III.1 Hydrogen Delivery Infrastructure Analysis

Marianne Mintz (Primary Contact) and
Amgad Elgowainy
Argonne National Laboratory
9700 S. Cass Ave.
Argonne, IL 60439
Phone: (630) 252-5627; 252-3074
E-mail: mmintz@anl.gov; aelgowainy@anl.gov

DOE Technology Development Manager:
Monterey Gardiner
Phone: (202) 586-1758
E-mail: Monterey.Gardiner@ee.doe.gov

Partners:
- National Renewable Energy Laboratory
- Pacific Northwest National Laboratory

Project Start Date: October 2007
Project End Date: Project continuation and direction determined annually by DOE

Objectives

- Refine technical and cost data in the Hydrogen Delivery Scenario Analysis Model (HDSAM) to incorporate additional industry input and evolving technology improvements.
- Expand the model to include advanced technologies and other pathway options leading to new versions of the models.
- Improve methodologies for estimating key aspects of delivery system operation and optimizing cost and performance parameters.
- Explore options to reduce hydrogen delivery cost, including higher pressure and/or lower temperature gases, and operating strategies.
- Provide analyses to support recommended hydrogen delivery strategies for initial and long-term use of hydrogen as a major energy carrier.

Technical Barriers

This project directly addresses Technical Barrier A (which implicitly includes barriers B, C, D, F, H and J) in the Delivery Technical Plan, as well as Barriers B, C and E in the Systems Analysis Plan of the Fuel Cell Technologies Multi-Year Research, Development and Demonstration Plan. These are:

(A) Lack of H2/Carrier Infrastructure Options Analysis
(B) Stove-Piped/Siloed Analytical Capability
(C) Inconsistent Data, Assumptions and Guidelines
(E) Unplanned Studies and Analysis

Technical Targets

The project is developing a computer model to evaluate alternative delivery infrastructure systems. Insights from the model are being used to help identify elements of an optimized delivery system which could meet DOE's long-term delivery cost target.

Accomplishments

- Completed Version 2.2 of HDSAM which is now available at http://www.hydrogen.energy.gov/h2a_delivery.html. As described in the *2009 Annual Progress Report for the DOE Hydrogen Program*, additions include:
  - Three new delivery pathways:
    - High-pressure gaseous tube trailers
    - Cryo-compressed (CcH2) hydrogen dispensing
    - 700-bar gaseous hydrogen dispensing
  - Two different station configurations for 700-bar dispensing:
    - High-pressure cascade system
    - Lower pressure cascade system (with dedicated boost compressors for each hose)
  - Option permitting user selection of station configuration.
- Added a "cold gas" tube-trailer pathway to the development version of HDSAM.
- Analyzed HDSAM fuel station footprint assumptions (including setbacks, separation distances, and other safety constraints) as compared with proposed new standards from the National Fire Protection Association (NFPA). Developed revised station footprints to better reflect minimum separation distances between different components.
- Analyzed cost, energy use and greenhouse gas (GHG) emissions to bring renewable hydrogen to Los Angeles. Estimates include hydrogen production from New Mexican wind power, transmission to the Los Angeles city gate, geologic storage, local distribution, and dispensing.

✧ ✧ ✧ ✧ ✧

Introduction

Initiated as part of the H2A project, HDSAM is an Excel-based tool that uses a design calculation approach to estimate the contribution of individual components of delivery infrastructure to hydrogen cost, energy use and GHGs. The model links the individual components in a systematic market setting to develop capacity/flow parameters for a complete hydrogen delivery infrastructure. Using that systems level perspective, HDSAM calculates the full, levelized cost (i.e., summed across all components) of hydrogen delivery, accounting for losses and tradeoffs among the various component costs. A graphical user interface permits users to specify a scenario of interest. A detailed User's Guide and access to the Energy Efficiency and Renewable Energy (EERE) help desk also assist users in running HDSAM.

Results

Work continued on updating and expanding HDSAM. Release 2.2 includes several high-pressure/low-temperature options discussed in last year's report. These were further refined, tested and reviewed prior to their inclusion in the new release. Results from work on HDSAM 2.21, to be released in late 2010, are described in the following.

