Life Cycle Design of Emerging Energy Generation Technologies

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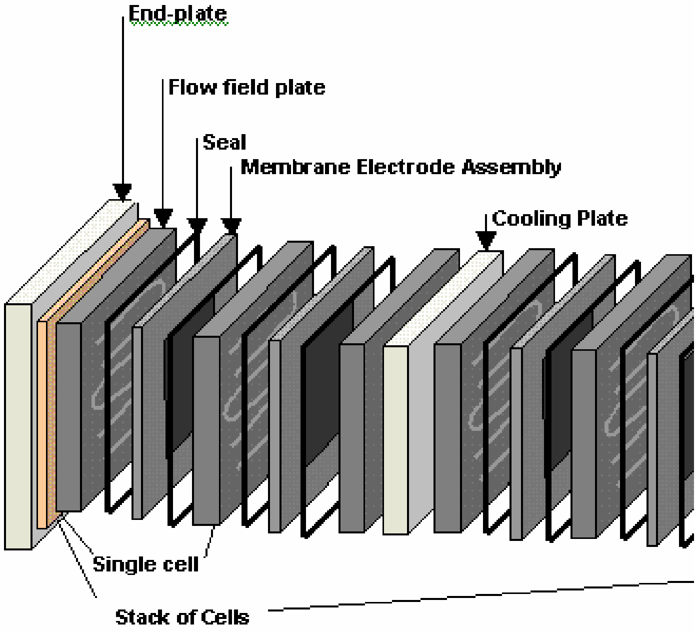
Life Cycle Design Tools

- Efforts to take advantage of LCA early in the design process have led to both general and product-specific design tools.
- “General” tools vs. product-specific LCA tools
- Movement of emerging energy generation technologies from development to production provides an example of the importance of product-specific design tools.

UWME LCA Research on PEM Fuel Cells

- A variety of fuel options
- A wide range of material choices
  - 16+ types of polymer electrolyte membranes
  - 2 types of gas diffusion layers
  - 8+ types of anode catalysts
  - 4+ types of cathode catalysts
  - 100+ FFP material combinations
- A wide range of configurations
  - FFP Integrated cooling
  - Internal vs. external manifolding
  - etc.



From Mehta and Cooper, *Journal of Power Sources*, 2003.

