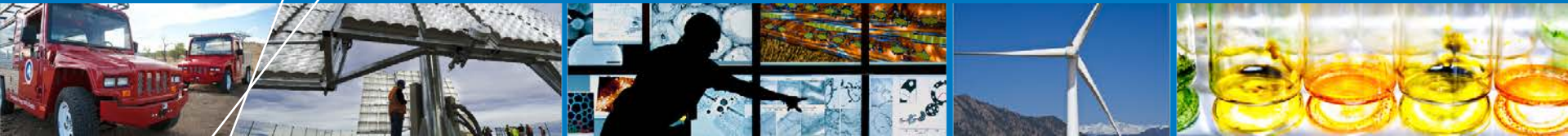




AN027

Cost, Energy Use, and Emissions of Tri-Generation Systems



2012 Annual Merit Review

Mark F. Ruth & Victor Diakov (NREL)

Tyler Evans (Notre Dame)

Timothy J. Sa & Michael E. Goldsby (SNL)

15 May 2012

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

Overview

Model Development and Analysis Timeline & Budget

Start date: Dec 2010

Status: Completed Oct 2011

100% DOE funded

- \$100K NREL
- \$30K Sandia NL

Overall MSM Timeline & Budget

Start date: Feb 2005

Status: ongoing

Percent complete: 80%

100% DOE funded

FY11 funding

- \$250K NREL/Systems Integration
- \$100K Sandia NL

FY12 funding

- \$150K NREL/SIO
- \$100K Sandia NL

Barriers

- Stovepiped / siloed analytical capability (B)
- Inconsistent data, assumptions and guidelines (C)
- Suite of models and tools (D)

