III.A.1 Hydrogen Delivery Infrastructure Options Analysis

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Objectives

- Refine the technical and the cost data in the H2A Component and Scenario models to incorporate additional industrial input and evolving technology improvements:
  - Industrial experience on equipment performance, capital cost, and operating cost.
  - Delivery system storage analysis and optimization.
- Explore new options to reduce hydrogen delivery cost, including novel carriers.
- Expand the H2A Component and Scenario Models to include new options leading to Version 2.0 models.
- Provide the bases to recommend hydrogen delivery strategies for the initial, and for the long-term, use of hydrogen as a major energy carrier.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Lack of Hydrogen/Carrier and Infrastructure Options Analysis
(E) Low Cost, High Capacity Solid and Liquid Hydrogen Carrier Systems
(F) Gaseous Hydrogen Storage and Tube Trailer Delivery Costs
(H) Geologic Storage
(I) Hydrogen Leakage and Sensors

Technical Targets

The project is compiling industrial data on hydrogen delivery and storage equipment, and developing infrastructure computer models. Insights from these studies will be applied to help manage research for delivery infrastructure which meets the following DOE hydrogen delivery infrastructure targets:

- By 2007, define criteria for a cost-effective and energy-efficient hydrogen delivery infrastructure for the initial and long-term use of hydrogen for transportation and stationary power.
- 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 and semi-central production facilities to the gate of refueling stations and other end user 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

2006

- Analyzed hydrogen/natural gas mixing, transmission, and separation using existing natural gas pipeline infrastructure.

- Evaluated refurbished natural gas pipelines for hydrogen transmission.
- Assembled industrial and commercial data for performance and cost improvements to H2A models and reviewed the V1 H2A Delivery Model.

2007

- Analyzed market demand and supply variations and delivery systems optimization for storage, compression, dispensing.
- Improved hydrogen compressor characterization: capacities and costs at refueling site and terminals.
- Improved storage vessel designs and costs at refueling sites and terminals.
- Improved estimates for hydrogen liquefaction energy requirements and plant costs.
- Modeled variable refueling site sizes: compressor capacities, cascade storage capacities, number of dispensers, electric power supply, etc.
- Revamped distribution pipeline costs.
- Analyzing novel carrier pathway options.

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Introduction

The Nexant team is conducting an in-depth comparative analysis of various infrastructure options for hydrogen delivery and distribution to refueling stations and stationary power generation facilities from large (>50,000 kg/day) and small (1,500-10,000 kg/day) production facilities. Based on the results of the analysis, the team will recommend to DOE the transition and long-term strategy for building hydrogen delivery infrastructure and related R&D plan.

The project will evaluate and analyze the following delivery options:

- Dedicated pipelines for gaseous hydrogen delivery.
- Use of existing natural gas or oil pipelines for gaseous hydrogen delivery.
- Use of existing natural gas pipelines by blending in gaseous hydrogen with separation of hydrogen from natural gas at the point of use.
- Truck or rail delivery of gaseous and liquid hydrogen.
- Use of novel solid or liquid H_2 carriers, in slurry or other form, transported by pipeline, rail, or trucks.

Approach

The study approach includes the following steps:

- Compile data on liquid and gas fuel distribution methods.
- Develop improved and expanded energy requirements, capital costs, and operating costs for 19 hydrogen delivery pathways.
- Evaluate capability of existing infrastructure to deliver hydrogen.
- Assess greenhouse gas and pollutant emissions for each delivery option.
- Compare and rank delivery options.
- Recommend hydrogen delivery strategies as a function of market development.

Results

The principal revisions to the H2A performance and cost models include the following:

- Refueling site compressor, and transmission pipeline compressor, costs as functions of capacity are shown in Figures 1 and 2, respectively.
- Hydrogen liquefaction plant energy requirements and capital costs as functions of daily production are shown in Figures 3 and 4, respectively.
- Distribution pipeline costs for urban and downtown locations as function of pipe diameter are shown in Figure 5.
- The unit capital cost for low pressure (2,500 psig) storage was estimated to be $1,340 per kg of gas stored; the costs included the storage vessels, shipping, auxiliaries, installation, engineering, site preparation, contingency, and permit fees.
- The unit capital cost for high pressure (6,250 psig) cascade storage at a refueling site was estimated to be $1,460 per kg of gas stored; the costs included