"Cold Gas" Tube-Trailer

This high-pressure/low-temperature pathway might be particularly well suited to early markets. Characterized in Fiscal Year (FY) 2010, this pathway assumes composite tube trailers (characterized by Lawrence Livermore National Laboratory) are loaded with gaseous hydrogen (GH2) at 350-bar (90 K) in order to deliver approximately 1,500 kg of hydrogen to a station where it is compressed to 600-bar (130 K) in a cascade charging unit and dispensed at 500-bar (190 K). Figure 1 shows the major stages in this pathway as compared with three other "early market" pathways contained in HDSAM 2.2. Figures 2 and 3 show preliminary results – installed capital costs of stations and the station portion of levelized hydrogen cost.[1] By eliminating the cascade system and reducing site storage and refrigeration, compression costs are much lower for CcH2 delivery (Figure 2) than for the other options. Cold gas delivery appears to get part way to the station savings of CcH2 because of reduced storage costs. Thus, station costs for cold gas delivery may be comparable to those for 350-bar GH2 delivery but with improved energy use and vehicle driving range. Note that some of the CcH2 "savings" is shifted upstream to terminals and tube trailers, thereby reducing the difference among delivery

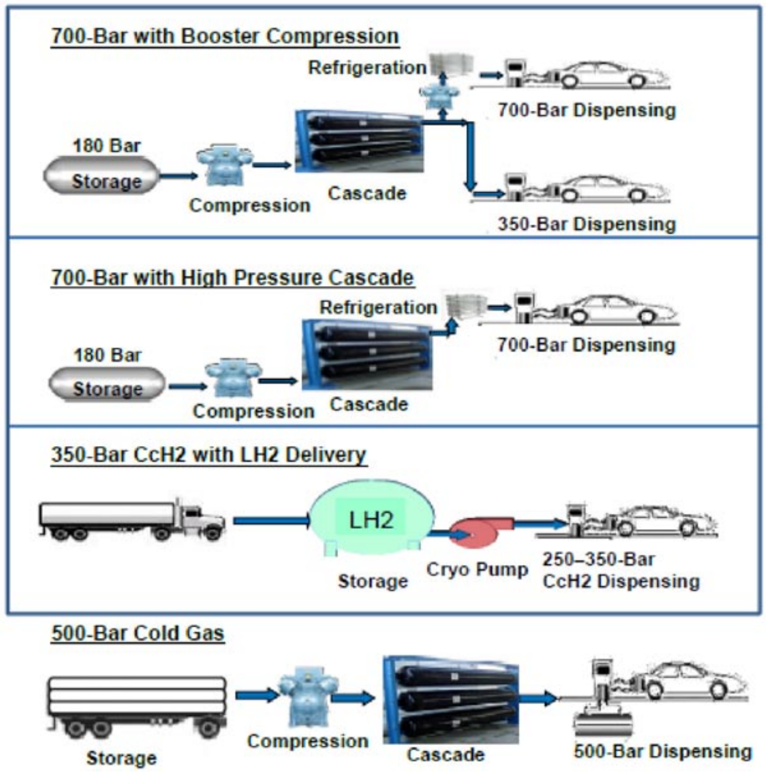

FIGURE 1. HDSAM Contains Several Early Market Delivery Options Including Cold Gas Tube-Trailer Delivery with 500-Bar Dispensing, Liquid Truck Delivery with Cryo-Compressed Dispensing, and 180-Bar Delivery with 700-Bar Cascade or Booster Compressed Dispensing

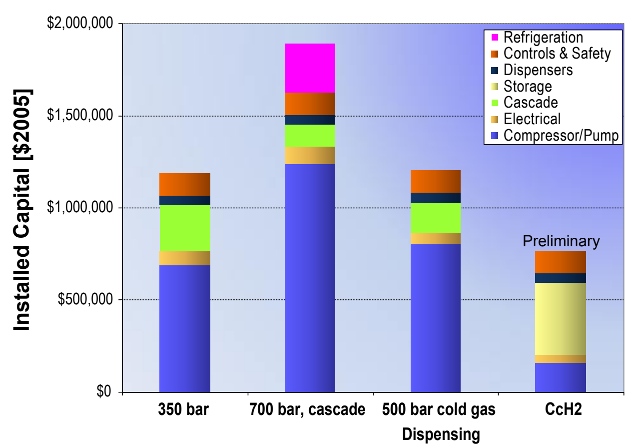

FIGURE 2. Station Costs May Be Comparable for 500-Bar Cold Gas and 350-Bar Pathways, Greater for 700-Bar and Less for Cryo-Compressed Pathways

[1] Note that 700-bar GH2 with high pressure cascade is less expensive than the booster-compressed option (not shown).

