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

Timeline

- Project start date: Oct 2011
- Project end date: Sept 2016
- Percent complete: 5%

Budget

- Total project funding
  - DOE share: $ 1.904M
  - Contractor share: n.a.
- Funding received in FY11: $100k
- Planned funding for FY12: $460k

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 envelop to total cost of ownership including externalities
- Lack of High-Volume Membrane Electrode Assembly Processes
- Lack of High-Speed Bipolar Plate Manufacturing Processes

Partners

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

Relevance & Goals

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

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

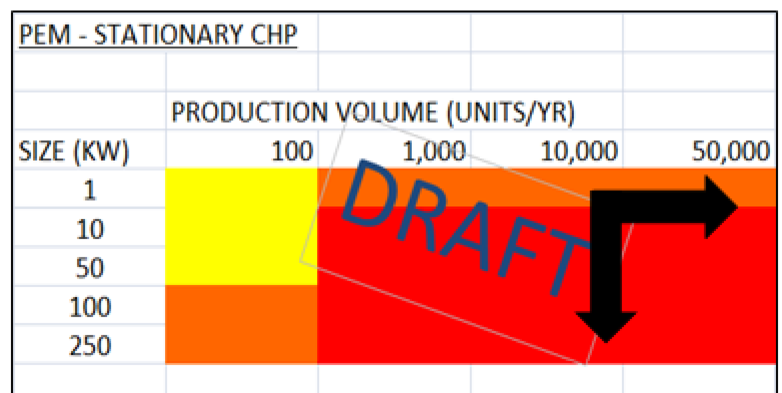
- **carbon credits, end-of-life recycling, reduced costs for building operation**

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.



Chemistries and applications

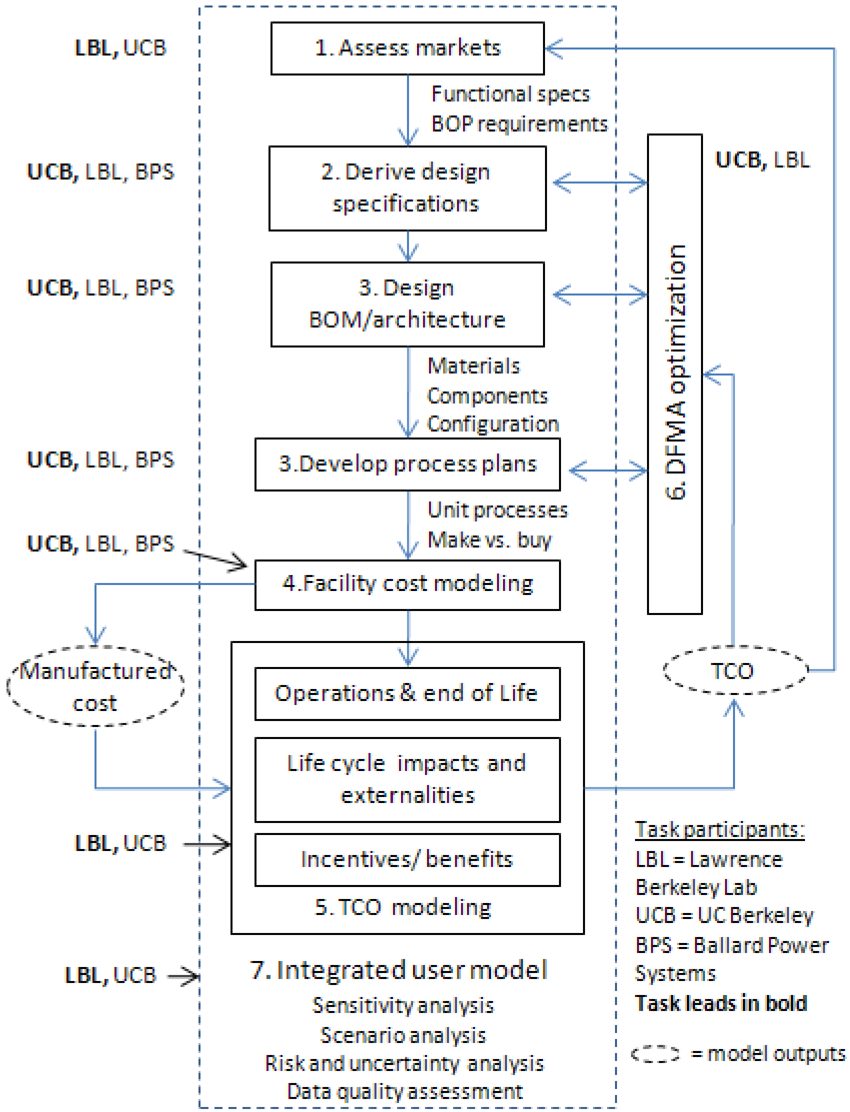
- **Fuel cell types to be considered:**
  - Conventional PEM fuel-cell technology (~80°C)
  - High-temperature PEM fuel-cell technology (~180°C)
  - Solid-oxide fuel-cell technology (SOFC)
- **Application Space:**

APPLICATION	SIZE [KW]	PRODUCTION VOLUME (UNITS/YEAR)			
		100	1000	10,000	50,000
PRIMARY POWER BACKUP 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 [KW]	PRODUCTION VOLUME (UNITS/YEAR)			
		100	1000	10,000	50,000
LIFT-TRUCK SYSTEMS	1	x	x	x	x
	5	x	x	x	x
	10	x	x	x	x

APPLICATION	SIZE [KW]	PRODUCTION VOLUME (UNITS/YEAR)			
		100	1000	10,000	50,000
DIESEL AUX POWER UNITS	1	x	x	x	x
	5	x	x	x	x

