III.2 Hydrogen Delivery Infrastructure Analysis

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- Pacific Northwest National Laboratory (PNNL), Richland, WA

Objectives

- Refine technical and cost data in the Hydrogen Delivery Components Model and Hydrogen Delivery Scenario Analysis Model (HDSAM) to incorporate additional industry input and evolving technology improvements.
- Expand the Hydrogen Delivery Models 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, novel carriers and management strategies.
- Provide the bases to recommend 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 from Section 3.2 and Barriers C, D and E from Section 4.5 of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan. These are:

(A) Lack of Hydrogen/Carrier and Infrastructure Options Analysis
(C) Inconsistent Data, Assumptions and Guidelines
(D) Suite of Models and Tools
(E) Unplanned Studies and Analysis

Technical Targets

The project is developing infrastructure computer models to evaluate alternative delivery systems. Insights from these models will be applied toward identifying an optimized delivery infrastructure which meets the following DOE hydrogen delivery infrastructure targets:

- By 2010, reduce the cost of compression, storage, and dispensing at refueling stations and stationary power facilities to <$0.80/gge of hydrogen (independent of transport).
- By 2012, reduce the cost of hydrogen transport from central production facilities to the gate of refueling stations and other end-users to <$0.90/gge of hydrogen.
- By 2015, reduce the cost of compression, storage, and dispensing at refueling stations and stationary power facilities to <$0.40/gge of hydrogen (independent of transport).
- By 2017, reduce the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units to <$1.00/gge of hydrogen in total.

Accomplishments

- Used results of Nexant project to refine technical and cost data in H2A Delivery Models (Hydrogen Delivery Components Model and HDSAM).
- Added capability to estimate energy and greenhouse gas emissions of alternative delivery options to HDSAM.
- Expanded HDSAM capabilities to permit user specification of different transport modes for bulk transmission versus local distribution, and consideration of a combined urban and interstate market.
- Improved consideration of daily and seasonal demand peaks and production plant outages in determining HDSAM's requirements for bulk system storage and component capacities.
- Improved techniques for sizing pathway components and for optimizing compression and storage at the fuel station.
- Began to explore options to reduce hydrogen delivery cost.
- Completed Versions 2.0 of the Hydrogen Delivery Components Model and Scenario Analysis Model, and posted them on the DOE Energy Efficiency and Renewable Energy (EERE) Web site.

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Introduction

As part of the H2A project, which was initiated in 2003, Versions 1.0 of the Hydrogen Delivery Components Model and HDSAM were released on the H2A Web site in April 2006 following extensive beta testing and peer review. The Delivery Components Model is an Excel-based program that uses a design calculation approach to estimate the contribution of individual components of delivery infrastructure to hydrogen cost. Each of those components is described in an individual spreadsheet or tab. The model is documented in a comprehensive users' guide (also posted on the Web site) which includes detailed descriptions of inputs, assumptions and methodologies. HDSAM (which includes many of the tabs of the Components Model) links the costs of individual components in a systematic market setting to develop capacity/flow parameters for a complete hydrogen delivery infrastructure. Using that systems level perspective, the HDSAM calculates the full, levelized cost (i.e., summed across all components) of hydrogen delivery, accounting for tradeoffs among the various component costs. A graphical user interface permits users to specify a scenario of interest for which costs are calculated. A detailed users' guide and access to the EERE help desk also assist users in running HDSAM.

In June 2005, a team headed by Nexant, Inc. was selected to examine alternative delivery options and develop the necessary input data to permit expansion of the two delivery models. In Fiscal Year 2008, that work was substantially complete. Versions 2.0 of the Hydrogen Delivery Components Model and HDSAM were released in May 2008. Users' guide and documentation of the Nexant-led work are currently under development.

Results

The delivery infrastructure team (Argonne, NREL and PNNL) worked with Nexant and its partners to transfer data and analyses of infrastructure options to the existing Hydrogen Delivery Components Model and HDSAM, to enhance the capabilities of the subject models, and to expand the range of pathways in HDSAM. Nexant contributions included revised cost estimation equations for hydrogen liquefiers, liquid handling equipment, compressors, pipelines, low-pressure site storage, labor, indirect capital, and operation and maintenance costs, as well as advice and assistance on model logic and quality assurance.

