XI.10 Cost, Energy Use, and Emissions of Tri-Generation Systems

Mark F. Ruth* (Primary Contact),
Michael E. Goldsby†, Timothy J. Sa†, Victor Diakov*
*National Renewable Energy Laboratory
15013 Denver West Pkwy.
Golden, CO 80401
Phone: (303) 817-6160
Email: Mark.Ruth@nrel.gov
† Sandia National Laboratories

DOE Manager
HQ: Fred Joseck
Phone: (202) 586-7932
Email: Fred.Joseck@ee.doe.gov

Project Start Date: December 1, 2010
Project End Date: October 31, 2011

Fiscal Year (FY) 2012 Objectives

- Develop a macro-system model (MSM):
  - Aimed at performing rapid cross-cutting analysis
  - Utilizing and linking other models
  - Improving consistency between models
- Incorporate tri-generation systems into the MSM and develop a methodology for MSM users to analyze optimized tri-generation (also known as combined hydrogen, heat, and power – CHHP) scenarios easily.
- Support decisions regarding programmatic investments through MSM analyses and sensitivity runs on tri-generation systems focusing on quantification of levelized cost and greenhouse gas (GHG) emissions for various fuel cell types, building types, and building locations.

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section of the Fuel Technologies Program Multi-Year Research, Development and Demonstration Plan:

(B) Stove-piped/Siloed Analytical Capability
(C) Inconsistent Data, Assumptions and Guidelines
(D) Insufficient Suite of Models and Tools

Contribution to Achievement of DOE Systems Analysis Milestones

This project will contribute to achievement of the following DOE milestones from the Systems Analysis section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

- Milestone 1.1: Complete an analysis of the hydrogen infrastructure and technical target progress for hydrogen fuel and vehicles. (2Q, 2011)
- Milestone 1.4: Complete evaluation of fueling station costs for early vehicle penetration to determine the cost of fueling pathways for low and moderate fueling demand rates. (4Q, 2012)
- Milestone 2.1: Complete the 2nd version of the Macro-System Model to include the analytical capabilities to evaluate the electrical infrastructure. (2Q, 2011)
- Milestone 2.2: Annual model update and validation. (4Q, 2011 through 4Q, 2020)

FY 2012 Accomplishments

- Linked the Fuel Cell Power Model (FC Power) in the MSM framework.
- Performed an analysis on tri-generation systems focusing on quantification of levelized cost and GHG emissions for various fuel cell types, building types, and building locations.

✧ ✧ ✧ ✧ ✧

Introduction

At the DOE Hydrogen Program's behest, we are developing an MSM to analyze cross-cutting issues because no existing model sufficiently simulates the entire system, including feedstock, conversion, infrastructure, and vehicles, with the necessary level of technical detail. In addition, development of the MSM exposes inconsistencies in methodologies and assumptions between different component models so that they can be identified and corrected when necessary. Version 1.0 of the MSM was developed previously and is available to the hydrogen analysis community. It links H2A Production, HDSAM, the Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) model, and physical property information from the Hydrogen Analysis Resource Center to estimate the economics, primary energy source requirements, and emissions of multiple hydrogen production/delivery pathways.

Version 2.0 of the MSM links the H2A Power [1] model that simulates reformers and fuel cells providing heat and power for buildings and hydrogen for transportation. Version 2.0 also links Hydrogen Demand and Resource Analysis [2] data to incorporate county-specific grid mixes and natural gas costs. Utilizing the updated MSM, an analysis was performed on CHHP for various building types, in various locations, and with two different types of fuel cells.

Approach

The MSM is being developed as a tool that links or federates existing models across multiple platforms. This approach was chosen because the task of building a single monolithic model incorporating all of the relevant information in the existing models would have been overwhelming because the necessary expertise to do so was spread among half a dozen DOE laboratories and a dozen or more universities and private contractors. Linking models allows model users that depend on data from component models to continue using their models while retrieving data from component models in a less labor-intensive manner. In addition, it provides a common platform for data exchange necessary to update integrated models when the component models have been updated.