Research and Modeling Approach: Task Flow



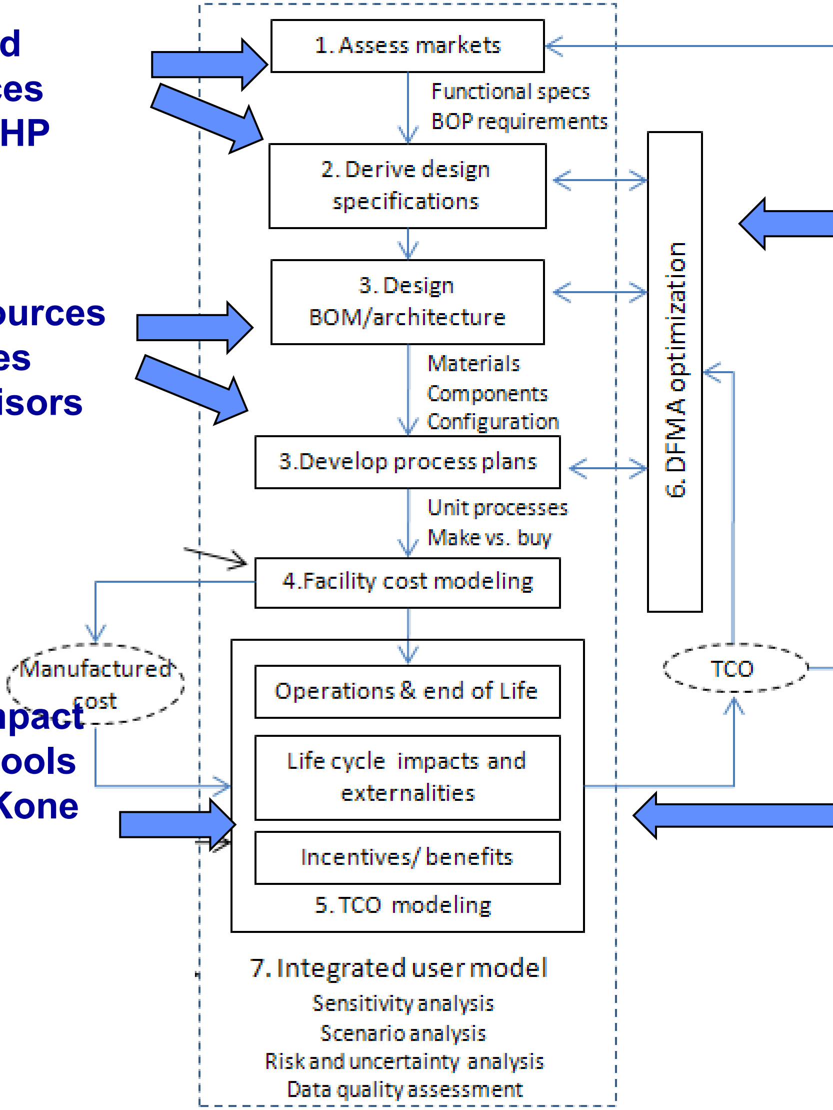
BOM: Bill of materials
DFMA: Design for manufacturing and assembly
TCO: Total cost of Ownership

Research and Modeling Approach: Inputs and Tools

Literature and Patent Sources DER-CAM (CHP Apps)