Partners

Sandia National Laboratories

- Computational development

NREL

- Fuel Cell Power Model

Argonne National Laboratory

- GREET

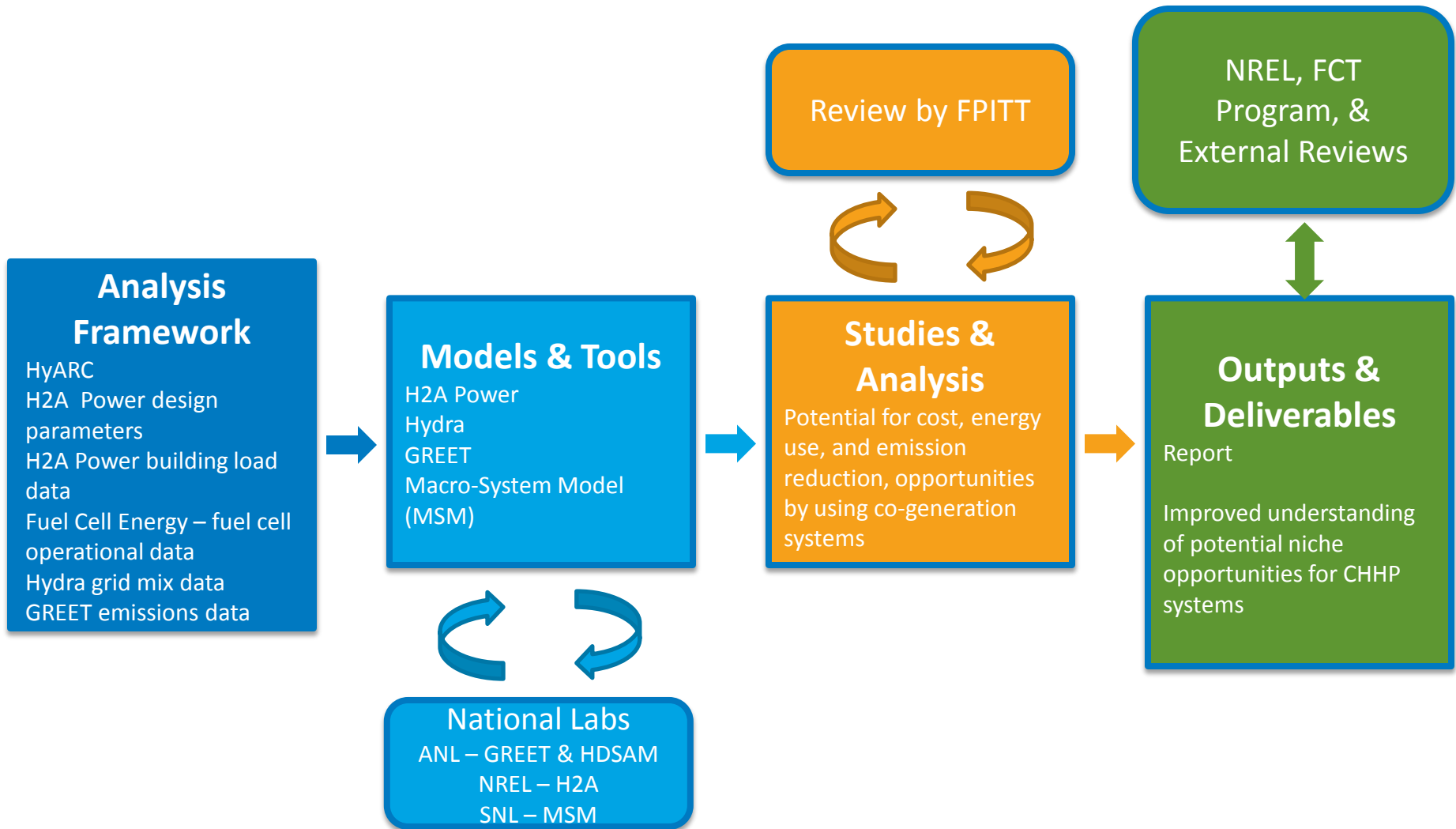
Fuel Cell Energy

- Information provided in development of the FC Power Model

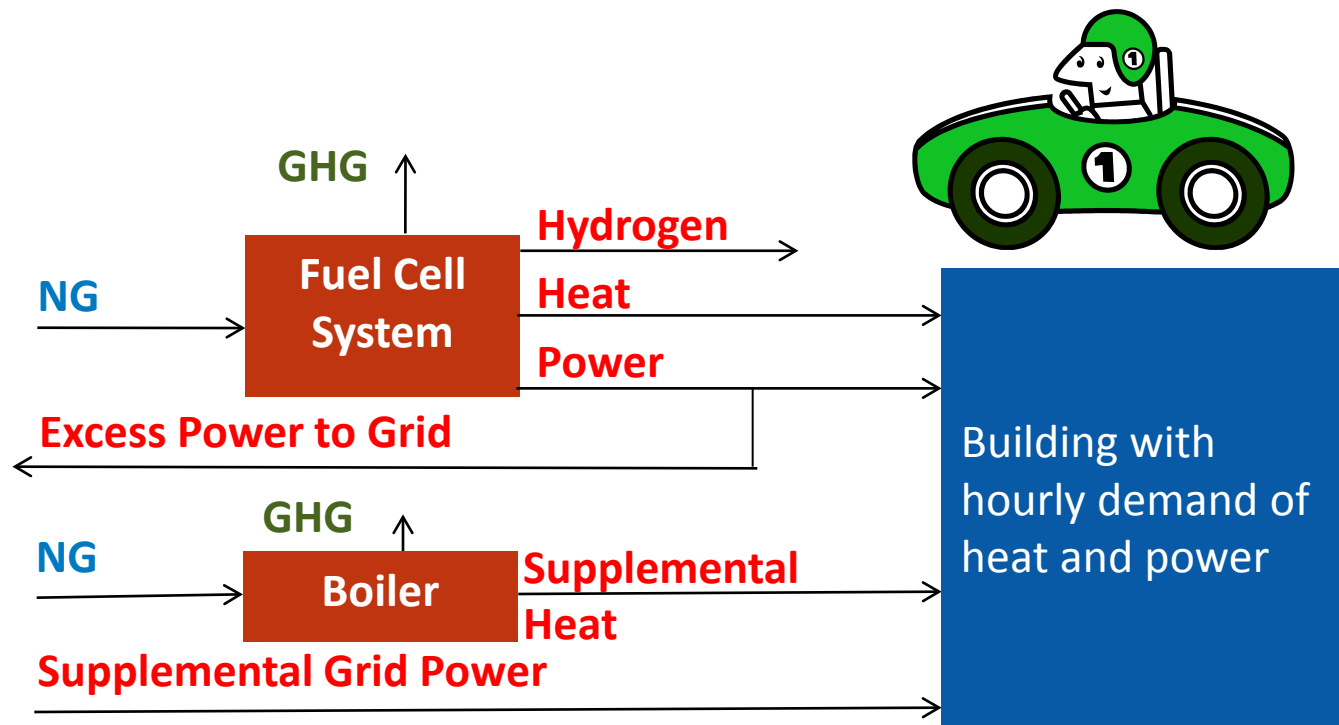
SENTECH

- MSM User Guide

Cost, Energy Use, and Emissions of Tri-Generation Systems



Tri-generation Concept



Hydrogen levelized cost and associated greenhouse gas (GHG) emissions might be reduced by combining with fuel cell combined heat and power (CHP) systems.