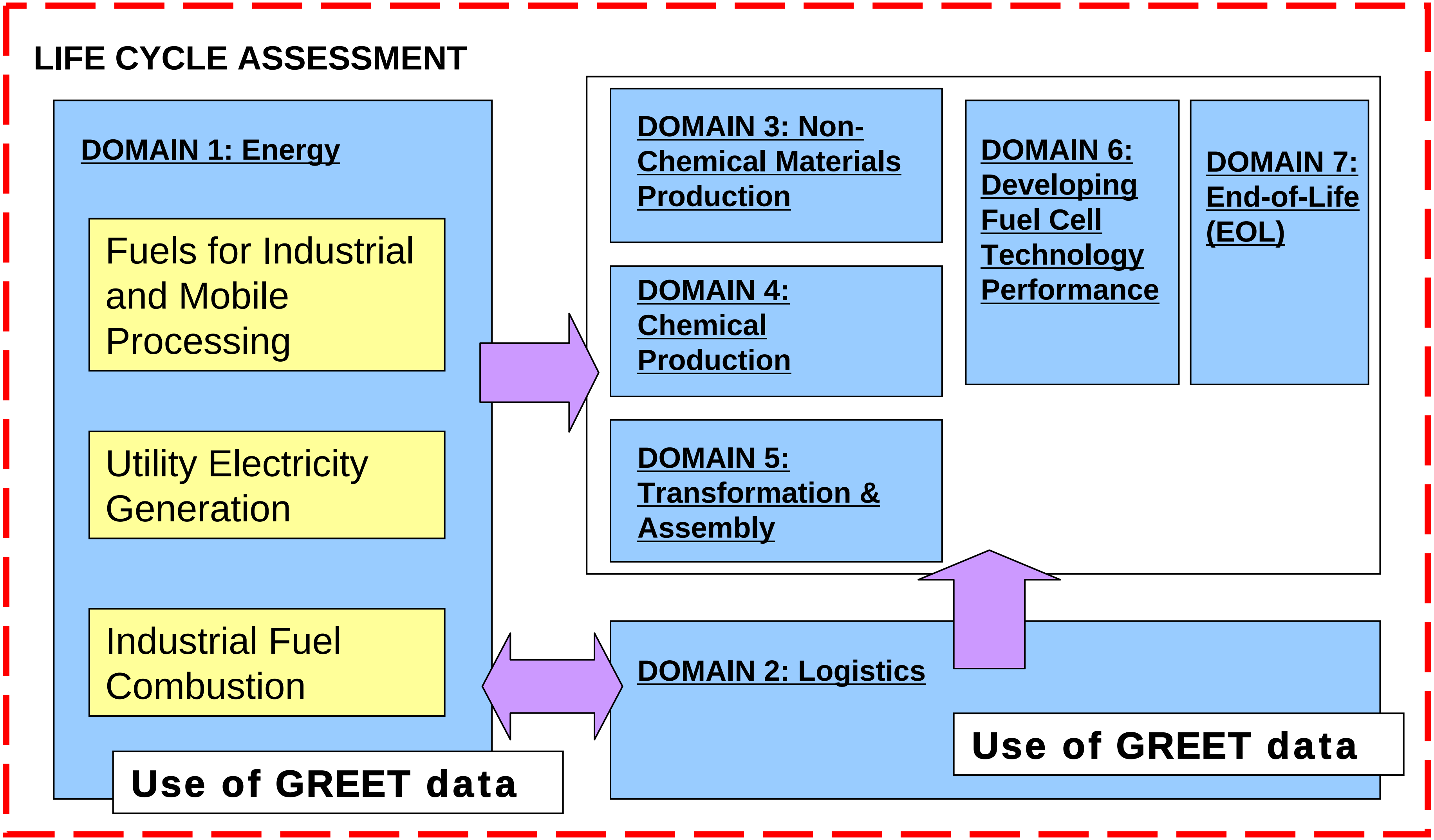
Agenda

- In the development of a set of life cycle design tools for PEM fuel cell stacks and fuel production systems
  - Modeling methods, key data issues, design interface issues
  - Example results
  - Generalization of the tool development process to emerging energy generation technologies.

Project Scope: The Plug Power GenSys Case Study

- Plug Power is a leader in fuel cell innovation and ready for next step in design evaluation (i.e. LCA)
- Phase 1
  - Assessment of life cycle energy consumption and key air emissions
    - Extend DOE’s GREET fuel LCA model by adding analyses of fuel cell system hardware materials and their life cycles.
  - Consideration of fuel cell system disassembly issues and remanufacturing scenarios
  - Addition of a fuel cell system life cycle design interface

LCA Model Domains



LIFE CYCLE ASSESSMENT

DOMAIN 1: Energy

- Fuels for Industrial and Mobile Processing
- Utility Electricity Generation
- Industrial Fuel Combustion

Use of GREET data

DOMAIN 3: Non-Chemical Materials Production

DOMAIN 4: Chemical Production

DOMAIN 5: Transformation & Assembly

DOMAIN 6: Developing Fuel Cell Technology Performance

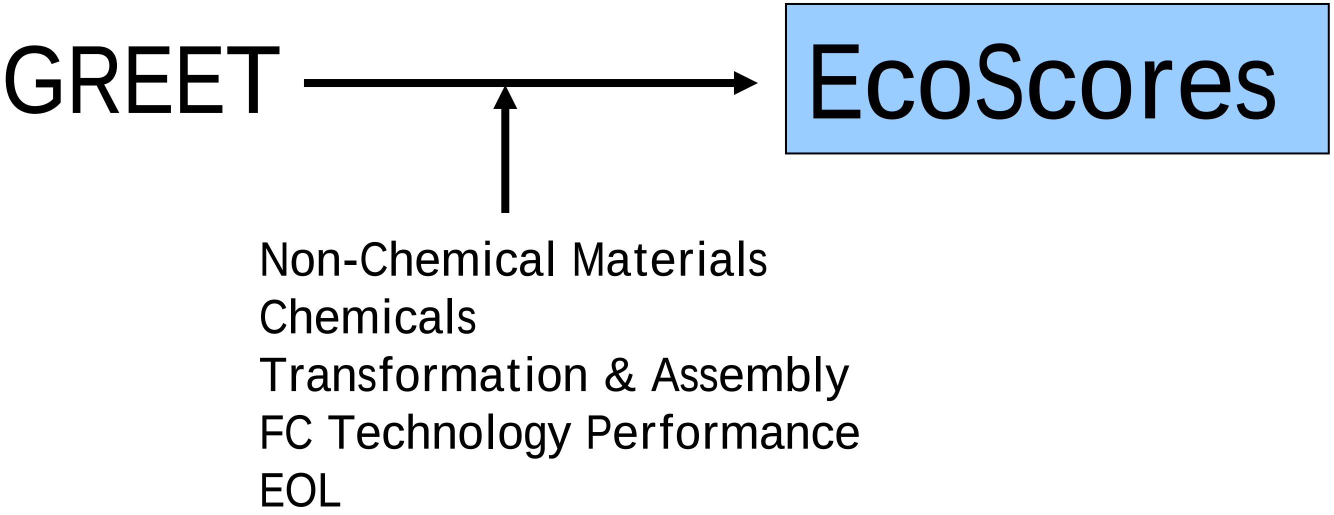
DOMAIN 7: End-of-Life (EOL)