Lit./Patent sources
Vendor quotes
Industry advisors

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

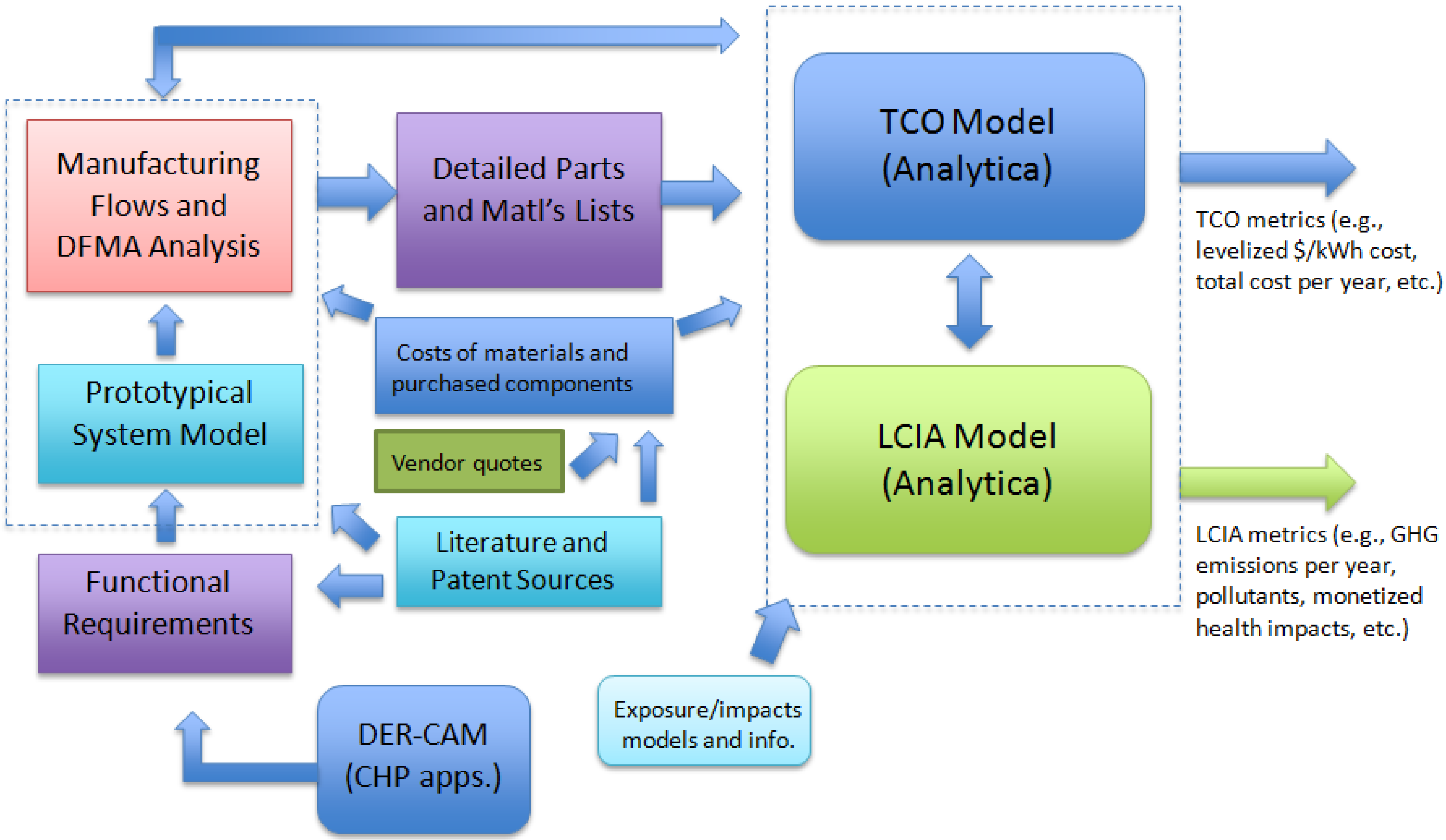


Boothroyd Dewhurst DFMA® Software

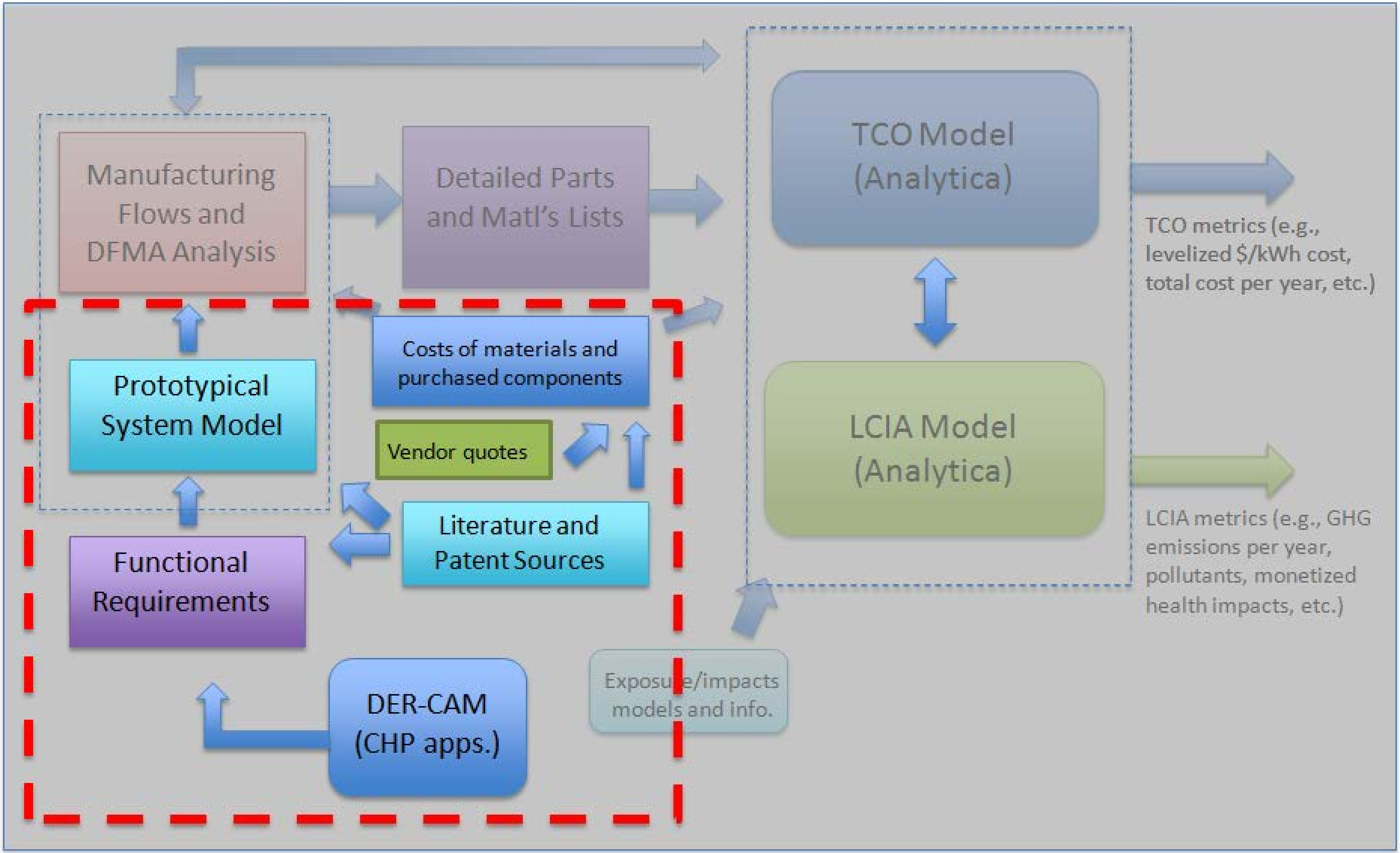
LCA database tools, Integrated Model in Analytica

Research and Modeling Approach: Functional Flow

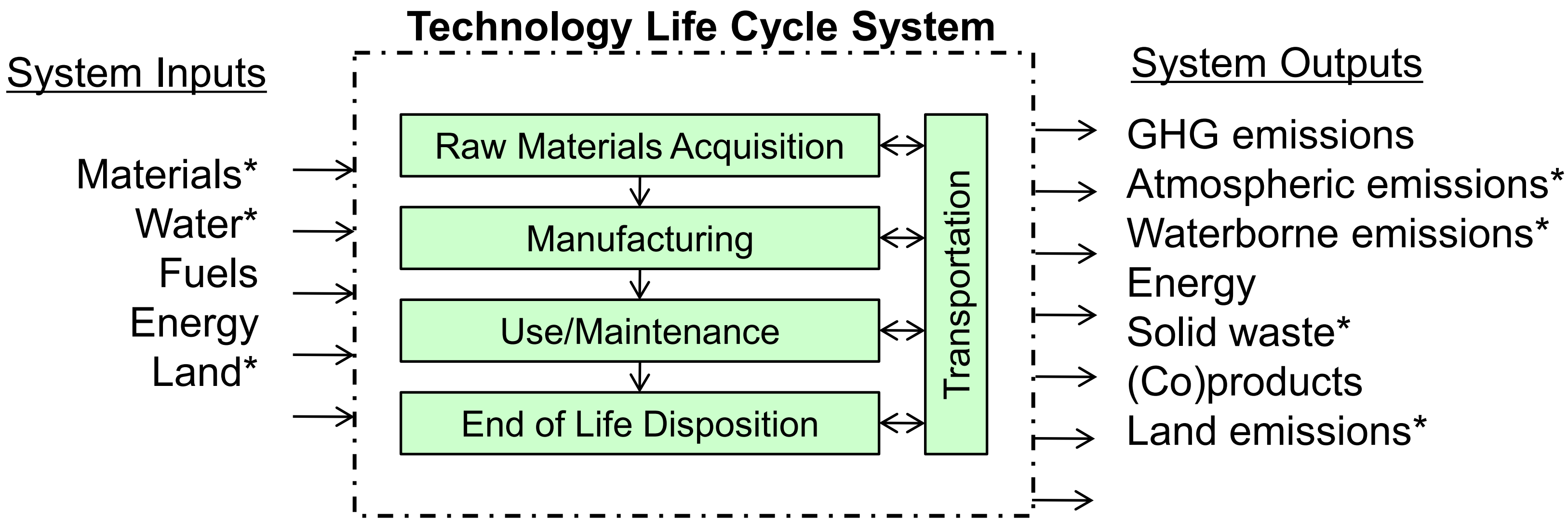
Coupled "Fuel Cell Total Cost of Ownership (TCO) and Environmental Lifecycle Impact Assessment (LCIA) Model"



Research and Modeling Approach: FY12 Focus Areas



Advanced Life Cycle Assessment (LCA) for Technology Characterization



* Systems that are currently poorly characterized

Spatial considerations (status quo = most LCAs ignore spatial aspects)