The MSM is being built on a framework inspired by an example of a federated object model (FOM). The MSM uses a common interlingua that is extensible (accommodates new models with a minimum of difficulty), distributable (can be used by multiple people in different areas of the country), and scalable (to a larger number of participating models) using exogenous data. FOMs are exemplified by the Department of Defense high-level architecture [3]. Version 2.0 of the MSM uses Ruby and Ruby interfaces to Microsoft Excel and other platforms to collect, transfer, and calculate data.

Results

To run FC Power, the user defines the size of the fuel cell (kW capacity) and the hydrogen demand. Using the MSM, multiple fuel cell sizes are tested. For each size, the maximum hydrogen production level is determined. A range of hydrogen production levels up to the maximum were run to determine the levelized hydrogen cost of each production level. The production level with the minimum levelized cost was defined as the optimimum for that fuel cell size. As seen on the Figure 1, for any given fuel cell size, the levelized hydrogen cost in both molten carbonate fuel cell (MCFC) and phosphoric acid fuel cell (PAFC) reaches its minimum at high hydrogen production levels; this trend holds for all cases considered within this study. Additionally, the fuel cell size is a strong factor affecting the hydrogen costs; consequently, in the following sections the size of the fuel cell is optimized for each location and building type.

The MCFC fuel cell energy output for a large office building in Los Angeles is shown in Figure 2a and the PAFC energy output is shown in Figure 2c. For the MCFC, the two largest constituents are electricity supplied and hydrogen produced with heat supplied to the building and electricity sold to the grid as other energy uses. The overall building energy loads are met by electricity and heat generated from

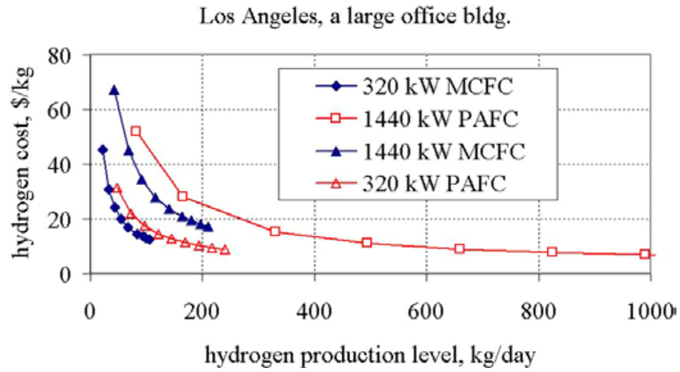

FIGURE 1. Hydrogen cost for various fuel cell types (MCFC and PAFC), sizes (320 and 1,440 kW maximal alternating current rating) depending on hydrogen production level. Each curve (except for 1,440 kW PAFC) is shown as limited by the maximum hydrogen production level allowed for the correspondent fuel cell size (maximum allowed H2 production level for 1,440 kW PAFC is 1,630 kg/day and falls beyond the figure limits)

natural gas supplied to the fuel cell, natural gas supplied to the peak burner, and supplemental electricity from the grid as shown in Figure 2b. In the case shown in Figure 2b, the fuel cell capacity (320 kW) is sufficient for supplying most of the electric load to the building while consuming only a small fraction from the grid. For the MCFC, the main contributors to the hydrogen levelized costs are capital costs and variable expenses. Byproduct credits offset an insignificant portion of the hydrogen levelized cost (Figure 3a). In addition to fuel cell system, compression, storage and dispensing (CSD) are the major contributors to the overall capital costs (Figure 3b).

If the building had a large (1,440 kW) electricity load-following PAFC the results would be different. Hydrogen becomes the dominant product (Figure 2c); the fuel cell provides almost all necessary electricity so there is virtually no electricity bought from the grid (Figure 2d); and capital costs account for as much as half of the hydrogen cost at the pump (Figure 3c) with fuel cost being the second major contributor. The capital costs distribution (Figure 3d) is similar to the MCFC case shown above. For both MCFC (Figure 3a) and PAFC (Figure 3c), capital costs are the leading contributor to the levelized hydrogen cost. This is the reason why lower hydrogen cost is achieved at the maximal (for a given fuel cell size) hydrogen production level.