The following enhancements have been incorporated into Versions 2.0 of the delivery models:

- Revised representations of fuel station components (e.g., cascade vs. low-pressure storage, compressor and other electrical requirements, evaporator/pump, boil-off recovery),
- An optimization routine to size fuel station components to a user-defined daily dispensing rate and an expected demand profile, allowing for sufficient on-site storage to accommodate daily and hourly demand variations,
- Revised pipeline geometry and footprints for fuel stations and terminals,
- Imposition of practical limitations on liquefier and compressor sizes,
- Development of additional HDSAM user options (e.g., a combined urban and intercity market, the ability to separate bulk transmission from local distribution, the ability to select a range of fuel station sizes, the ability to adjust peak seasonal, daily and hourly demand profiles, to specify the length of planned production plant outages, and to choose liquid or geologic storage to supply hydrogen during planned outages), and
- Calculation of energy and greenhouse gas emissions associated with HDSAM delivery pathways.

The resulting model updates underwent an extensive peer-review process within the project team and by the broader hydrogen modeling community. In May 2008, the Version 2.0 releases were posted on the EERE Web site at http://www.hydrogen.energy.gov/h2a_delivery.html.

One of the major improvements in HDSAM 2.0 is the ability to size pathway components to accommodate supply outages and seasonal demand patterns. Figure 1 illustrates the relationship between central plant production and daily demand in the course of a typical year. With the exception of a single planned outage for annual maintenance (assumed to occur during the off-peak season), the production rate is assumed to be constant throughout the year. During the annual outage (shown on Figure 1 as the period during which production drops to zero), supply is assumed to come from bulk storage which has been built up during the rest of the year from a slip stream of liquefied product stored in cryogenic tanks or gaseous product stored in geologic formations. Thus, steady-state production satisfies average demand (which varies both seasonally and daily) and the buildup of stored product (which is drawn down during plant outages and seasonal demand peaks).

Site storage is used to meet daily and hourly peaks. As shown in the hourly profile, which is based on Chevron data (see Figure 1), peak demand is assumed to occur on a Friday afternoon. Within the peak hour, demand is assumed to peak further, requiring all hoses to dispense at their design flow for the first three minutes[1]. HDSAM sizes the delivery infrastructure to satisfy hourly, daily and seasonal demands and optimizes the

[1] As shown in Figure 1, the hose occupied fraction is assumed to be 100% for the first three minutes.

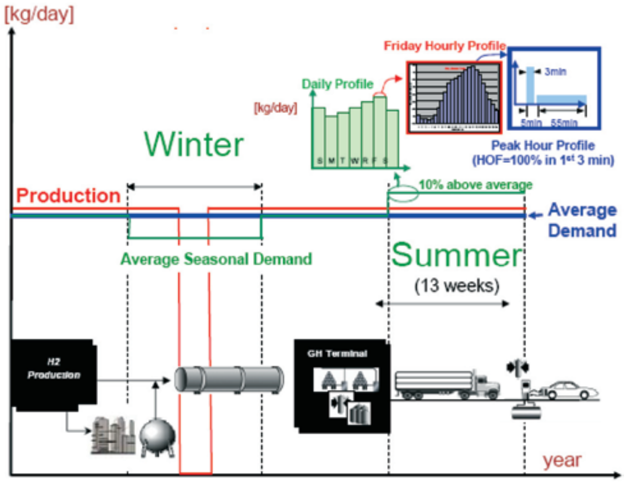

FIGURE 1. In HDSAM the Delivery System Accommodates Seasonal, Daily and Hourly Demand Peaks and Planned Production Plant Outages

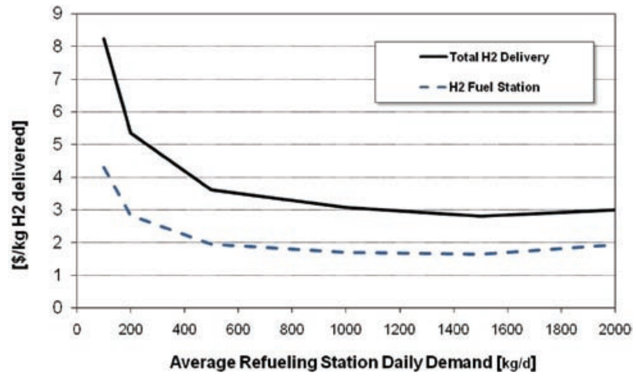

FIGURE 2. Fuel Stations Are Likely to Account for More than Half the Cost of Hydrogen Delivery