Modeling scales: Local → Regional → National → Global

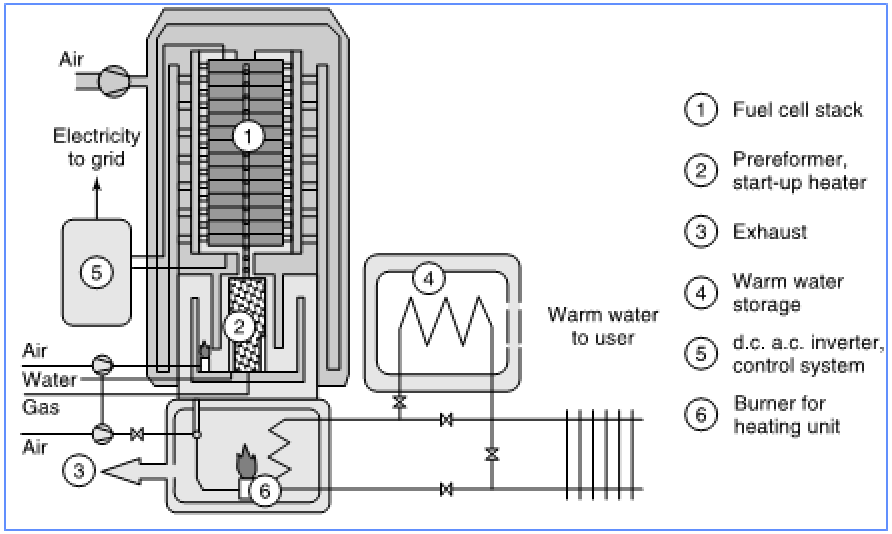
Temporal considerations (status quo = most LCAs are static)

Modeling scales: Short-term (5-10 years) → Mid-term (10-25 years) → Long-term (25+ years)

System Design

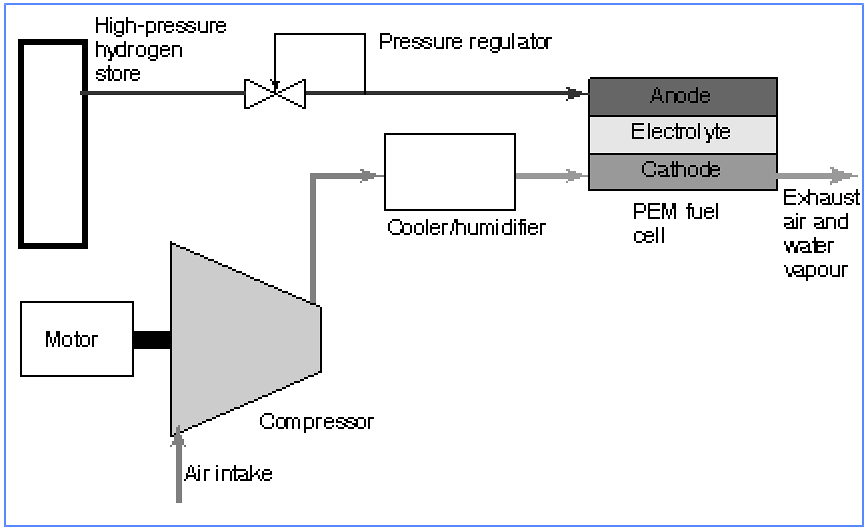
- We will be defining system design by technology and application
- Key part of cost analysis and Q2 focus area.

Stationary SOFC



Fuel Cell Handbook (2010)

PEM



Fuel Cells Explained (2004)

Will add cooling system, inverter, stack sensors & control module as appropriate per application.

High Level Milestones

- Annual Review May 2012: Literature review including review of Fuel Cell design and manufacturing patents
- **Yr 1**: Technical and performance specifications for technology/application anchor points; detailed design plans and technology bill of materials (BOMs) for low temp PEM; Ballard and other industry partners engaged
- **Yr 2**: All BOMs and manufacturing flows completed; manufacturing and operation cost model
- **Yr 3**: Design for manufacturing and assembly (DFMA) analysis and TCO model complete for low- and high-temperature PEM systems
- **Yr 4**: DFMA analysis and TCO modeling modules completed for SOFC systems
- **Yr 5**: Update cost model modules and DFMA analysis; all scenario and sensitivity analysis completed

Approach: 2012 Milestones

#	Date	Milestones	Status
1	Mar-12	• Conduct comprehensive review of fuel cell and fuel processor design and manufacturing patents for 3 fuel cell system types (PEM, “high temperature” PEM, and solid oxide) and 5 applications (stationary, stationary with combined heat and power, backup power, auxiliary power units and materials handling).	**IN PROGRESS** • Focus on FC system design and manufacturing patents. • ECD April 2012
2	Jun-12	• Regular meetings established with Ballard and other industry advisors	**ON TRACK** • Ballard sub-contract in place • Other partners (Nuvera, UTC, Altergy) to be engaged on regular basis
3	Jun-12	• Develop technical and performance specifications for 3 fuel cell types (LTPEM, HTPEM, SOFC) and 5 applications (stationary, CHP, backup, auxiliary power and material handling)	**ON TRACK** • Initial focus on CHP and back-up power applications, followed by APU and forklifts. • Literature review and industry advisor inputs.
4	Sep-12	• Initial set of parametric relationships of system designs and component costs for the applications defined in Task 1for 2015 and 2020, and initial set of parametric relationships of system designs and component costs as a function of key performance and design variables for both fuel-cell-based systems and leading technology incumbents.	**ON TRACK** • Synthesis of existing cost studies in-progress • Identifying key functional system design specifications for system types identified; • Initial compilation of cost information for development of parametric relationships of component costs with variations in key design/performance metrics.
5	Sep-12	• Detailed low-temperature PEMFC design plans and technology BOMs for the project target markets identified in Task 1 • Design plans include cell stack, fuel processing, and balance-of-plant while BOMs will include materials and component requirements and cost estimates from suppliers/OEMs	**ON TRACK** System designs — April/May BOM materials/components — June/July Material/Component Cost Estimates — June-Aug

Literature Review - Cost Studies

	AMR DTI (2010)	AMR TIAX (2010)	AMR Battelle (2010)
Scope	Automotive PEMFC manufacturing costs at various production rates	Automotive PEMFC manufacturing costs	Small-scale stationary PEMFC manufacturing costs
System Cost	51 $/kW (@500,000 units/yr)	49 – 65 $/kW (@500,000 units/yr)	1300 $/kW (@2000 units/yr)
Key Learnings	• **Catalyst Ink & Application** cost dominates at high volume; **Membrane** cost dominates at low volume • Top three cost drivers: **power density**, GDL, and **catalyst loading**	• **MEA** followed by **BPP** dominates stack costs • Switching from Carbon to Metal+Coating BPP greatly increased costs • Top three cost drivers: **catalyst loading**, **power density**, and catalyst costs	• **MEA** followed by **BPP** dominates stack costs • Raw material is the key cost driver (especially for the MEA and BPP) • BOP accounts for over 50% of the system cost
Key Assumptions	• Vertical integration and direct manufacturing (some facility capital covered in Tiax and Battelle) • Various process steps for each component excluded from analysis • Manual labor at low-volume, automated mfg at high-volume (DTI)		