DOMAIN 2: Logistics

Use of GREET data

LCA Delivery to the Design Process: EcoScores

- The fully developed LCA model facilitated the development of LCA-based EcoScores
  - This is not new! (see Pré's EcoIndicators and Okala Impact Factors)



GREET

EcoScores

Non-Chemical Materials
Chemicals
Transformation & Assembly
FC Technology Performance
EOL

Characteristics of Our EcoScores

- We were interested in an indicator system that:
  - Is based on US or publicly peer reviewed and accessible LCA data
  - Allows the weighting scheme to be specified (as in BEEs)
  - Facilitates custom evaluations of recycled materials use, system recycling, and local material sourcing
  - Can account for fuel cell operating emissions
  - Allows the reference technology to be specified for normalization (here, Plug systems are compared to the US Grid).

EcoScore Format

- EcoScores are fuel, transport, component, and materials management-specific scores based on LCA data and an impact weighting scheme. Adding the scores for each item allows the development of system level scores:
  - System EcoScore = $\sum ES_i I_i$

    where:

    ES_i = the EcoScore for item i

    I_i = the inventory flow for item i (user inputs)

	ES_i	**I_i**
Fuel cell energy use	EcoPoints/mmBTU	mmBTU
Fuel cell operating emissions	EcoPoints/lb	lb
Assembly energy	EcoPoints/(kWh or mmBTU)	kWh or mmBTU
Transport of the system to the customer	EcoPoints/ton-mile	ton-mile
Hardware fabrication	EcoPoints/lb	lb
Materials management	EcoPoints/lb	lb

EcoScores Developed

- Fuel cell energy use
  - 13 GREET fuel cell fuels (NG, LPG, H_2)
- Fuel cell operating emissions
  - VOCs, CO, NOx, PM10, SOx, CH_4, N_2O, and CO_2
- Assembly energy
  - Grid Electric Generation: Electricity Available, at POU
  - Natural Gas Industrial Boiler (10-100 mmBtu/hr input), at POU
  - Diesel Industrial Boiler, at POU
- Transport of the system to the customer
- Materials management
  - Metallic waste to landfill
  - Metallic scrap to recycle
  - Non-metallic waste to landfill
  - Non-metallic scrap to recycle
- Hardware fabrication
  - Aluminum: primary - Cast, at Point of use (POU)
  - Aluminum: primary - Extruded, at POU
  - Aluminum: primary - Machined/ Lathe, at POU
  - Aluminum: primary - Sheet rolled, at POU
  - Aluminum: primary - Stamped, at POU
  - Aluminum: recycled - Cast, at POU
  - Aluminum: recycled - Extrusion, at POU
  - Aluminum: recycled - Machine/ Lathe, at POU
  - … for brass, carbon steel, copper, stainless…

- 93 EcoScores overall

Tool Interface

- Energy Summary
  - Fuel Type
  - System size (kW)
  - Electric efficiency
  - Hours of operation
  - kWh output
  - Fuel cell operating emissions
  - Assembly electricity, NG, diesel use
  - Transport: Plug to customer (by truck, rail, barge, and freighter

- Hardware Summary
  - Materials
    - lb in system
    - lb replaced over life
    - % EOL recovery BASED ON <u>DISASSEMBLY ANALYSIS</u>
  - Fabrication Processes
    - % of each material that is Cast, Draw, Extrusion, Machine/ Lathe, Sheet rolling, Stamped, and Weld

Weighting Impacts

Impact Assessment Weighting Scheme

Energy consumption	11%
Fossil energy consumption	11%
Petroleum energy consumption	11%
Percent use of recycled material over the system life	11%
Percent end-of-life material recycled	11%
Contribution to global warming (from as CO2, N2O, & CH4)	11%
Contribution to photochemical smog (from CH4, NOx, CO, & VOCs)	11%
Contribution to acidification (from SOx & NOx)	11%
Contribution to human health criteria impacts (from NOx & PM10)	11%
	100%

Weights indicate the relative importance of each impact category (should sum to 100%).

