avoided emissions from power plants & building heating + fuel cell system emissions

Pollutant Emissions Modification

Air quality modeling

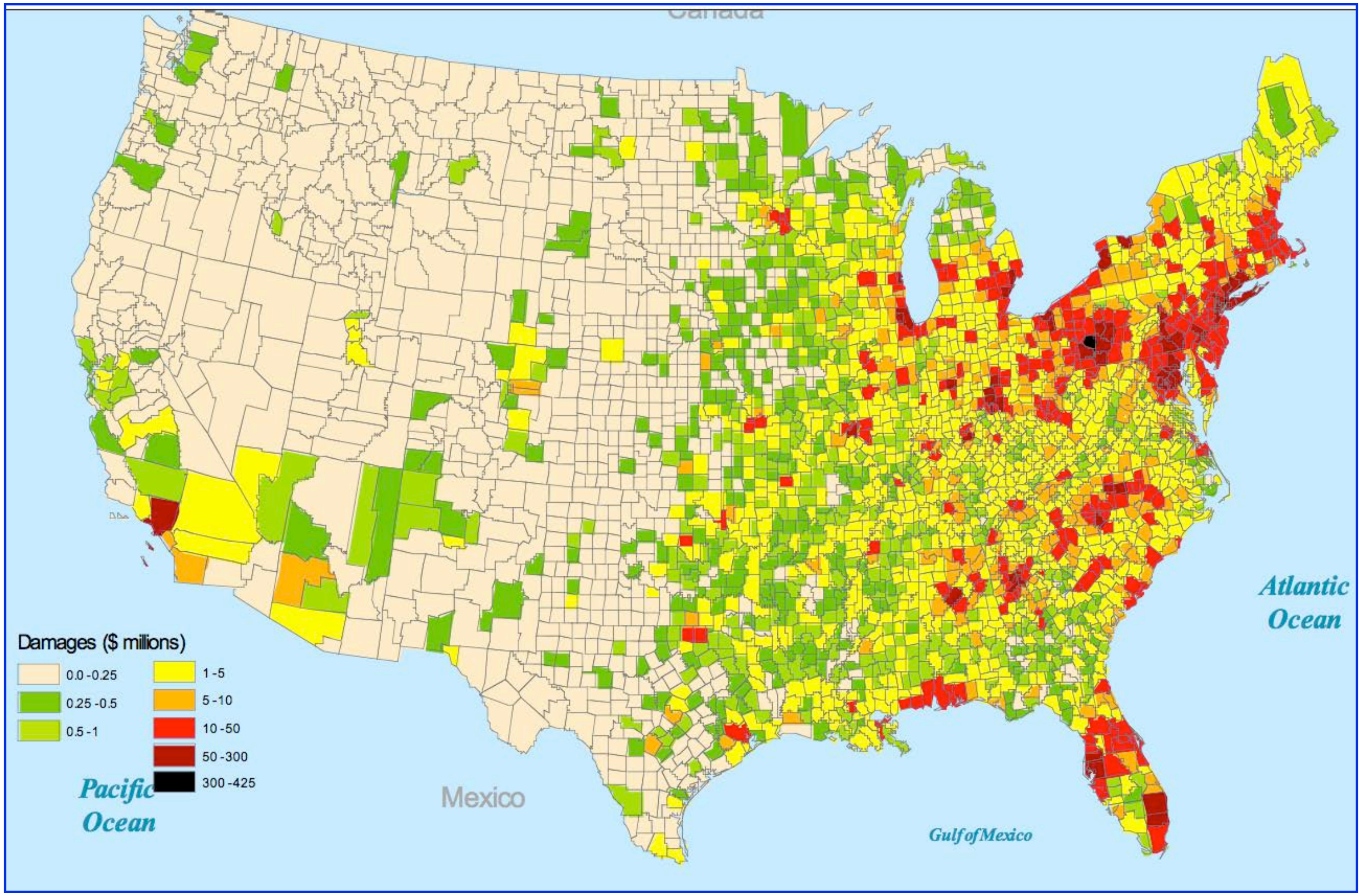
Intake fraction



Dose-response

Monetized damages

Example: monetized health damage from fossil fuel electric power plants



Ref: APEEP website, Nicholas Muller

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: ***System designs, functional specs, and manufacturing cost models for LT-PEM CHP and BU-Power systems. Demonstration of LCC cost modeling with DER-CAM.***

Collaboration: ***Partnerships with UC-Berkeley manufacturing analysis and transportation sustainability research groups and Ballard Power Systems. Collaboration with Altergy and ClearEdge Power, and planned with SA.***