Literature Review - Cost Studies

- In addition to existing cost methodologies:
  - Holistic life-cycle approach for TCO
  - Incorporate more parametric relationships
  - Build mathematical and semi-empirical models that relate design to performance

Level	Strategy/Plan
Materials	Include more parametric cost relationships with volume and country of origin
Process	More comprehensive process modeling (include more process steps such as cleaning operations) • Energy balance: electricity, heat, etc. • Mass balance: water, consumables, waste, etc.
Facility	Include more facility (and indirect manufacturing) costs • HVAC, lighting, etc. • Subsystems (e.g. compressed air, water/thermal management, etc.)
Externalities	Pollution, environment, etc.

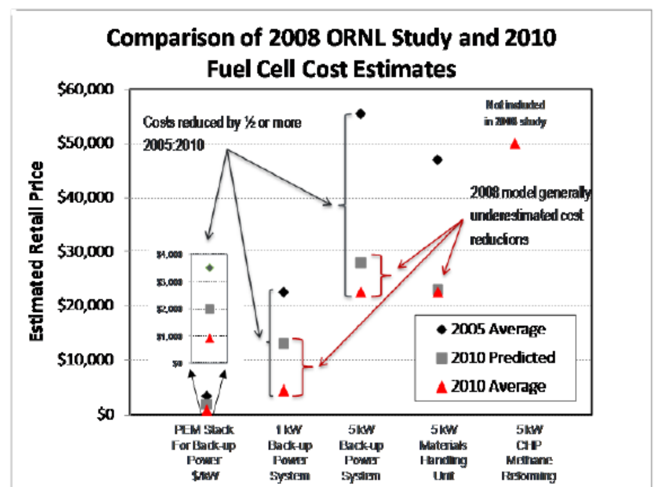
Literature Review - General/Market Studies

- General / Market studies: DOE market reports, Battelle 2007, Oak Ridge 2011
- Key scope: Stationary and materials handling markets
- Cost, reliability, utilization are key drivers.
  - Progress ratio data with doubling of output reducing costs 20-30% (ORNL)
- Forklift / material handling systems, BU power key market opportunities
  - Forklifts : Cost sensitivity vs hours of operation, hydrogen cost, fuel cell replacement costs
  - BU Power: Telecom towers, emergency response towers, data centers, ...
- MicroCHP opportunity: large expensive homes in cold climates; CHP-commercial may be another opportunity but examples all larger than 250kW

Cost Assumptions for NPV Analysis of PEM Fuel Cell- and Battery-Powered Forklifts.

	Scenario 1		Scenario 2	
	Battery-Powered Pallet Truck	PEM Fuel Cell-Powered Pallet Truck	Battery-Powered Sit-Down Truck	PEM Fuel Cell-Powered Sit-Down Truck
Cost ($)	8,000	13,500	25,000	35,000
Lifetime (yrs)	15	15	15	15
Hours of Operation (hrs/yr)	7,644[1]	7644[1]	5,460[2]	5,460[2]
Cost of Accessories ($)	2,406[3]	-	2,406[3]	-
Battery Charger	1,800	-	1,800	-
Cranes/Hoists	210	-	210	-
Cost for Battery Room	396	-	396	-
Routine Maintenance Costs ($/yr)	3,600[4]	720[5]	3,600[4]	720[5]
Electricity/Hydrogen Fuel Costs ($/yr)	1,307[6]	4,380[7]	1,307[6]	5,612[8]
Time for Refueling (min/day)	30	3	15	3
Cost of Refueling/Recharging ($/yr)	8,213[9]	274[10]	2,925[11]	390[12]
Replacement Costs ($)	1,800 – Batteries every 5 years	9,000 – Fuel cell module every 5 years	4,000 – Batteries every 5 years	24,000 – Fuel cell module every 5 years 2,600 – Ultracapacitors every 10 years

Battelle 2007



2005 and 2010 averages based on estimates supplied by OEMs. 2010 predicted assumed government procurements of 2,175 units per year, total for all market segments. Predictions assumed a progress ratio of 0.9 and scale elasticity of -0.2.

Figure 4. Comparison of 2008 ORNL Study and 2010 FC Cost Estimates.

ORNL 2011

CHP Functional Requirements Scoping

- Provide functional requirements (electrical and thermal load profiles) and more realistic operational parameters for CHP applications (capacity, cycling, etc).
  - **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.

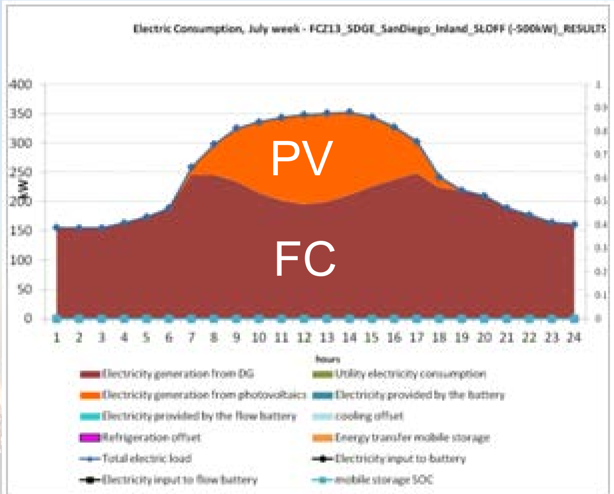
Peak Load of Building	Number of Types	Total number in SDG&E	%
100 – 250 kW	4	620	35%
250 – 500 kW	3	574	32%
above 500 kW (***)	9	589	33%
Total		1783	

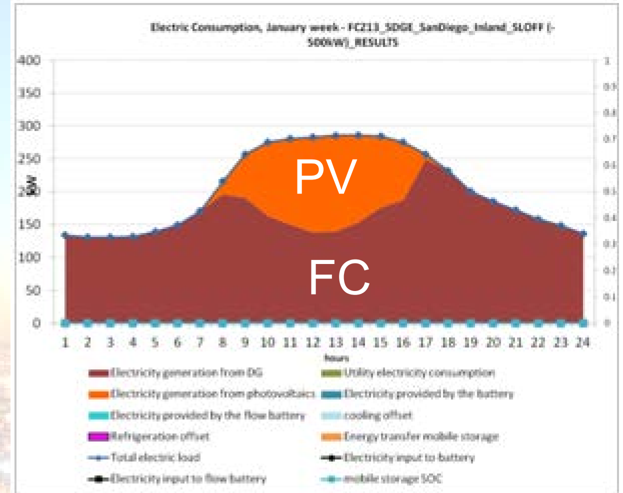
- Operational parameters can be an input to total cost of ownership model and can vary as function of building type and climate zone.