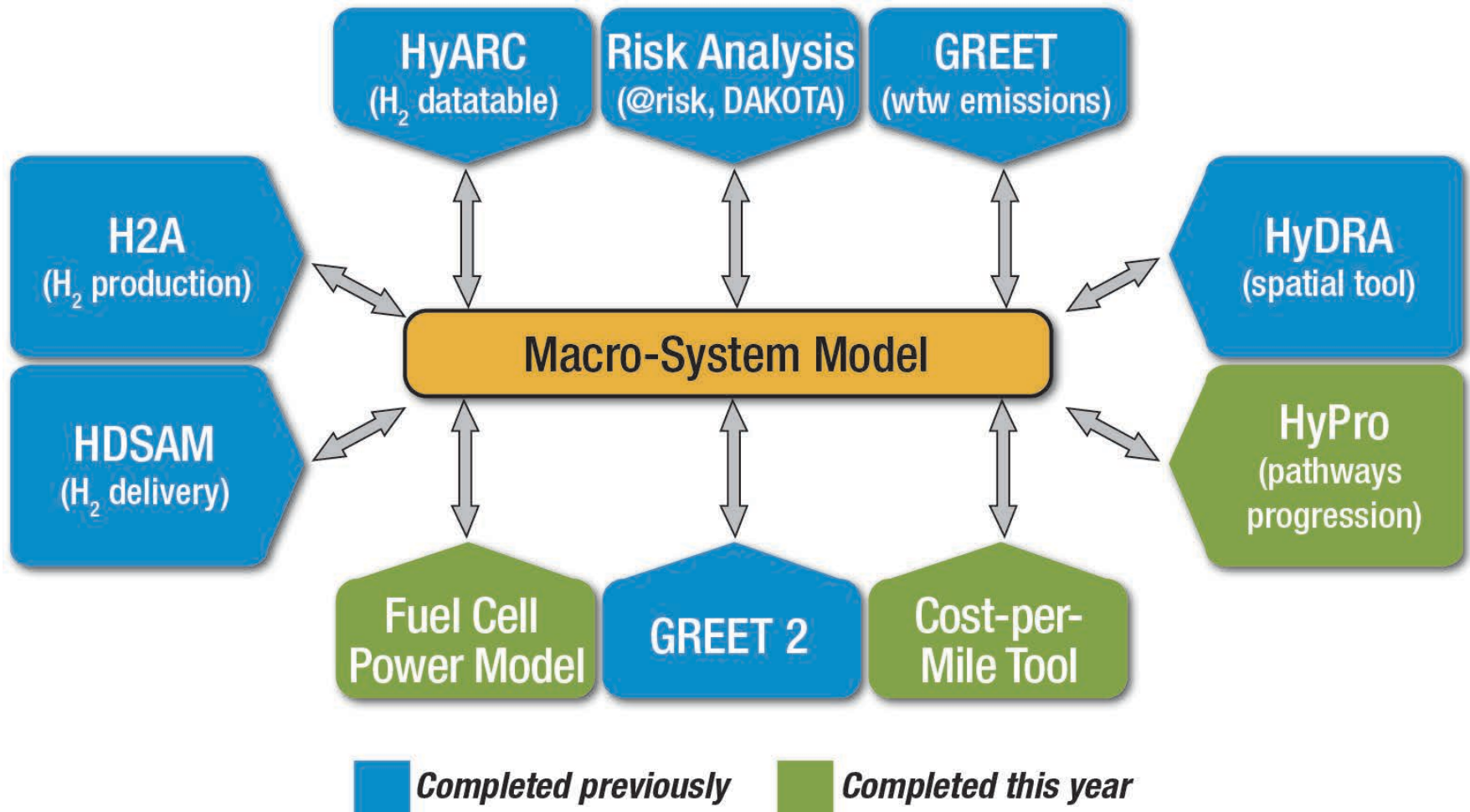
Quantify levelized cost and GHG emissions from tri-generation [combined heat, hydrogen, and power (CHHP)] systems for various:

- **Fuel cell types**
- **Building types**
- **Building locations**

Develop a methodology for MSM users to create optimized CHHP scenarios easily

Primary Analytical Tool: MSM

The Macro-System Model (MSM) provides a **central transfer station** to simplify communication across models and guarantee consistency in simulations that involve multiple models. A graphical user interface (GUI) allows users to easily use the models.

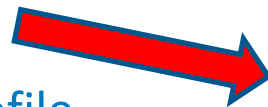


- Models tri-generation systems for buildings
- Built in Excel on H2A platform
- Includes user options of molten carbonate fuel cells (MCFC) or phosphoric acid fuel cells (PAFC)
- Allows for multiple inputs (natural gas; grid, solar, and wind-generated electricity), energy storage as hydrogen, and multiple outputs (electricity, heat, hydrogen)
- Utilizes hourly heat and building demand-profile databases
- Designed to follow building electricity demand, building heat demand, and then to produce hydrogen.
- Available at http://www.hydrogen.energy.gov/fc_power_analysis.html

Adding the fuel cell power model to the MSM simplifies inclusion of regional costs, upstream energy use, and emissions in the FC Power model

User interface inputs:

- Unit capacity, cost
- Choice of power demand profile (office/hotel/mall; geographic location)
- Profile location so costs and grid mix can be imported from HyDRA



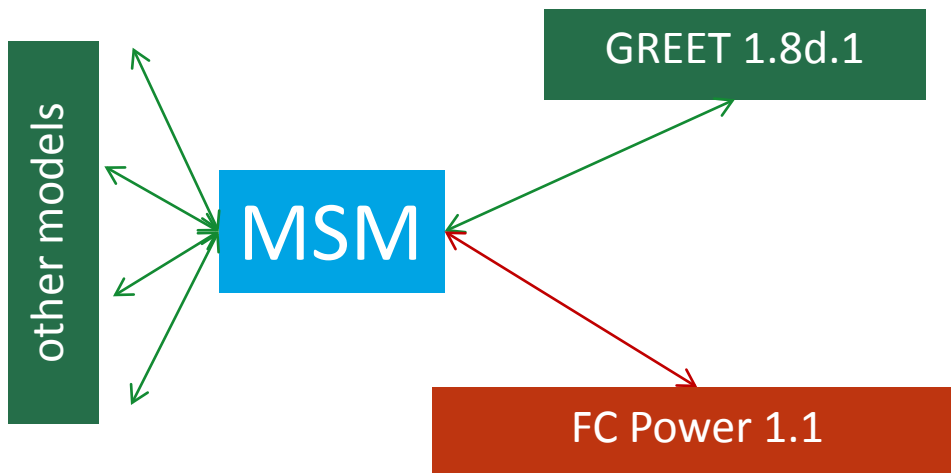
GREET calculates:

- annual average electricity fuel-cycle energy use & emissions
- annual average upstream natural gas (NG) energy use and total emissions



FC Power gets upstream energy & emissions entries for NG and electricity:

- total energy
- fossil fuels
- petroleum
- CO₂, N₂O, GHG



The MSM allows the user to easily provide desired inputs and easily see annual average quantities of energy products, levelized cost of hydrogen, well-to-wheels (WTW) energy use, and WTW emissions. Example screenshots are below.

H2 Macro System Model - BETA

Interactive | Upload file | Multi-param

System: Wells to Wheels | Year: 2005

Production Size/Delivery: Central Distributed | Liquid Truck

Feedstock/Process: FC phosphoric acid

City: Population: 1247364 | H2 penetration (%): 50

Vehicle Fuel Economy: User defined (mi/GGE) | 45

Select regional data (optional): Region: CO | Boulder | Resource cost: none

Title: PAFC Trigen for Boulder with 80 kg/day demand | User: mruth

Optional inputs: Detailed Inputs (Feedstock, Utilities, Production Facility, CHHP Production Options, Dispensing Forecourt, Vehicle Characterization, Vehicle Cost Parameters, Default Values (Constants))

daily hydrogen demand: Value: 80 | Units: kg/day | Description: average daily hydrogen demand

Results: Serial #1190

161748 Btu Electricity Coproduct | 116279 Btu Heat Coproduct | 19.46 \$/kg Levelized Cost of H2 at Pump

610000 Btu Natural Gas | 0 Btu Ethanol | 0 Btu Biomass | 0 Btu Coal | 0 Btu Electricity

216000 Btu Energy Lost

118000 Btu Hydrogen Gas

Energy Use and Emissions

Well-to-Wheels Total Energy Use (Btu/mile)	4392
Well-to-Wheels Petroleum Energy Use (Btu/mile)	17
Well-to-Wheels Fossil Energy Use (Btu/mile)	4389
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	418
WTP Emissions (lb CO2 Equivalent / GGE fuel available) GHG	42

Energy Efficiency

Production Process Energy Efficiency (%)	85
Pathway Efficiency (%)	85
WTP Efficiency (%)	59

Case Definition

Year	2005
Form of Hydrogen	Gas
Production Means	Forecourt
Feedstock	NG for FC PA
Sequestration	NO
Transport for Delivery	None
Vehicle efficiency (miles/GGE)	45
City Hydrogen Use (kg/day)	344451
Vehicle ownership period (yrs)	5
Building type	large hotel
Building location	Colorado (Boulder)

Model Information

HyARC	1.0
GREET	1.2011
HDSAM	2.2
H2APOW	1.0
CPM	2
GREET2	2.7

Other Information

Application version	1.3 BETA (Jun 2010)
Run serial number	1190
Title	PAFC Trigen for Boulder with 8...
Submitted	2012-04-18 08:08:48

Disclaimer

The MSM is being validated so these results are not guaranteed. If any results are problematic please inform the MSM team at msm@nrel.gov

Many assumptions are embedded in the models being linked but can be changed in sensitivity runs.

Buildings

- Types: Large hotel, large office, small hotel, small office, supermarket
- Locations: Seattle, Los Angeles, Chicago, Baltimore
- Electricity and heat load sources: NREL's Electricity, Resources, and Buildings Integration Center databases

CHHP

- 320 and 1440 kW fuel cells used for this analysis
- Fuel cell cost: \$3000/kW (purchased)
- Rent: \$38,700/yr
- Compressor and dispenser replacement every 10 years
- PAFC catalyst and reformer replacement every 5 years and refurbishment every 10 years