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

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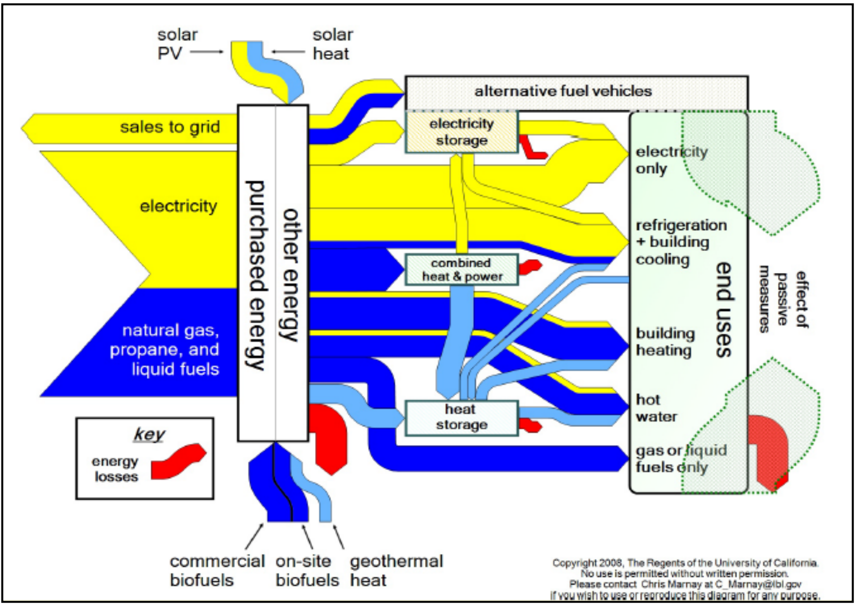
Backup technical slides