"Smaller" LARGE OFFICE BUILDING (N = 331 in SDG&E, HT PEM CHP 250kW, 2020)

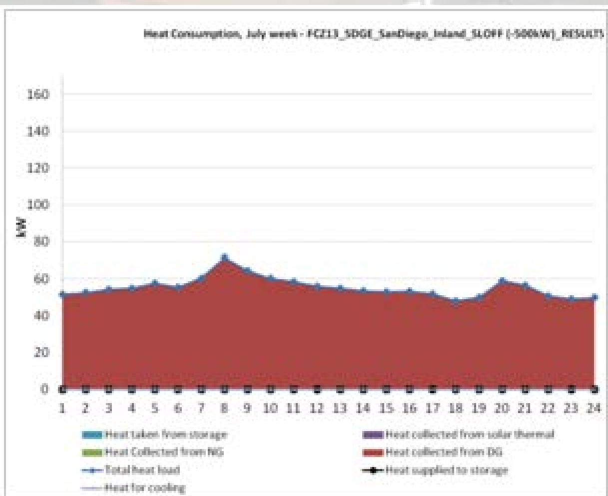
Summer | Winter

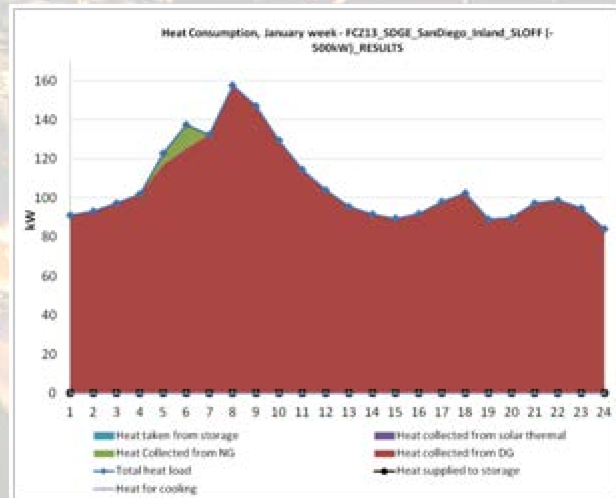
Electricity Load





Thermal Load





Collaborations

- **Partners**

  University of California Berkeley

  Laboratory for Manufacturing and Sustainability, Department 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 Design/BOP, BOM definition, parametric relationships

  — CHP applications and functional requirements

  Ballard Power Systems:

  Consultation on fuel cell system design and manufacturing processes

- **Other collaborators**

  — **Altergy**: Consultation on backup power system

  — **Nuvera:** Consultation on forklift fuel cell systems

  — **UTC:** Consultation on back up power/primary power fuel cell systems

Future Work

FY12 Specific plans / risk mitigation:

- Development of system designs / BOP and BOM for LTPEM
  - Patent and literature review
  - Industry advisors
  - Evaluation of strengths/weaknesses of existing cost studies
  - Identification of knowledge gaps and targeted efforts to address them

FY13 Specific plans / risk mitigation:

- All BOMs and manufacturing flows completed; manufacturing and operation cost model developed
  - CHP, BU Power applications and LTPEM, HTPEM, SOFC systems
  - Develop manufacturing process flows and costing including mass and energy flows
  - Develop parametric relationships as function of manufacturing volume, system design and system performance
  - DFMA analysis

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 including mass flow and energy balance for integrated lifecycle cost analysis (LCA) impacts.

Technical Accomplishments and Progress: Literature review of key cost studies and initial patent review completed; functional requirements characterized for key applications.

Collaboration: Working partnerships with UC Berkeley manufacturing analysis group, transportation sustainability research group, and Ballard Power Systems. Will collaborate with other fuel-cell companies including Altergy, Nuvera, UTC Power.

Proposed Next-Year Research: System designs/balance-of-plant (BOP) and material/component bill of materials (BOM) and costing.

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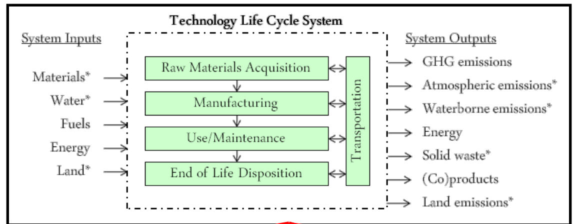
Backup technical slides (5)

Spatial and Temporal Technology Deployment Assessment

Advanced LCA models



Key new analytical bridges to complementary systems models

- Regional Energy Systems Models (e.g., SEDS, NEMS, MARKAL)
- Energy-Resource Systems Models (Input-Output, water-energy nexus)
- Geographical Information Systems (GIS) and Resource System Models
- Others