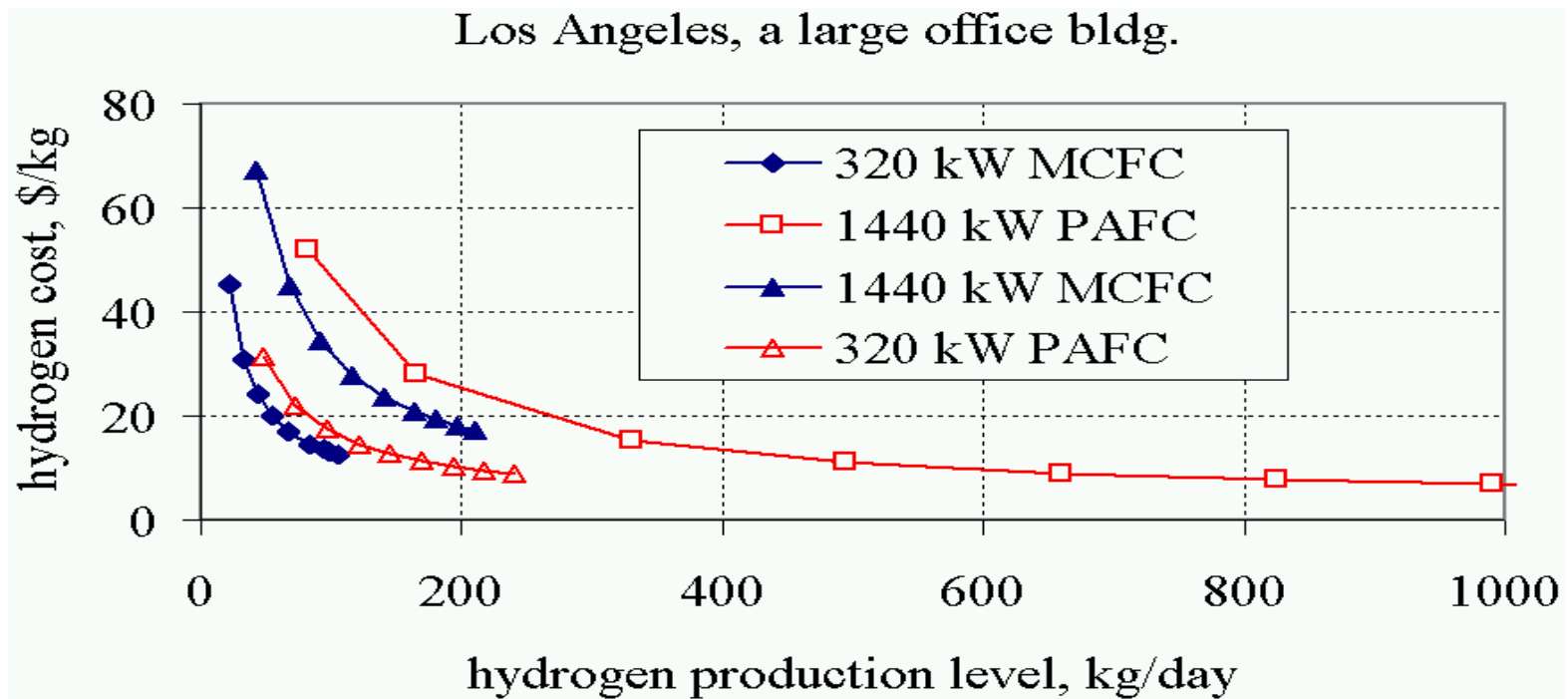
Financial

- 10% IRR
- 20 year lifetime
- MACRS depreciation where appropriate
- 1.9% inflation
- Commercial electricity and natural gas prices from Hydra
- No incentive programs or costs of carbon

GREET

- Grid mixes from Hydra databases
- Upstream energy use, efficiencies and emissions from GREET databases

Minimum hydrogen levelized cost was used for this analysis. Maximizing hydrogen production minimizes the levelized cost of hydrogen for PAFCs and most MCFC scenarios.



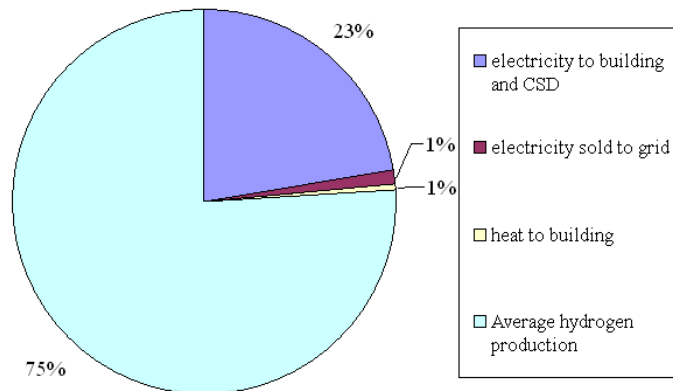
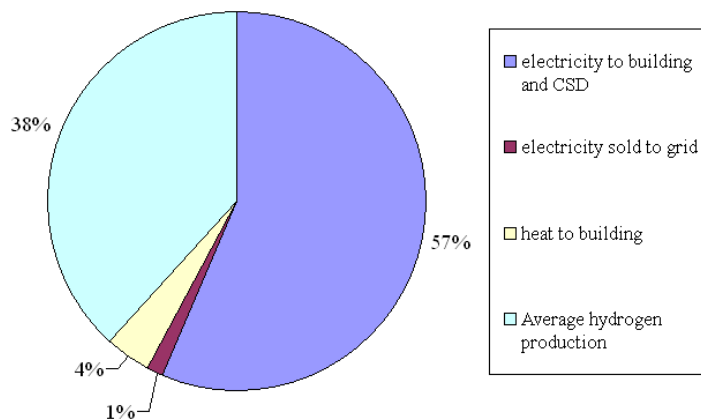
- Hydrogen cost estimates for various fuel cell types (MCFC and PAFC) and sizes (320 and 1,440 kW maximum AC rating) for a large office building in Los Angeles are shown.
- The values of electricity and heat are set equivalent to market values of commercial grid electricity and cost to produce heat from NG using a commercial boiler.