Weighting Impacts

Impact Assessment Weighting Scheme

Energy consumption	30%
Fossil energy consumption	5%
Petroleum energy consumption	5%
Percent use of recycled material over the system life	20%
Percent end-of-life material recycled	4%
Contribution to global warming (from as CO2, N2O, & CH4)	16%
Contribution to photochemical smog (from CH4, NOx, CO, & VOCs)	13%
Contribution to acidification (from SOx & NOx)	3%
Contribution to human health criteria impacts (from NOx & PM10)	4%
	100%

Weights indicate the relative importance of each impact category (should sum to 100%).

Example Results

* Changing the weighting factors or the reference technology changes the EcoScores.

- Baseline = current GenSys NG design
- Alternative =
  - The fuel source has been changed to assume connection to the pipeline without additional transport.
  - The electrical efficiency has been increased from 22% to 30%.
  - The study materials used in component fabrication are assumed to be from recycled feedstocks.
  - Disassembly issues are assumed to be resolved.

	Baseline GenSys	Alternative GenSys	US Grid
Fuel Production and Fuel Cell Operation EcoScore	**111,051**	**78,837**	**340,900**
(ratio to the US Grid)	0.33	0.23	1.00
Hardware EcoScore	**1,536**	**710**	**-**
(ratio to the baseline design)	2.16	1.00	-
(transport % of hardware EcoScore)	27%	55%	-

RESULTS, lower scores are preferred

Sample Breakdown of Results

System EcoScore $= \sum ES_i I_i$

			Weighting Scheme			
		100%	11.11%	11.11%	11.11%	
			Contribution to global warming (from CO_2, N_2O, & CH_4)	Contribution to photochemical smog (from CH_4, NOx, CO, & VOCs)	Contribution to acidification (from SOx & NOx)	• • • • •
Category		EcoScores	CO2 equiv	NOX equiv	H+ equiv	
	US Grid	7.78E-01 /kWh	7.92E+02	1.58E+00	1.64E+02	• • • • •
	Fuel Production and Operation Analysis					
Fuel Cell Energy Use	G Hydrogen (electricity), at POU	287.22 /mmBTU	3.41E+05	6.80E+02	7.06E+04	
	G Hydrogen (Ethanol), at POU	194.06 /mmBTU	2.12E+05	6.40E+02	3.75E+04	• • • • •
	G Hydrogen (Methanol), at POU	176.05 /mmBTU	2.66E+05	4.65E+02	2.58E+04	
	G Hydrogen (GREET combination), at POU	52.25 /mmBTU	1.19E+05	1.14E+02	6.95E+03	
Fuel Cell Operation	Operating emissions					
	VOC	3.09E+01 / lb	0.00E+00	4.39E+02	0.00E+00	
	CO	5.30E-01 / lb	0.00E+00	7.53E+00	0.00E+00	• • • • •
	NOx	5.32E+01 / lb	0.00E+00	5.62E+02	1.82E+04	
⋮	⋮	⋮	⋮	⋮	⋮	

Generalization of Design Tools

- A opportunity exists to develop emerging energy generation technology life cycle design tools that:
  - Assess a wide variety of system hardware options, fuels, and fuel production scenarios
  - Base assessments on <u>publicly available, highly peer reviewed quantitative LCA data</u>
  - Are able to produce results in a timeframe and format useful to the design process.

Generalization of Design Tools: Recommendations

1. Division of LCA into model domains
2. Key model parameters to each technology
    - Include very detailed results for the arguably smaller number of materials used in the product of interest (graphite)
    - Base inputs on multi-material components for selection by the user
    - Use terminology and the design-process characteristics of the sector
3. Move beyond prototypes (baseline vs. alternative designs)

QUESTIONS

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