Scenario and Uncertainty Analysis

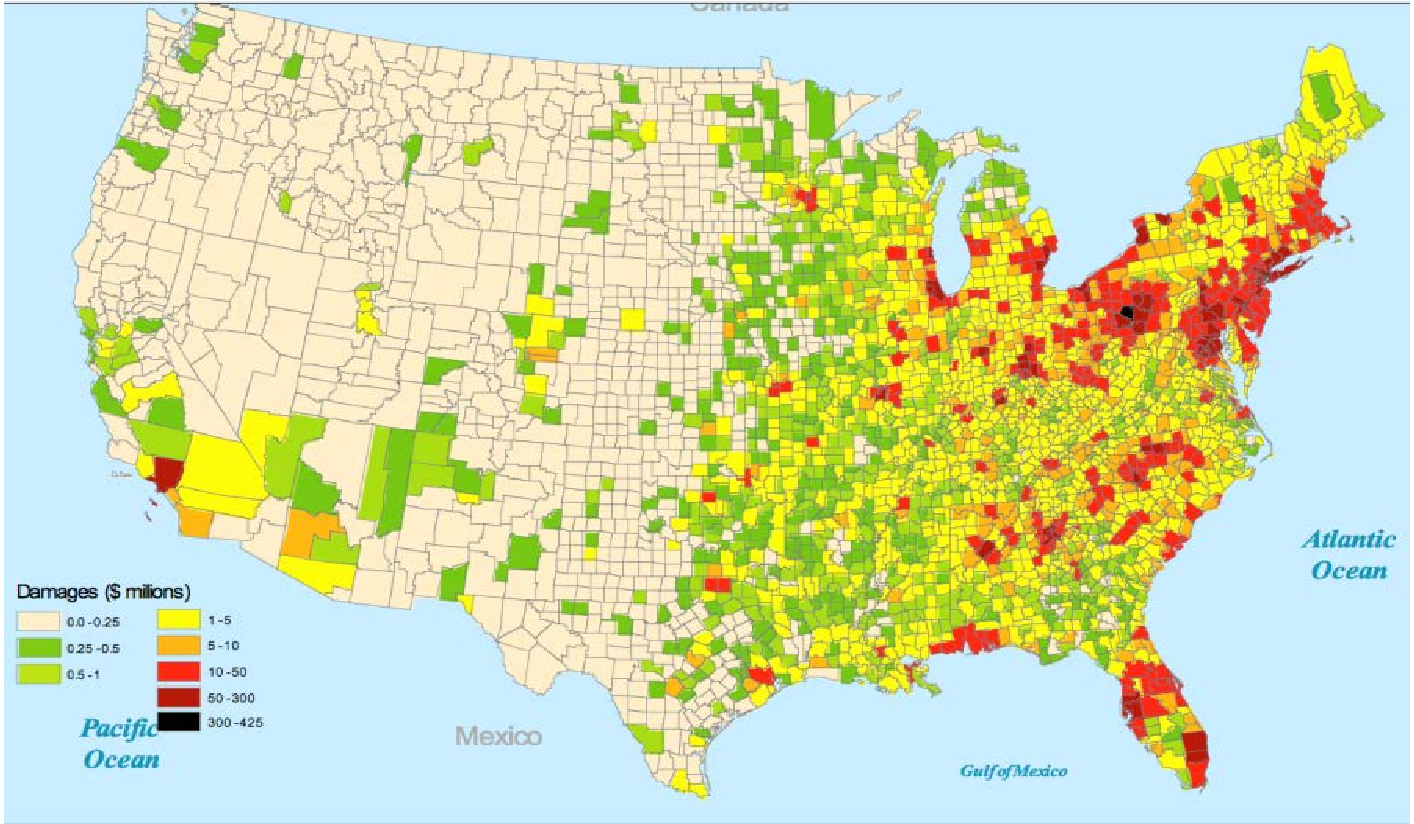
Assessment of policy, technological, societal, and economic changes over time

Net **Technology Life-Cycle Inputs and Outputs at Various Spatial and Temporal Scales**

Critical for sound modeling of technology impacts

Example: Hidden Costs

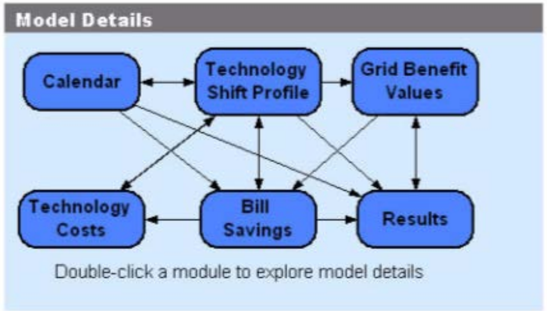
Monetized Health Damage from Fossil-fuel Electric Power Generators

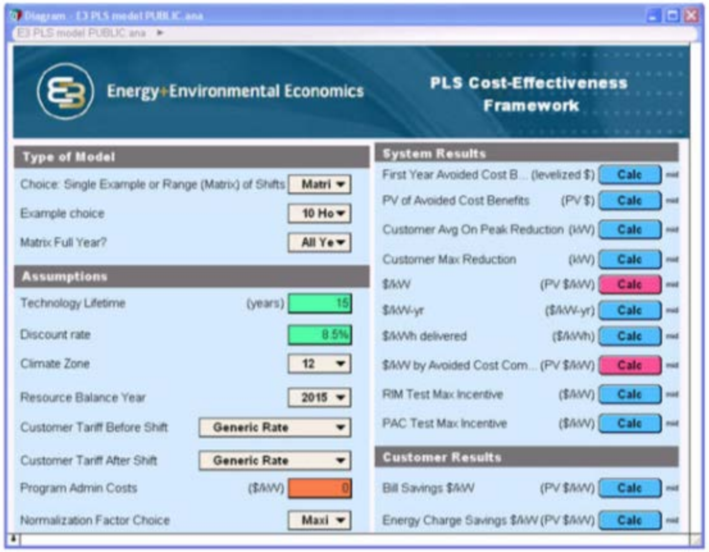


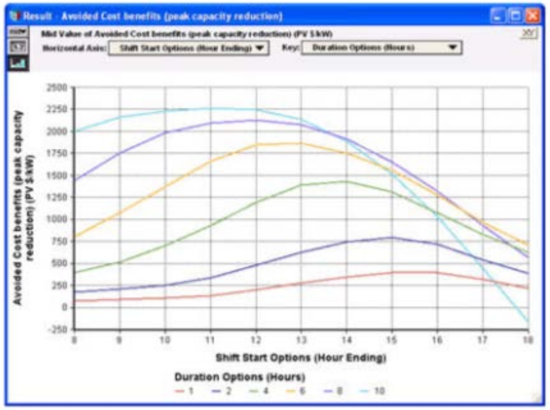
Source: NRC (2010)