The smaller MCFC system mirrors building load needs while the larger PAFC is essentially a hydrogen and power generator for outside use.

320 kW MCFC

Energy output:
11 MMkWh/yr
Building load:
16,000 MMBtu/yr

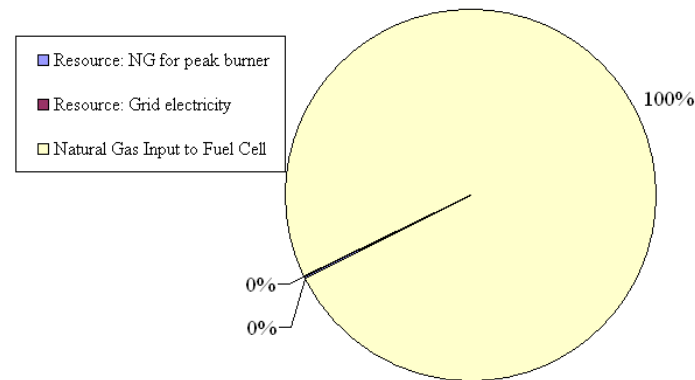
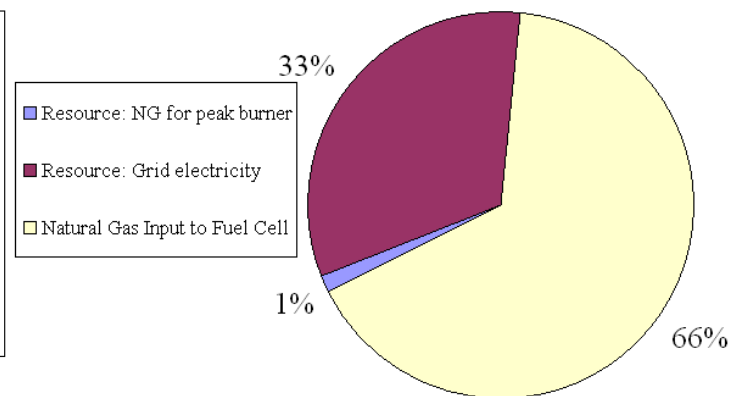
320 kW MCFC energy output, 3.42 million kWh/yr



1,440 kW PAFC

Energy output:
27 MMkWh/yr
Building load:
16,000 MMBtu/yr

resources to meet building loads, mmBtu/year



Large office building with Los Angeles climate, electricity cost & grid mix, and NG cost

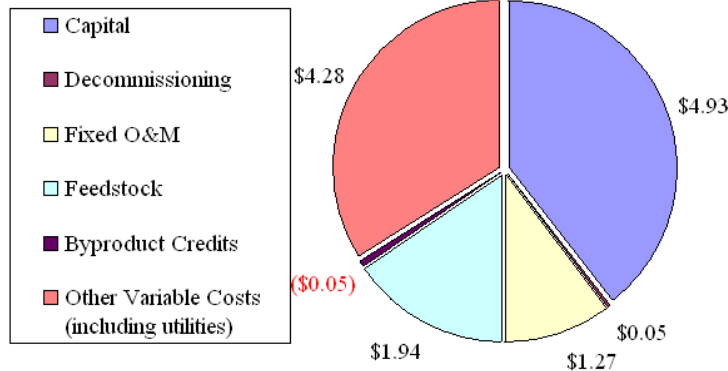
Capital is the primary cost driver for all these systems; variable costs (rent and labor, primarily) are the secondary drivers for the smaller MCFC system.