As stated, the objective was to not only investigate CHHP for a large office building in Los Angeles but to investigate the opportunity for different building types in various locations. The procedure described above was used to select CHHP configurations for the analysis. Levelized cost and GHG emissions results are reported in Table 1 and Table 2, respectively.

For both MCFC and PAFC, a large office building in Los Angeles presents the lowest H2 cost option (Table 1). The same location (when compared to Seattle, Chicago and Baltimore) is favorable for any building type with an MCFC

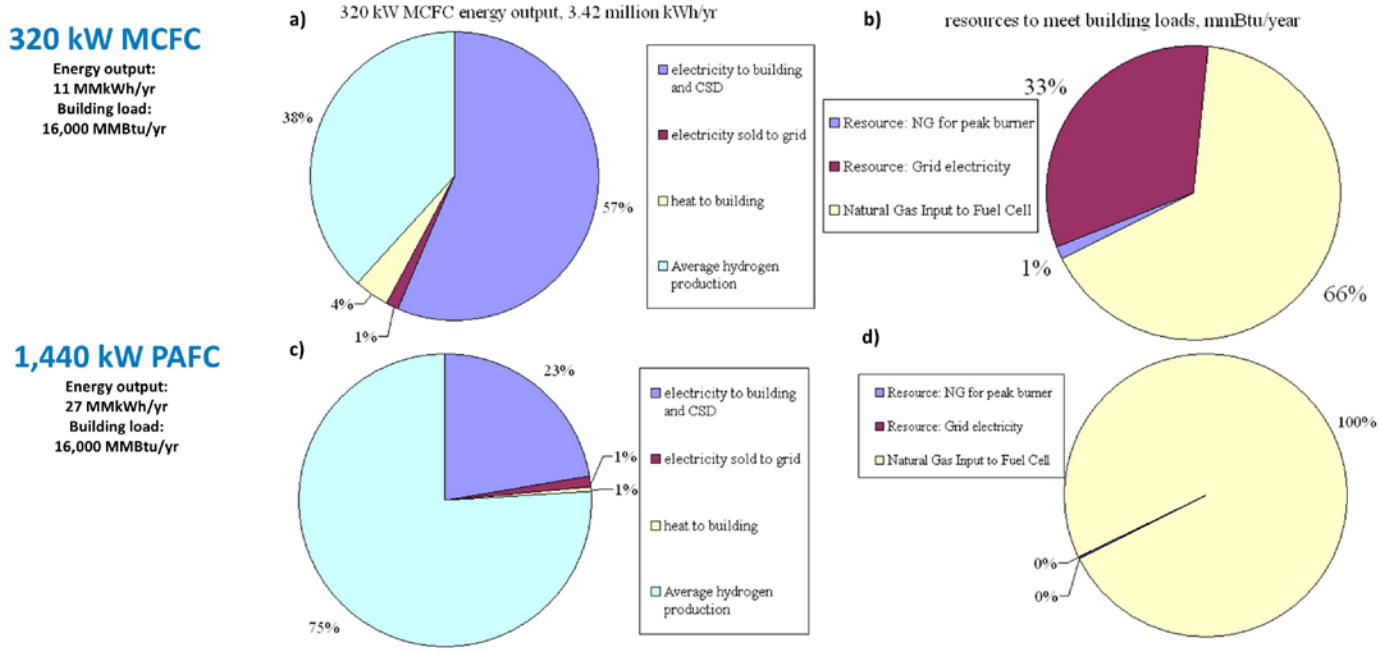

FIGURE 2. CHHP system energy output distribution for a large office building in Los Angeles, CA using 320 kW MCFC (a,b) and 1,440 kW PAFC (c,d) system: energy output distribution (a,c) and resources used to meet the building's energy loads (b, c).