Analytica and user tool

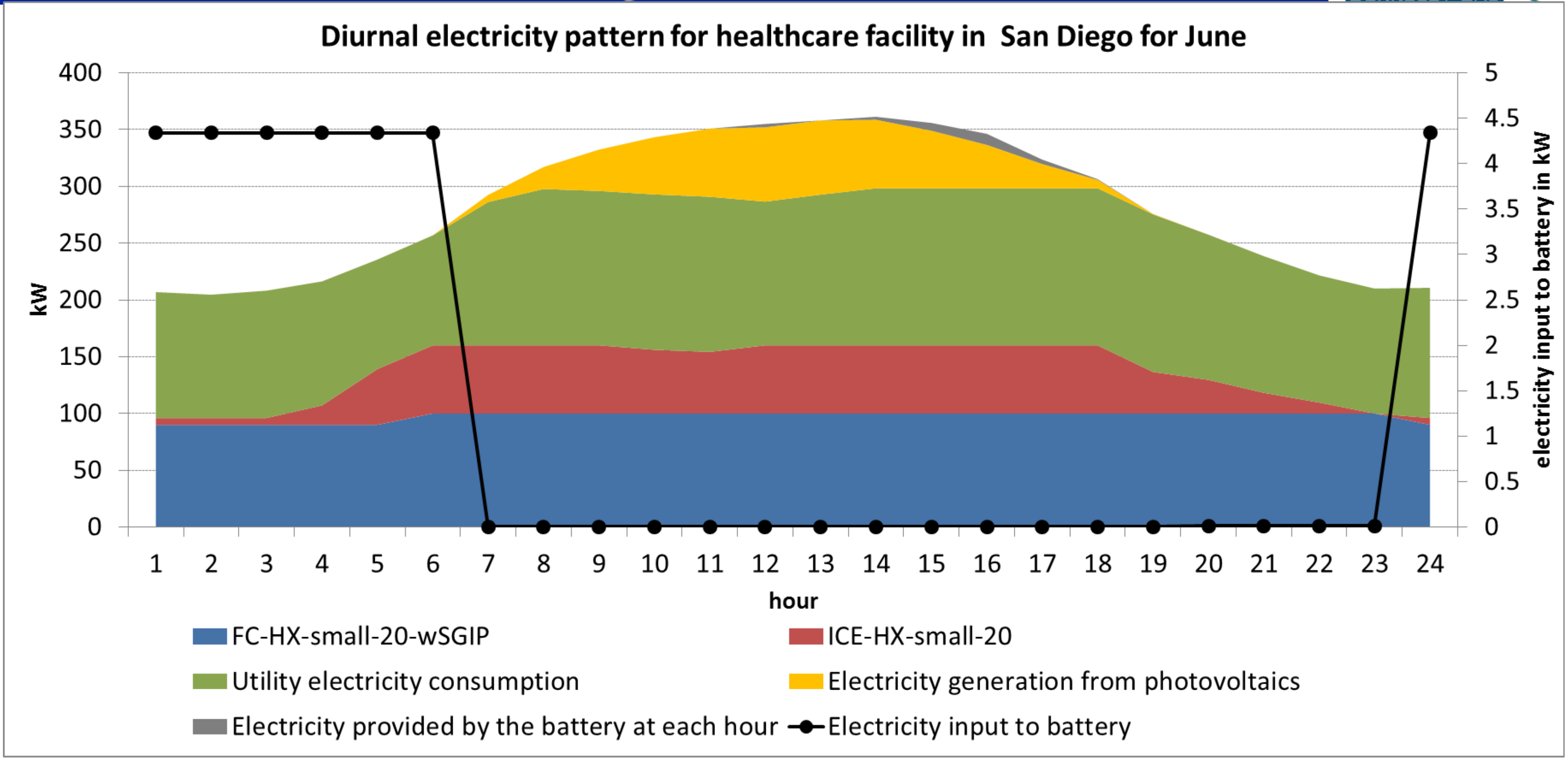
- Free Analytica Player allows public users to view and run existing models, including making changes to input variables
- Intuitive, "influence diagram" interface, decision-centric modeling with built in uncertainty, risk analysis and Monte Carlo simulation.







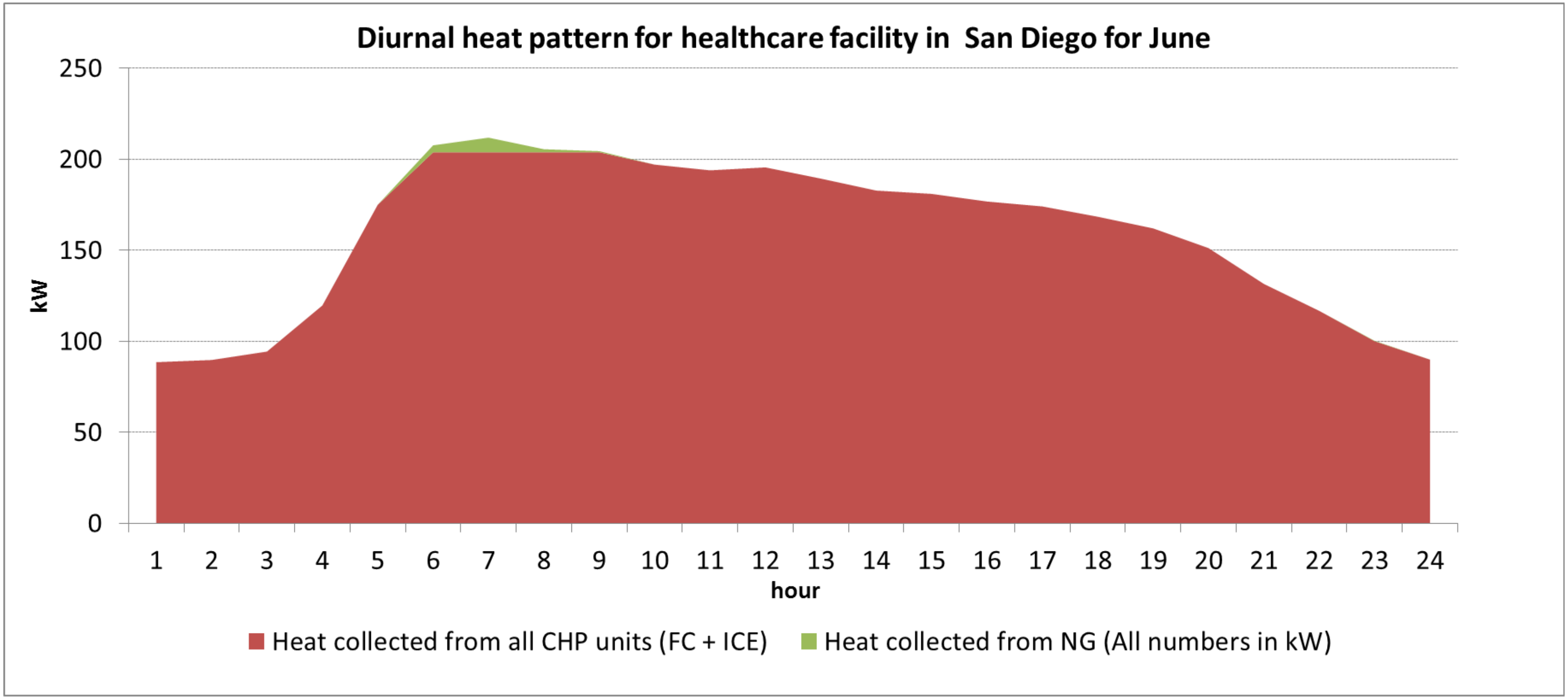
Single Bldg Investment Analysis with DER-CAM: Electricity Balance Result



- 100 kW fuel cell with heat to power ratio of 1 runs 24 hours
- 60 kW ICE and utility purchase follow load
- PV during day hours, and
- electric storage charged during morning hours and discharged in the afternoon

FC…fuel cell
ICE…internal combustion engine
HX…heat exchanger

Heat Balance Result



- almost all heat is provided by CHP systems
- CHP systems seem heat driven and the amount of heat needed at the building limits the FC and ICE adoption