320 kW

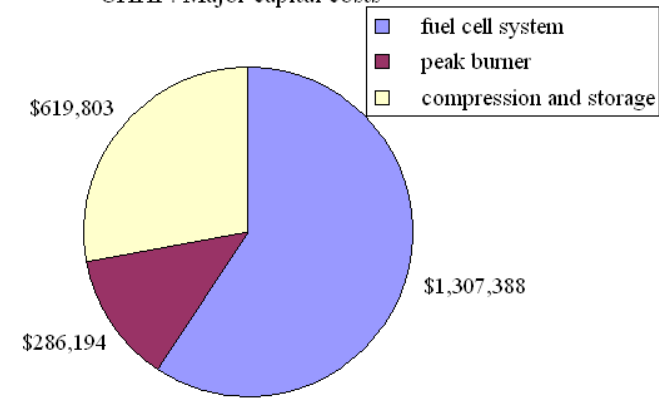
MCFC

105 kg/day
 Levelized Cost:
 \$12.10 / kg
 Capital Cost:
 \$2,200,000

CHHP: Hydrogen cost at the pump contributions



CHHP: Major capital costs

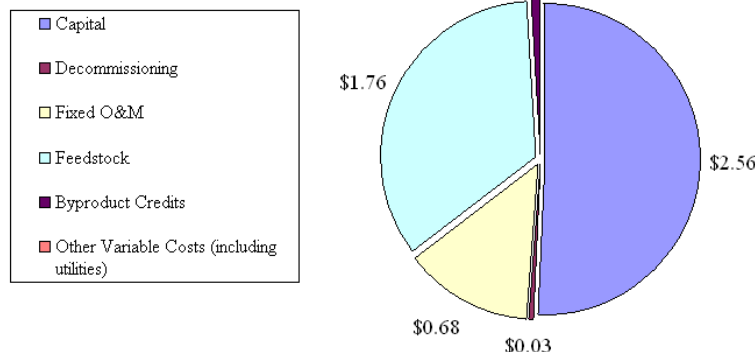


1,440

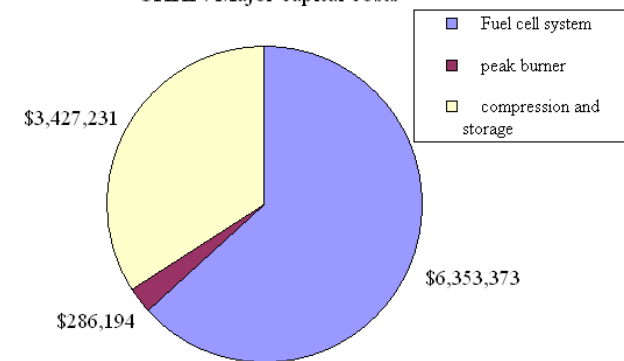
kW PAFC

1630 kg/day
 Levelized Cost:
 \$5.00 / kg
 Capital Cost:
 \$10,100,000

CHHP: Hydrogen cost at the pump contributions



CHHP: Major capital costs



Large office building with Los Angeles climate, electricity cost & grid mix, and NG cost

Levelized Cost Results for Various Options

Minimizing the levelized cost of hydrogen results in costs higher than conventional systems.

320 kW MCFC: H₂ cost, \$ / kg (and % change to the baseline system)				
	Large hotel	Large Office	Supermarket	Small hotel
Seattle, WA	\$15.90 (+52%)	\$14.30 (+66%)	\$16.60 (+59%)	\$27.70 (+79%)
Los Angeles, CA	\$12.20 (+28%)	\$12.10 (+38%)	\$13.30 (+36%)	\$23.50 (+61%)
Chicago, IL	\$16.20 (+57%)	\$14.50 (+71%)	\$47.80(+231%)	\$58.00(+198%)
Baltimore, MD	\$14.70 (+41%)	\$13.40 (+53%)	\$15.70 (+49%)	\$25.30 (+67%)
1440 kW PAFC: H₂ cost, \$ / kg (and % change to the baseline system)				
	Large hotel	Large Office	Supermarket	Small hotel
Seattle, WA	\$ 5.70 (+31%)	\$ 5.40 (+51%)	\$ 6.90 (+28%)	\$ 9.70 (+30%)
Los Angeles, CA	\$ 6.20 (+20%)	\$ 5.00 (+40%)	\$ 7.40 (+23%)	\$10.90 (+29%)
Chicago, IL	\$ 6.00 (+34%)	\$ 5.60 (+55%)	\$ 6.10 (+22%)	\$ 8.70 (+23%)
Baltimore, MD	\$ 6.20 (+30%)	\$ 5.70 (+48%)	\$ 7.40 (+28%)	\$10.10 (+28%)

For consistency, hydrogen costs are compared for CHHP vs. conventional systems at equal production levels.

Levelized costs of hydrogen are reported in the table. The increases in cost over a baseline system [grid electricity, NG boiler for heat, and steam methane reforming (SMR) for hydrogen] are reported parenthetically.

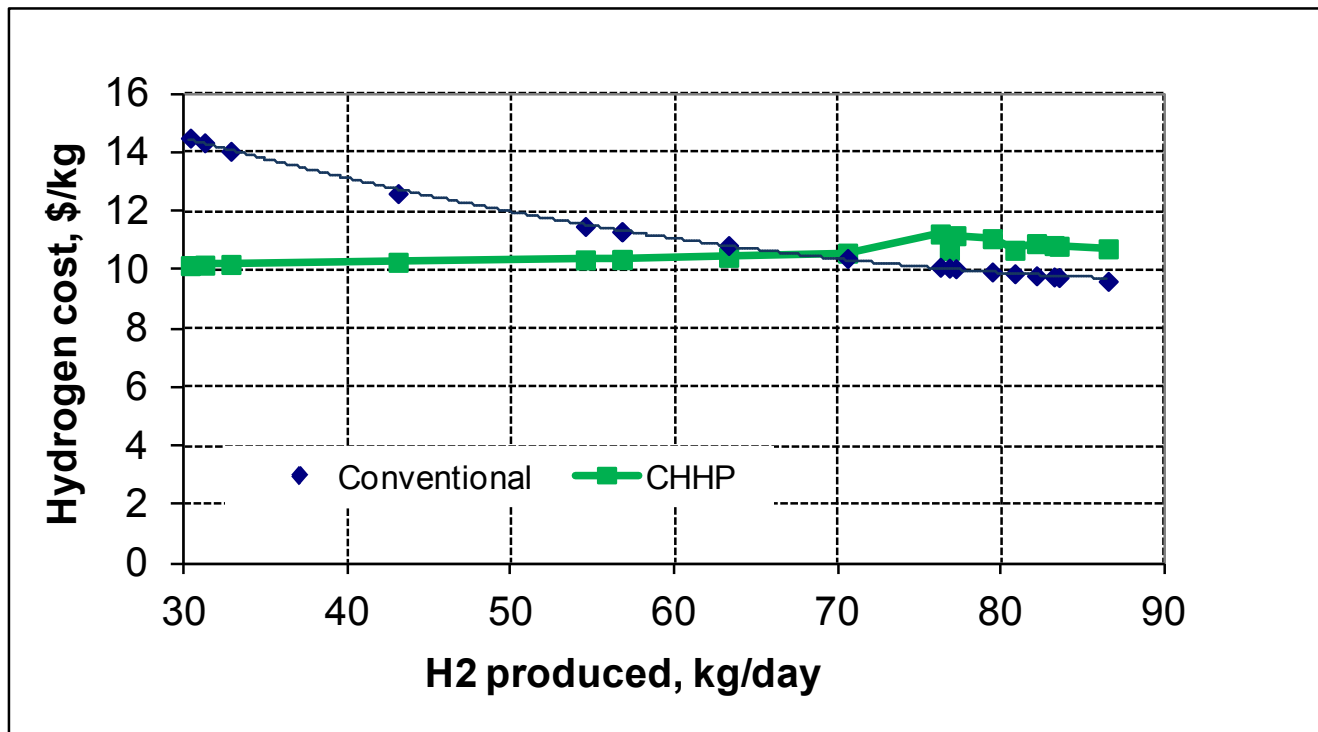
GHG Emissions Results for Various Options