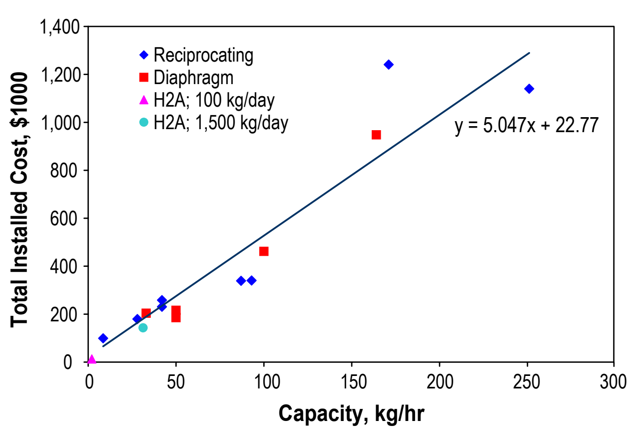

FIGURE 1. Refueling Site Compressor Costs as a Function of Capacity

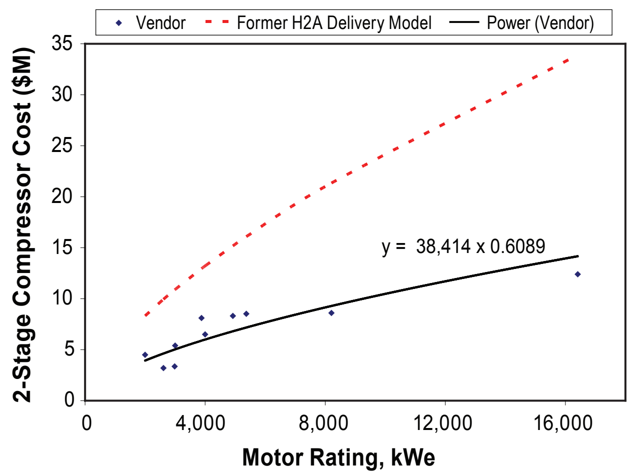

FIGURE 2. Transmission Pipeline Compressor Costs as a Function of Power Demand

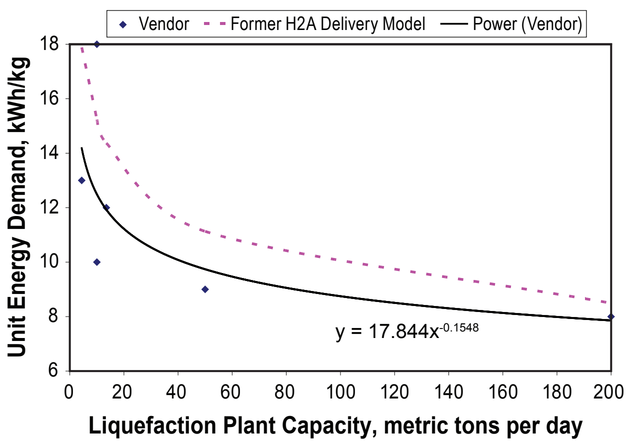

FIGURE 3. Hydrogen Liquefaction Energy Demand as a Function of Plant Capacity

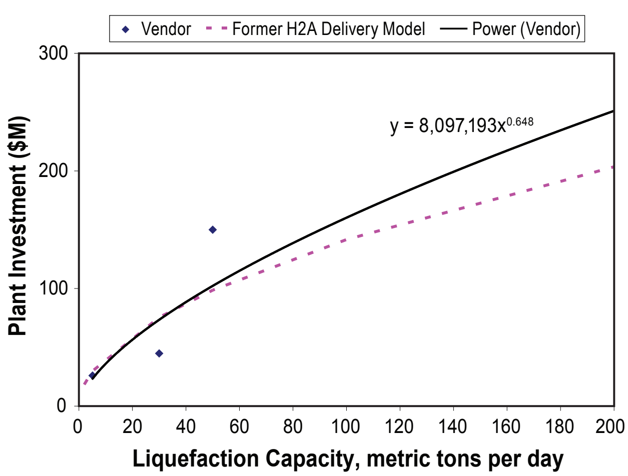

FIGURE 4. Hydrogen Liquefaction Capital Cost as a Function of Plant Capacity

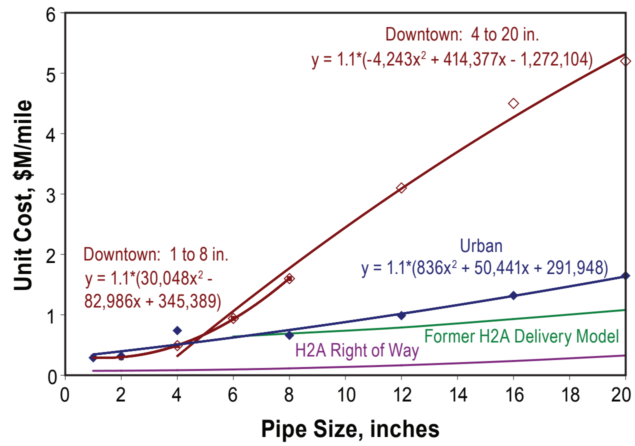

FIGURE 5. Distribution Pipeline Costs as a Function of Pipe Diameter

the storage vessels, shipping, auxiliaries, installation, engineering, site preparation, contingency, and permit fees.