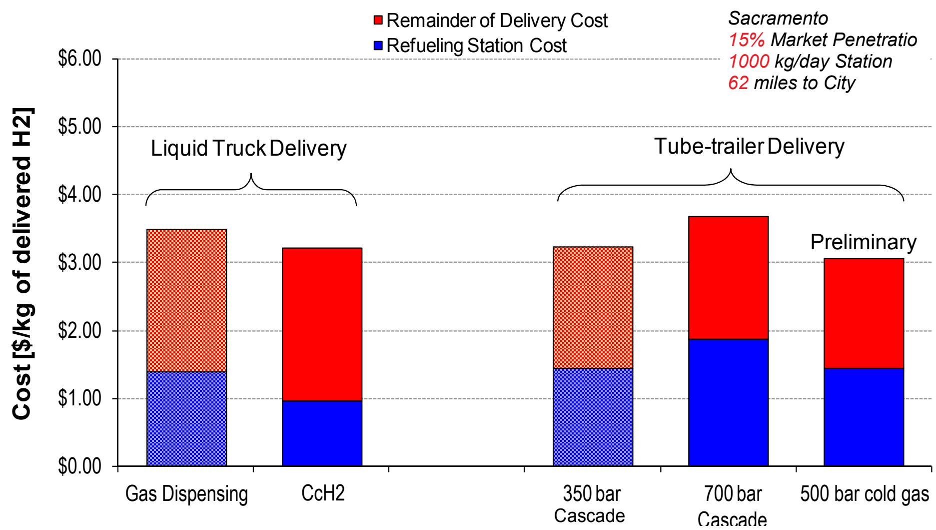

FIGURE 3. Levelized Total Delivery Costs for 500-Bar Cold Gas May Be Comparable to Cryo-Compressed and 350-Bar GH2 Pathways

options. As shown in Figure 3, total levelized delivery cost differs by less than $0.40 among CcH2, cold gas and 350-bar delivery pathways.

Station Footprint Analyses

Default footprints in HDSAM 2.2 are approximately 110 x 130 ft for GH2 stations and 150 x 170 ft for liquefied hydrogen (LH2) stations. In response to industry concern that land areas are insufficient to accommodate required setbacks, separation distances and delivery truck maneuvers, layouts were reviewed and compared with proposed NFPA rules for setback and separation distances. Results suggest that GH2 total station land area should be increased from 3,950 to 16,500 ft^2 (about two-thirds of which is due to land requirements for an additional hydrogen tube-trailer bay, a cascade storage system, truck maneuvering and associated separation distances). Note that HDSAM does not allocate the cost of land occupied by convenience stores, parking, car washes or other amenities to hydrogen storage and dispensing. The impact of fully NFPA-compliant station size on levelized hydrogen cost may be seen in Figure 4. For GH2 stations, full NFPA compliance adds $1.35/kg for stations dispensing 50 kg/day but only $0.17/kg to stations dispensing 1,000 kg/day. For LH2 stations (not shown) the effect is less – full NFPA compliance adds $0.57/kg for stations dispensing 50 kg/day and only $0.07/kg for stations dispensing 1,000 kg/day.

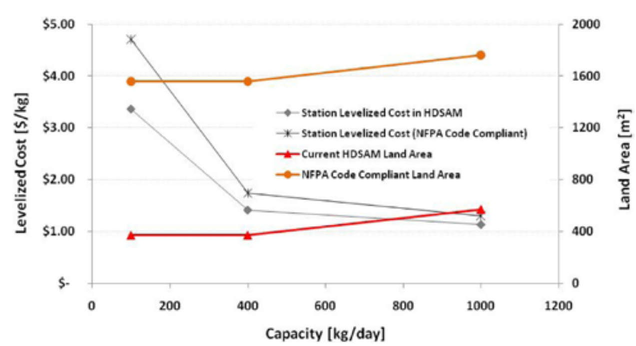

FIGURE 4. Levelized Cost Contribution of GH2 Station with Tube Trailer Delivery, HDSAM 2.2 Versus Proposed NFPA-Compliant Station