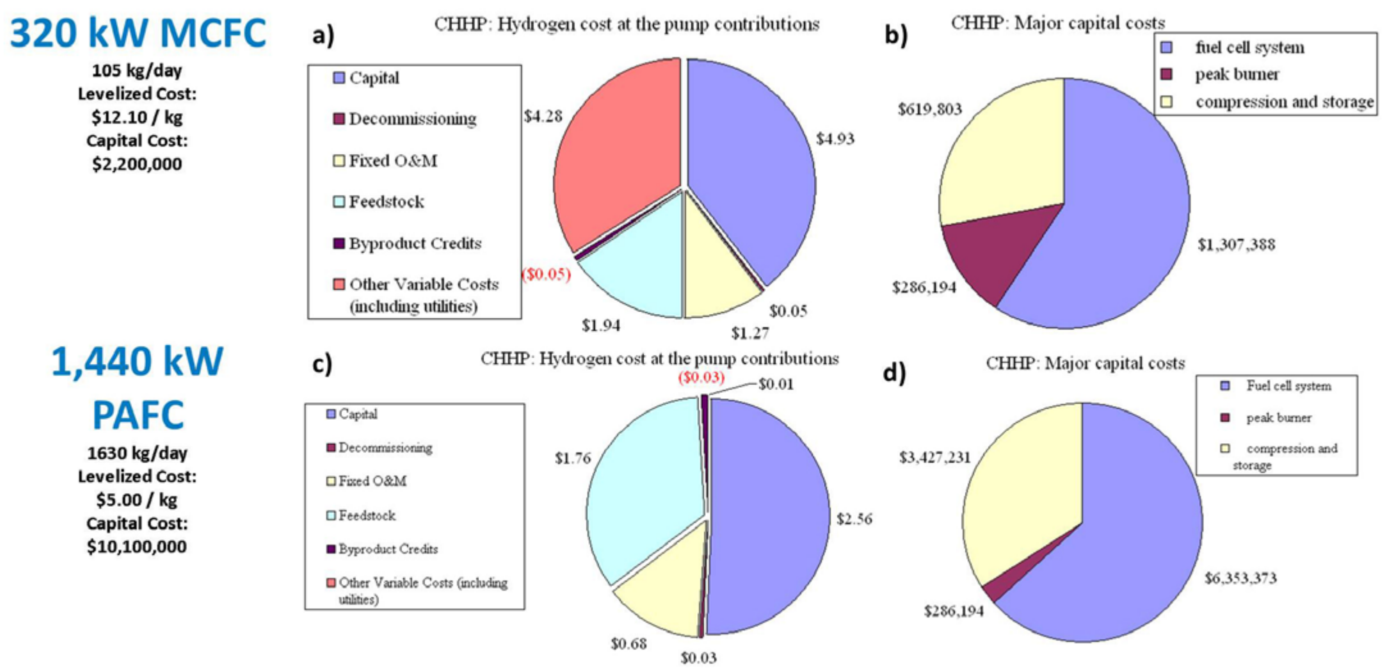

FIGURE 3. CHHP system energy output distribution for a large office building in Los Angeles, CA using 320 kW MCFC (a,b) and 1,440 kW PAFC (c,d) system: hydrogen cost breakdown (a, c), and capital costs (b, d).

system because of lower feedstock natural gas price ($9.48/mmBtu in Los Angeles vs. $10.58 in Seattle, $10.70 in Chicago and $12.10 in Baltimore).

Most hydrogen costs for MCFC in each column of the upper half of Table 1 are close, with exception of a supermarket and a small hotel in Chicago. There are several reasons why those differ so much from the others. First, for a MCFC, the feedstock cost does not represent a large fraction of the hydrogen cost (Figure 3a). Second, a comparison between Chicago large and small hotel cases (not shown) indicates that the CHHP model's optimization routine chooses to produce excess electricity rather than produce