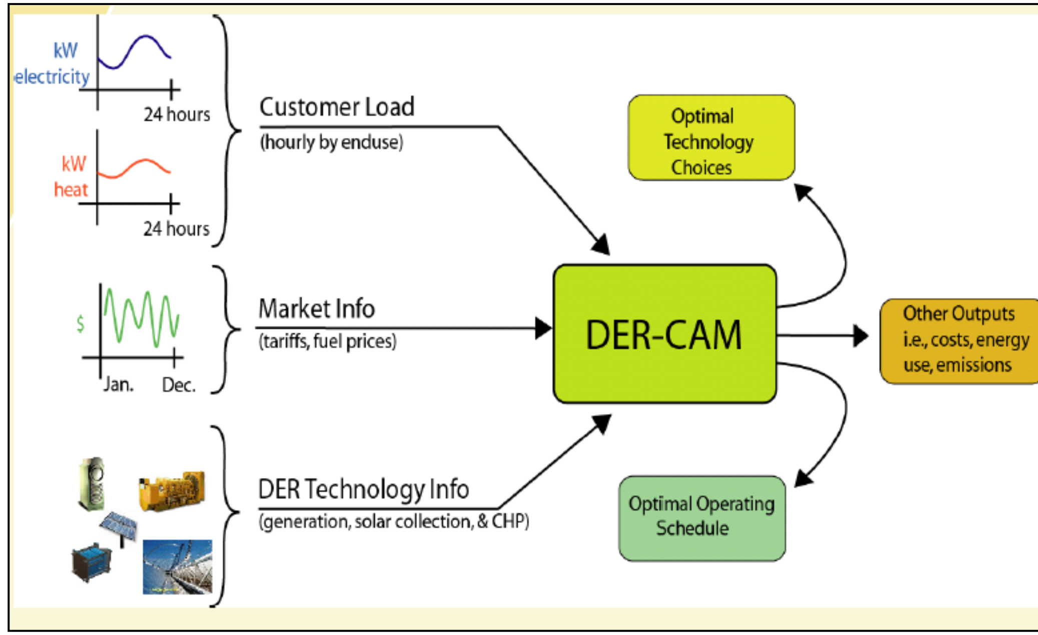
Balance of Plant Components

- **Direct costing example, CHP with H2 fuel system**

Balance of Plant - Stationary PEMFC		Plant Capacity [in kW]				
Subsytems		**250**	**100**	**50**	**10**	**1**
Subsystem 1: Fuel	Hydrogen Tank	$ 1,280.00	$ 1,198.00	$ 1,174.00	$ 1,096.00	$ 1,096.00
	Hydrogen Purifier	$ 2,226.00	$ 1,785.00	$ 1,207.00	$ 987.00	$ 777.00
	Hydrogen Pump	$ 3,066.00	$ 1,763.00	$ 1,120.00	$ 740.00	$ 388.00
	Hydrogen Pump Motor	$ 2,122.00	$ 1,293.00	$ 781.00	$ 752.00	$ 676.00
	Hydrogen Piping	$ 420.00	$ 210.00	$ 105.00	$ 52.50	$ 26.25
		$ 9,114.00	**$ 6,249.00**	**$ 4,387.00**	**$ 3,627.50**	**$ 2,963.25**
Subsystem 2: Air	Air Humidfier Tank	$ 2,426.62	$ 1,302.76	$ 794.56	$ 491.23	$ 46.25
	Humidification Pump	$ 639.00	$ 544.00	$ 388.00	$ 315.00	$ 305.00
	Air Pump Motor	$ 3,944.31	$ 1,648.00	$ 559.00	$ 326.00	$ 435.00
	Radiator	$ 2,890.00	$ 2,500.00	$ 2,100.00	$ 1,700.00	$ 1,500.00
	Humidifciation Pump Motor	$ 338.00	$ 258.00	$ 237.00	$ 231.00	$ 226.00
		$ 10,237.93	**$ 6,252.76**	**$ 4,078.56**	**$ 3,063.23**	**$ 2,512.25**
Subsystem 3: Coolant	Coolant Tank	$ 2,186.00	$ 1,598.93	$ 289.39	$ 75.04	$ 68.52
	Coolant Pump Motor	$ 1,682.00	$ 1,155.00	$ 940.00	$ 586.00	$ 549.00
	Coolant Piping***	$ 280.00	$ 140.00	$ 70.00	$ 35.00	$ 21.00
	External Cooling Motor	$ 360.00	$ 271.35	$ 234.00	$ 191.70	$ 170.00
	Heat Exchanger	$ 7,635.00	$ 6,350.00	$ 5,185.00	$ 4,645.00	$ 3,270.00
		$ 12,143.00	**$ 9,515.28**	**$ 6,718.39**	**$ 5,532.74**	**$ 4,078.52**
Subsytem 4: Power System	Power Inverter	$ 1,299.65	$ 923.96	$ 704.00	$ 132.48	$ 46.53
	Braking Transistors	$ 2,730.10	$ 2,047.00	$ 1,943.00	$ 1,840.00	$ 1,840.00
		$ 4,029.75	**$ 2,970.96**	**$ 2,647.00**	**$ 1,972.48**	**$ 1,886.53**
Subsystem 5: Controls/Meters	Variable Frequency Drive	$ 3,549.88	$ 1,907.95	$ 1,067.98	$ 528.53	$ 300.13
	Coriolis Flow Meter* ** (optional)	$ 12,433.00	$ -	$ -	$ -	$ -
	Thermosets	$ 704.00	$ 704.00	$ 704.00	$ 704.00	$ 704.00
	CPU	$ 1,208.56	$ 1,026.77	$ 774.96	$ 264.50	$ 208.57
		$ 17,895.44	**$ 3,638.72**	**$ 2,546.94**	**$ 1,497.03**	**$ 1,212.70**
Subsystem 6: Misc. Components	Tubing	$ 2,145.76	$ 604.28	$ 513.39	$ 154.99	$ 132.25
	Wiring	$ 222.48	$ 111.24	$ 55.62	$ 27.81	$ 13.91
	Enclosure/Housing	$ 8,038.92	$ 6,699.10	$ 5,359.28	$ 3,349.55	$ 1,339.82
	Fasterners	$ 184.50	$ 92.25	$ 46.12	$ 23.06	$ 12.23
	Labor Cost	$ 1,000.00	$ 700.00	$ 500.00	$ 200.00	$ 125.00
		$ 11,591.66	**$ 8,206.87**	**$ 6,474.41**	**$ 3,755.41**	**$ 1,623.21**
Total Cost	$/system	$ 65,011.78	$ 36,833.59	$ 26,852.30	$ 19,448.39	$ 14,276.46
	$/kW	$ 260.05	$ 368.34	$ 537.05	$ 1,944.84	$ 14,276.46