Wind-to-LH2 Analysis

In response to the California mandate that 30% of the state's hydrogen use must be produced from renewable sources, a study was initiated to evaluate the cost, energy use and GHG emissions of potential renewable hydrogen production/delivery options. As a first step, a "generic" site with Class 3 wind potential and relatively good access to Los Angeles (LA) was selected for analysis. Located near Albuquerque, NM, the site was assumed to include a 252-MW wind farm (i.e., 84 3-MW turbines), a 160-MW electrolyzer, a 40-tpd liquefier and 4,000 t of geologic storage. All output was dedicated to liquid hydrogen production (i.e., no electricity was exported to the grid) for 80,000 fuel cell vehicles approximately 800 miles to the west. Initially, five potential pathways, both renewable and nonrenewable were compared: Albuquerque-to-LA via wind-to LH2, Albuquerque-to-LA via steam methane reforming (SMR)-to-LH2, Albuquerque-to-LA via electrolysis-to-LH2; centralized production in LA via SMR, and centralized production in LA via electrolysis. Preliminary results (Figure 5) show that hydrogen production tends to be the major contributor to levelized

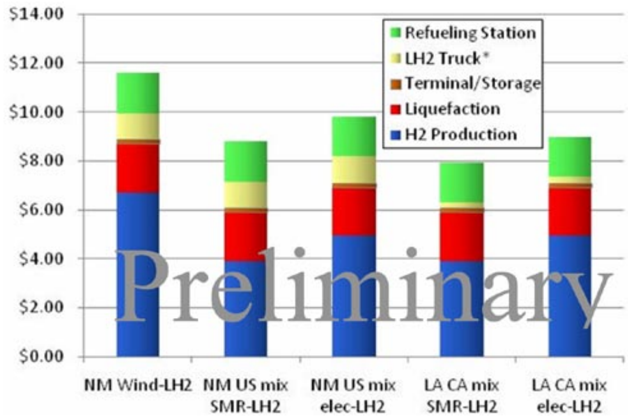

FIGURE 5. Levelized Cost of Hydrogen Delivered to Los Angeles Fuel Stations by Production and Delivery Pathway Component

hydrogen cost, followed by liquefaction and the fuel station. At roughly $8/kg, SMR is less expensive than electrolysis or wind power. However, the latter produces only 18 g CO_{2e}/mi on a well-to-wheel basis as compared with 446 g for conventional gasoline vehicles.

Conclusions and Future Directions

Hydrogen delivery infrastructure analysis seeks to identify aspects of hydrogen delivery that are likely to be especially costly (in capital and operating cost, energy and GHG emissions) and estimate the impact of alternative options on those costs. This project has developed a model of hydrogen delivery systems to quantify those costs and permit analyses of alternative technologies and operating strategies. This work has been conducted collaboratively by staff of Argonne National Laboratory, the National Renewable Energy Laboratory and Pacific Northwest National Laboratory with the advice and assistance of several industrial partners. Regular interaction has also occurred with the Fuel Pathways and Delivery Tech Teams.

Through FY 2010, results affirm that hydrogen delivery could add $4 or more to the levelized cost of hydrogen "at the pump." The most promising options for reducing delivery cost tend to smooth demand (thereby reducing the need for hydrogen storage) or increase the energy density of delivered fuel (by maintaining low temperature or high pressure in the delivery pathway). Tasks completed through June 2010 have been discussed above. The following tasks will be completed by the end of FY 2011:

- Further analyses of hydrogen delivery cost targets.
- Completion of the wind-to-liquid hydrogen analysis and publication of results.
- Further expansion of HDSAM's capabilities to include a cold gas tube-trailer pathway, advanced compression technologies, and revised approaches to modeling fuel station land requirements, cryo-compressed dispensing and geologic storage (the latter in conjunction with Sandia National Laboratories).
- Completion and posting of HDSAM 2.21 on the EERE Web site.
- Continued interaction and collaboration among the project partners and with the Fuel Pathways Integration Tech Team, the Delivery Tech Team, industry, and the broader hydrogen modeling community.

Publications/Presentations

1. Mintz, M. and A. Elgowainy, *Effect of High Pressure and Cryo-Compression on Hydrogen Delivery Cost*, National Hydrogen Association Annual Meeting, Long Beach, CA, May 4, 2010.

2. Mintz, M., A. Elgowainy and M. Gardiner, *Rethinking Hydrogen Fueling: Insights from Delivery Modeling*, Transportation Research Record 2139, Transportation Research Board, Journal of the Transportation Research Board, Washington, D.C., Dec. 2009.

3. Gillette, J., M. Mintz and A. Elgowainy, *Land Requirements for Hydrogen Fuel Stations and Distribution Terminals*, draft report, May 2010.

4. Elgowainy, A., M. Mintz and M. Gardiner, *Hydrogen Distribution*, in Handbook of Hydrogen Energy, L. Stefanakos (ed.), CRC Press, Boca Raton, publication pending.