TABLE 1. CHHP levelized hydrogen cost for various building types and locations

MCFC: H_2 cost, $/kg (and % change to the baseline system[1])				
	Large Hotel	Large Office	Supermarket	Small Hotel
Seattle, WA	$15.88 (+52%)	$14.34 (+66%)	$16.59 (+59%)	$27.70 (+79%)
Los Angeles, CA	$12.17 (+28%)	**$12.10** (+38%)	$13.27 (+36%)	$23.48 (+61%)
Chicago, IL	$16.17 (+57%)	$14.54 (+71%)	$47.76(+231%)	$58.00(+198%)
Baltimore, MD	$14.73 (+41%)	$13.36 (+53%)	$15.74 (+49%)	$25.31 (+67%)
PAFC: H_2 cost, $/kg (and % change to the baseline system)				
	Large Hotel	Large Office	Supermarket	Small Hotel
Seattle, WA	$5.73 (+31%)	$5.36 (+51%)	$6.95 (+28%)	$9.66 (+30%)
Los Angeles, CA	$6.21 (+20%)	$5.00 (+40%)	$7.43 (+23%)	$10.93 (+29%)
Chicago, IL	$6.02 (+34%)	$5.60 (+55%)	$6.13 (+22%)	$8.66 (+23%)
Baltimore, MD	$6.15 (+30%)	$5.71 (+48%)	$7.37 (+28%)	$10.12 (+28%)

[1]For consistency, hydrogen costs are compared for CHHP vs. baseline systems at equal production levels.

TABLE 2. GHG emissions reduction as compared to a baseline system

MCFC: GHG emissions reduction, %				
	Large Hotel	Large Office	Supermarket	Small Hotel
Seattle, WA	20.5%	23.6%	20.9%	17.8%
Los Angeles, CA	20.2%	8.3%	11.1%	4.3%
Chicago, IL	39.6%	38.8%	-2.8%	12.4%
Baltimore, MD	32.0%	25.0%	34.0%	33.0%
% = (emissions change/baseline emissions); negative = increase in emissions				
PAFC: GHG emissions reduction, %				
	Large Hotel	Large Office	Supermarket	Small Hotel
Seattle, WA	-2.0%	-8.7%	-3.5%	-6.2%
Los Angeles, CA	-2.0%	-15.0%	-13.3%	-17.1%
Chicago, IL	11.2%	6.7%	-7.9%	-2.4%
Baltimore, MD	4.3%	-2.1%	3.2%	1.4%

hydrogen. Lower hydrogen production levels result in higher H_2 production costs due to a lack of economies of scale for hydrogen compression, storage, and dispensing.

The MCFC, when compared to the PAFC, is more efficient in reducing the GHG emissions (Table 2) due to overall energy efficiency. For regions with cleaner electricity generation mix (California, Washington), the emission reductions by MCFC (top part of the table) are smaller; the two cases showing unusually high hydrogen costs (Table 1, MCFC, a supermarket and a small hotel in Chicago) also have smaller reduction in GHG emissions. It is not clear at this point what has the largest impact on GHG emissions reduction: is it just the overall load (and system size), or the shape of load profile (that also depends on building type and location).

The GHG emissions reduction for large hotel and large office buildings in Chicago (Table 2) compare well with 38% GHG emissions reduction expected for a hospital building in Chicago. The decrease in GHG emissions reduction for a supermarket or small hotel in Chicago, as compared to large buildings at same location, is likely induced by suboptimal fuel cell sizing discussed above.

Conclusions and Future Directions

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 steam methane reforming 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.

No additional funding is planned for this analysis. If we had additional funding, we would like to:

- Test other options for setting CHHP parameters in the MSM.
- Update GREET and H2A FC Power models.
- Analyze tri-generation systems to balance the grid where variable (or intermittent) generation 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.

FY 2012 Publications/Presentations

1. Ruth, M.; Diakov, V.; Evans, T. "Cost, Energy Use, and Emissions of Combined Hydrogen, Heat, and Power Tri-Generation Systems." NREL Report, in press.

References

1. Steward, D.; M. Penev, G. Saur, J. Zuboy. Fuel Cell Power Model: Startup Guide, System Designs, and Case Studies. Modeling Electricity, Heat, and Hydrogen Generation from Fuel Cell–Based Distributed Energy Systems.

Draft. November 2010. http://www.hydrogen.energy.gov/pdfs/fuel_cell_power_model_user_guide_version1.pdf.

2. Levene, J.; W. Sparks, D. Getman. "HyDRA: Hydrogen Demand and Resource Analysis Tool." 2010 DOE Hydrogen Program Annual Progress Report. Pp 1240-1243. November 2010.

3. Judith S. Dahmann, Richard Fujimoto, and Richard M.Weatherly. "The Department of Defense high level architecture." In Winter Simulation Conference, pages 142–149, 1997.