LBNL DER-CAM model / CEUS database



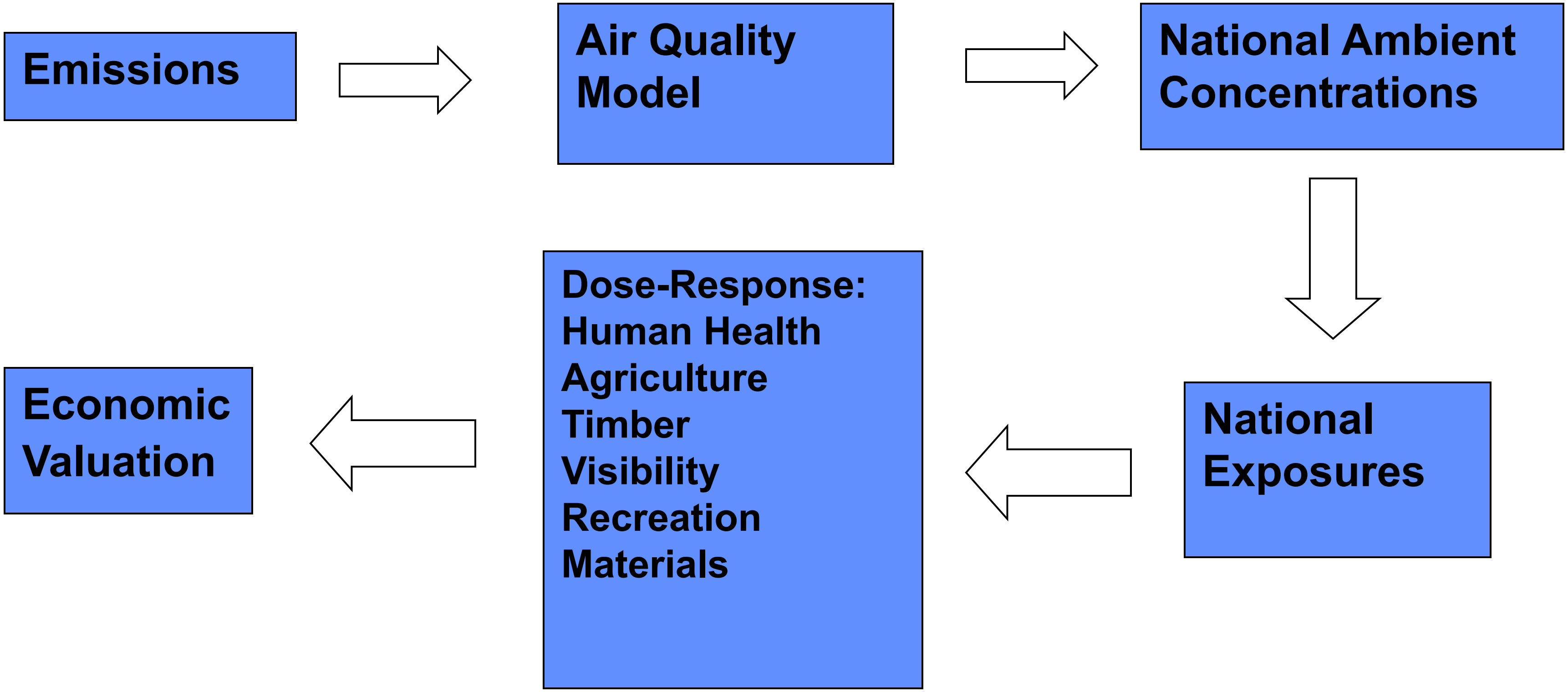


- **LBNL DER-CAM Model** (Distributed Energy Resources Customer Adoption Model)

- **CEUS database** of Commercial building electrical and thermal demand profiles in California: 90% of total commercial floor space is in buildings with a peak load < 1MW.

Peak Load of Building	Number of Types	Total number in SDG&E	%
100 – 250 kW	4	620	35%
250 – 500 kW	3	574	32%
above 500 kW (***)	9	589	33%
Total		1783	

Air Pollution Emissions Experiments and Policy Analysis Model (APEEP)



Nicholas Muller

APEEP Specifications: Air Quality Models

- Air quality model predictions calibrated to Community Multi-scale Air Quality model (Byun, Schere, 2006).
  – CMAQ: USEPA CAIR RIA.
- Focus on ambient concentrations of $PM_{2.5}$ and O_3 (dominant health and environmental externalities)
- Limitations of source-receptor matrix approach.
  – Pollution episodes, atmospheric inversions.
  – Spatial resolution: heterogeneity within county receptors.
  – Atmospheric chemistry.
- Advantages of source-receptor matrix approach.
  – Computational efficiency.
    - Model domain & resolution.

APEEP: Baseline PM2.5 (2002)