Gaseous Pipeline Delivery

- Hydrogen production/geologic storage/transmission line delivery to city gate/distribution lines to refueling stations/refueling station storage, cascade charging and compressor.
- Hydrogen production/liquefaction plant with liquid storage/transmission line delivery to city gate/distribution lines to refueling stations/refueling station storage, cascade charging and compressor.
- Hydrogen production/geologic storage/oversize transmission line delivery to city gate/distribution lines to refueling stations/refueling station storage, cascade charging and compressor.

Compressed Gas Distribution

- Hydrogen production/geologic storage/gas terminal/truck delivery/refueling station storage, cascade charging and compressor.
- Hydrogen production/liquefaction plant with liquid storage/gas terminal/truck delivery/refueling station storage, cascade charging and compressor.
- Hydrogen production/geologic storage/transmission line delivery to city gate/gas terminal/truck delivery/refueling station storage, cascade charging and compressor.
- Hydrogen production/liquefaction plant with liquid storage/transmission line delivery to city gate/gas terminal/truck delivery/refueling station storage, cascade charging and compressor.

Liquid Distribution

- Hydrogen production/liquefaction terminal/truck delivery/refueling station storage, vaporizer, cascade storage, and compressor.
- Hydrogen production/geologic storage/transmission line delivery to city gate/liquefaction plant/liquid terminal/truck delivery/refueling station storage, vaporizer, cascade storage, and compressor.
- Hydrogen production/gas terminal storage/transmission line delivery to city gate/liquefaction plant/liquid terminal/truck delivery/refueling station storage, vaporizer, cascade storage, and compressor.

Using Delivery Pathway 1 above as an example, the system optimization process involved the following steps:

1. The hour-by-hour demand for fuel at a typical gas station was provided by industry, as illustrated in Figure 6.
2. The hourly demand for gasoline was converted to an equivalent minute-by-minute demand for hydrogen at a refueling site, as shown in Figure 7.
3. Combinations of refueling site compressor capacities and cascade charging capacities to meet the minute-by-minute demand were developed, as shown in Figure 8.
4. Using the compressor cost data in Figure 1, and the unit cascade storage costs noted above, capital cost estimates were developed for the full range of refueling site capacities, from which the optimum compressor and cascade storage capacities were selected. The results from the optimization studies are illustrated in Figure 9.