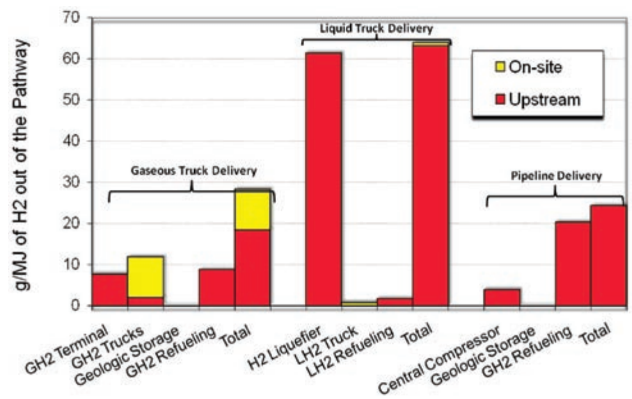

FIGURE 3. Hydrogen Liquefiers Account for More CO_2-Equivalent Emissions than any Other Delivery Component

tradeoff between site storage and compression to reduce fuel station cost.

HDSAM 2.0 calculates the cost of delivering hydrogen (in $/kg) by compressed gas truck, liquid tanker or various pipeline configurations to different markets, and the contribution of major components to that cost. As shown in Figure 2, fuel stations account for over half the cost of hydrogen delivery by pipeline, regardless of station size. This result is robust across a range of markets, levels of demand and delivery modes.

In FY 2008 another major enhancement to HDSAM was the addition of a tool to calculate energy and greenhouse gas emissions for each of the major components in hydrogen delivery pathways, using reference data from the GREET (Greenhouse gases, Regulated Emissions and Energy use in Transportation) model. Figure 3 compares results (in grams of CO_2-equivalent emissions) by major component and delivery pathway and disaggregates totals into CO_2-equivalent emissions produced directly by a particular component (i.e., "on-site") and CO_2-equivalent emissions associated with producing the electricity consumed by that component (i.e., "upstream"). Clearly, the electricity used in liquefaction accounts for the bulk of CO_2-equivalent or greenhouse gas emissions.

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 greenhouse gas emissions) and estimate the impact of alternative conditioning, storage and distribution options on those costs. For the Office of Hydrogen, Fuel Cells and Infrastructure Technologies this project has developed models of hydrogen delivery components and systems to quantify those costs and permit analyses of alternative technologies and operating strategies. This work has been conducted collaboratively by staff of ANL, NREL and PNNL with the assistance of Nexant, Inc. and its partners. Regular interaction has also occurred with the Fuel Pathways Integration and Delivery Tech Teams.

Tasks completed through June of FY 2008 have been discussed above. The following tasks will be completed by the end of FY 2009:

- Users' guides for the 2.0 releases of the hydrogen delivery models will be revised and posted on the EERE Web site.
- The H2A Delivery Models will be enhanced further and their capabilities will be expanded. Expansions will focus on revising the fuel station footprint, component costs and operating procedures (per Delivery Tech Team recommendations); adding 700 bar and cryo-compressed dispensing, hydrogen carriers and other advanced conditioning options, and centralized production to the models; and model enhancements to permit delivery to multiple urban areas.

- Continued interaction and collaboration among the project partners and with the Fuel Pathways Integration Tech Team, the Delivery Tech Team, and the broader hydrogen modeling community.

FY 2008 Publications/Presentations

1. A. Elgowainy, M. Mintz, J. Gillette, M. Paster, M. Hooks and B. Kelly, *Technical and Economic Analysis of Hydrogen Refueling Stations*, National Hydrogen Association, Sacramento, CA, April 1, 2008.

2. M. Mintz, A. Elgowainy, J. Gillette, M. Paster, M. Ringer, D. Brown, M. Hooks and B. Kelly, *HDSAM 2.0: Expanded Capabilities, Enhanced Results in Hydrogen Delivery Modeling,* National Hydrogen Association, April 1, 2008.

3. A. Elgowainy, M. Mintz, B. Kelly, M. Hooks and M. Paster, *Optimization of Compression and Storage Requirements at Hydrogen Refueling Stations*, Proceedings of the 2008 ASME Pressure Vessels and Piping Conference, July 27-31, 2008, Chicago, PVP2008-61638.

4. A. Elgowainy, M. Mintz, and M. Paster, *Hydrogen Delivery Scenario Analysis Model (HDSAM): Enhancements and Results,* ITS-DOE Meeting on Hydrogen Infrastructure Studies, UC Davis, August 20, 2007.

5. Mintz, M., M. Ringer, J. Gillette, A. Elgowainy, and D. Brown, *H2A Delivery: Enhanced Models, New Results*, National Hydrogen Association Annual Meeting, San Antonio, March 21, 2007.