GHG emissions from tri-generation systems are lower than for the conventional option when the system size matches the building load.

320 kW MCFC: GHG emissions reduction, %				
	Large hotel	Large Office	Supermarket	Small hotel
Seattle, WA	21%	24%	21%	18%
Los Angeles, CA	20%	8%	11%	4%
Chicago, IL	40%	39%	-3%	12%
Baltimore, MD	32%	25%	34%	33%
<i>% = (emissions change / baseline emissions); negative = increase in emissions</i>				
1440 kW PAFC: GHG emissions reduction, %				
	Large hotel	Large Office	Supermarket	Small hotel
Seattle, WA	-2%	-9%	-4%	-6%
Los Angeles, CA	-2%	-15%	-13%	-17%
Chicago, IL	11%	7%	-8%	-2%
Baltimore, MD	4%	-2%	3%	1%

System-wide WTW GHG emissions are reported in the table . The increases in emissions over a baseline system (grid electricity, NG boiler for heat, and SMR for hydrogen) are reported parenthetically.

At hydrogen production less than 70 kg/day, the levelized cost of hydrogen produced by MCFC tri-generation system for a small office in Los Angeles is less than that of a similarly sized SMR providing costs for rent are scaled.



Conclusions

- **Hydrogen cost is minimized at the highest hydrogen production rate due to economies of scale for the costs of dispensing.**
- **But those resulting levelized costs may not be the most competitive with conventional technologies**
- **Levelized costs of hydrogen can compete with SMR at low production capacities (<70 kg/day) providing the cost of rent scales.**
- **GHG emissions from tri-generation systems are lower than the conventional option when the system size matches the building load.**

Proposed Future Work

No additional funding is planned for this analysis and the only future work is finalizing the report. If we had additional funding, we would like to:

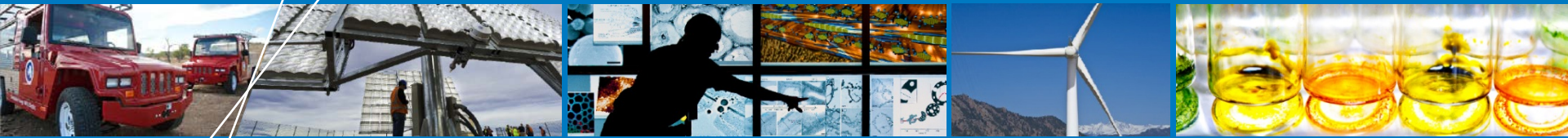
- Test other options for setting CHHP parameters in the MSM**
- Update GREET & H2A FC Power models**
- Analyze tri-generation systems to balance the grid where variable generation (intermittent) is in place.**
- Additional review of parameters and gap analysis**

As ongoing projects, the MSM is being updated and an analysis of the parameters used in estimating levelized cost and energy use and emissions is underway.

Collaborations

- **NREL - FC Power Model & Hydra**
- **Fuel Cell Energy – Fuel cell operational data**
- **Argonne National Laboratory - GREET**
- **Fuel Pathway Integration Tech Team (FPITT) - Review and discussion**

Technical Backup Slides



Approach: Model Validation

- Model inputs and results were reviewed by the Fuel Pathway Integration Tech Team (FPITT), others in the H₂ analysis community and industry experts
- One major MSM output – Pathway Report(s) – undergoes thorough reviews by FPITT. The data reported in that report were used for this analysis.
- The H2A Production models and HDSAM are built in a transparent way and undergo their own validation prior to being published; these models are reviewed by the Production Tech team and by the Delivery Tech team
- GREET is widely used and is being constantly reviewed and updated

Validating models at both integrated and component levels