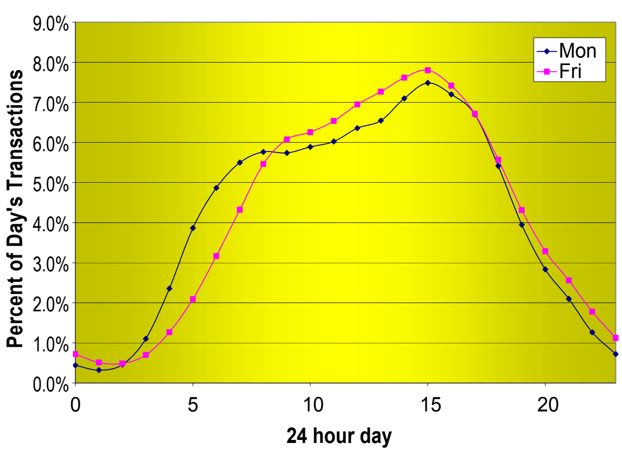

FIGURE 6. Hour-by-Hour Demand at a Typical Gas Station

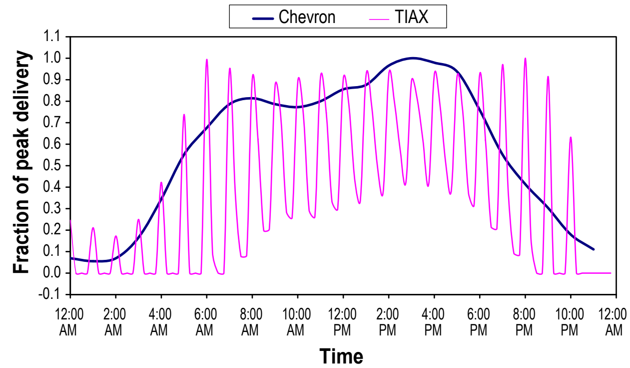

FIGURE 7. Minute-by-Minute Demand at a Hydrogen Refueling Site

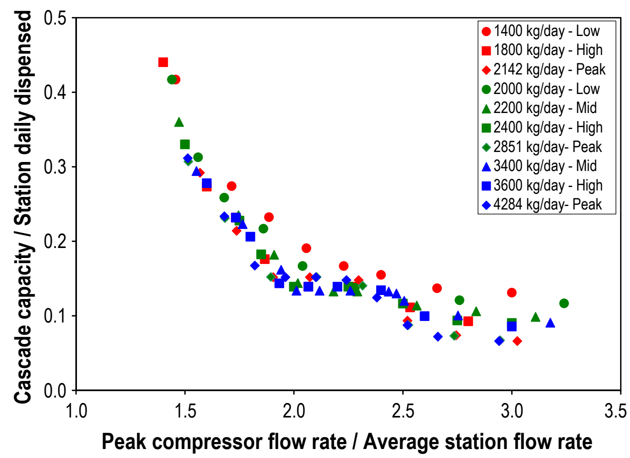

FIGURE 8. Permissible Combinations of Refueling Site Compressor and Cascade Storage Capacities

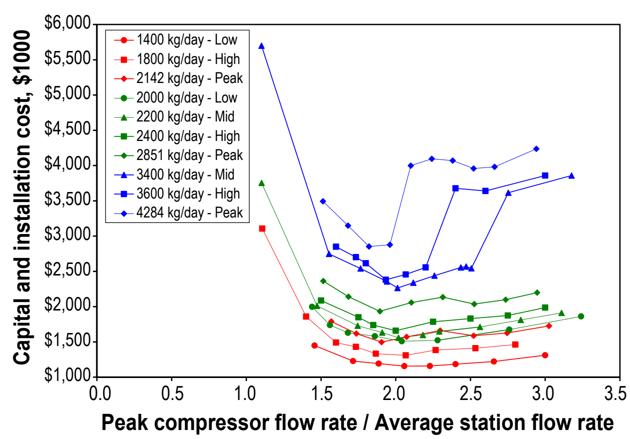

FIGURE 9. Optimum Combinations of Refueling Site Compressor and Cascade Storage Capacities

5. Using estimates of production plant outage periods, and estimates of the seasonal variation in refueling site demand, multi-day geologic or liquefied hydrogen storage capacity requirements were calculated.
6. The results from the refueling site optimization, together with existing H2A equations for the cost of transmission pipelines, geologic storage and liquefication and liquid storage, allowed a complete, optimized delivery pathway to be assembled.

Conclusions and Future Directions

Significant additions to the H2A model inputs were made in the following areas: large hydrogen compressors; refueling site compressors; refueling site cascade charging; hydrogen liquefaction plants; gas storage terminals; distribution pipelines within a city; land areas; and variable-sized refueling sites (100 to 6,000 kg/day average daily capacity).

Analyses of market demand and supply variations contributed to the development of optimized infrastructure models, which included the following features:

- Seasonable demand variations and production plant maintenance outages: geologic gas storage, or liquid storage.
- Daily demand variations: low pressure gas terminals, liquid storage terminals, or oversize transmission lines.
- Hourly demand variation: Refueling site low pressure storage, high pressure cascade storage, and compressor capacities. Alternate approaches include tube trailer storage, and liquid storage, vaporizer, cascade storage, and compressor.

Future activities include the following:

- Publish Version 2.0 of the H2A model later this year.
- Complete novel carrier options analyses and incorporate in the model.
- Incorporate GREET and explicit results for pathway energy efficiency, greenhouse gas emissions, and water demand.
- Recommend delivery strategies at each market penetration.

FY 2007 Publications/Presentations

1. H2A Delivery: Enhanced Models, New Results. *Marianne Mintz, Matthew Ringer, Jerry Gillette, Amgad Elgowainy, and Daryl Brown*, National Hydrogen Association, San Antonio, TX, March 22, 2007.

2. Hydrogen Production and Delivery Analysis in U.S. Markets: Cost, Energy and Greenhouse Gas Emissions. *M. Mintz, J. Gillette and A. Elgowainy*, International Conference on Non-Electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and Other Industrial Applications, Oarai, Japan, April 16-19, 2007.

3. Improvements to Hydrogen Delivery Scenario Analysis Model (HDSAM) and Results. *Amgad Elgowainy*, Hydrogen Delivery Analysis Meeting, Washington, D.C., May 8, 2007.

4. Hydrogen Delivery Infrastructure Options Analysis, *Bruce Kelly*, DOE Hydrogen Program 2007 Annual Merit Review, Washington, D.C., May 17, 2007.

5. Hydrogen Delivery Scenario Analysis Model (HDSAM): Enhancements and Results. *Marianne Mintz and Amgad Elgowainy*, Fuels Pathway Integration Tech Team Meeting, Naperville, IL, June 14, 2007.