III.2 Hydrogen Delivery Infrastructure Analysis

Amgad Elgowainy (Primary Contact), Marianne Mintz and Krishna Reddi
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-3074
Email: aelgowainy@anl.gov

DOE Manager
HQ: Erika Sutherland
Phone: (202) 586-3152
Email: Erika.Sutherland@ee.doe.gov

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

Fiscal Year (FY) 2012 Objectives

- Identify cost drivers of current technologies for hydrogen delivery to early market applications of fuel cells
- Evaluate role of high-pressure tube-trailers in reducing hydrogen delivery cost
- Identify and evaluate benefits of synergies between hydrogen delivery options to various markets (e.g., forklift market, fuel cell vehicle market)

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, D and E in the Systems Analysis Plan of the Fuel Cell Technologies Multi-Year Research, Development and Demonstration Plan. These are:

(A) Lack of Hydrogen/Carrier and Infrastructure Options Analysis
(B) Stove-Piped/Siloed Analytical Capability
(C) Inconsistent Data, Assumptions and Guidelines
(D) Insufficient Suite of Models and Tools
(E) Unplanned Studies and Analysis

Technical Targets

The project is using a computer model to evaluate alternative delivery infrastructure systems and components. 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.

FY 2012 Accomplishments

- Evaluated current cost and power requirement of refueling station compression and pumping technologies
- Evaluated various configurations of high-pressure tube-trailers within U.S. Department of Transportation (DOT) specified weight and size constraints, including:
  - Tube fill pressure
  - Tube diameter/thickness
  - Number of tubes
  - Tube material (steel vs. composite)
- Characterized and examined hydrogen delivery and refueling cost for forklift markets

✧ ✧ ✧ ✧ ✧

Introduction

Initiated as part of the H2A project, the Hydrogen Delivery Scenario Analysis Model (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 greenhouse gas emissions. The model links 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 assists users in defining scenarios and running HDSAM. Users can specify their own inputs to the model or select default inputs – which are based on data from the literature, from vendors of specific delivery components or from stakeholder inputs, or derived from basic engineering design calculations. The quality of the data and the direction of the analysis are vetted in formal interaction with partners from other national laboratories and independent consultants and via briefings to the hydrogen delivery technical team.

From our previous analyses, the refueling station was found to contribute about half of total delivery cost in a mature fuel cell vehicle (FCV) market and refueling station compression and storage were shown to constitute the bulk of station capital cost. Thus, the focus of our analysis this FY was on identifying circumstances that tend to elevate fueling station investment and levelized cost in early markets (e.g., diseconomies of scale, underutilization of capital, and high risks) and examining the cost and power requirements of current compression technologies for hydrogen refueling. We also evaluated different configurations of high-pressure tube-trailers and their viability for hydrogen delivery to early markets, hydrogen delivery and refueling for forklift applications, and potential synergies and differences between materials handling and FCV markets.

Results

Compression Analysis

Four vendors of piston and diaphragm compressors were surveyed to obtain information on capital costs and power requirements as a function of throughput and dispensing pressure. Figure 1 shows the cost of purchasing a single compressor unit from each vendor as a function of throughput for 350-bar and 700-bar dispensing pressures. The figure reveals an apparent lack of production cost economy with increased throughput. The figure also shows a high compression cost per unit of throughput as well as a large variation in the cost of a single compressor unit between vendors at the same throughput, especially for 700-bar dispensing. The large variation in compressor cost between vendors reflects the different compression technologies but does not address the comparative reliability of these technologies. This is a subject that requires further investigation. We also identified that the cost of a high-pressure (900 bar) liquid pump combined with a vaporizer is more than 50% less than the cost of an equivalent gas compressor. However, the liquid pump option shifts much of the packaging cost to upstream of the refueling station at the liquefaction plant.

High-Pressure Tube Trailer Analysis

Figure 2 shows the relationship between the increase in hydrogen payload of high-pressure (250 bar) composite tubes within an International Organization for Standardization (ISO) container (8 ft wide x 8 ft high x 40 ft long) and the corresponding increase in the cost of these tubes. The payload increase is achieved through packaging more tubes in the ISO container via various inline (NxN) and staggered (NxN-1) arrangements of smaller tube diameters, thus improving the volume utilization of the container at any given pressure. The figure shows that the capital cost of the tubes increase is nearly linear with the payload increase up to a certain payload, above which the volume utilization of the container levels off. We note that the increase in the payload of the tubes would lead to less frequent deliveries, reduced delivery cost and smoother operation at the refueling sites. We also note that improving the volume utilization via packing more tubes in the ISO container requires that the tubes be made of light-weight material (e.g., carbon fiber composites) to comply with the U.S. DOT weight limit of 80,000 lbs. gross combination weight. Figure 3 shows the maximum payload of hydrogen in an ISO container at different loading pressures for steel and composite tubes. While the payload of the composite tubes increases with pressure up to 430 bar, the corresponding payload of the steel tubes drops with pressure to satisfy the aforementioned weight constraint of 80,000 lb. We conclude that high-pressure tube trailers require light weight material to achieve significant increase in hydrogen payload at increased loading pressure. Furthermore, the high-pressure tube trailer can reduce the compression demand at the refueling station, especially in early markets where the utilization of the station compressor is low. This option has the potential to reduce the refueling station capital cost by up to 20% at 50% utilization.

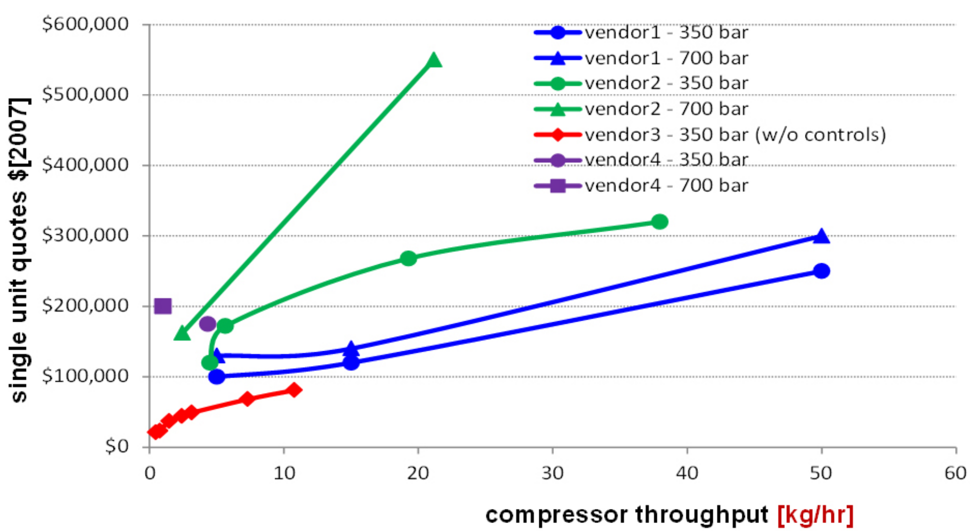

FIGURE 1. Cost of Single Unit Hydrogen Refueling Compressors

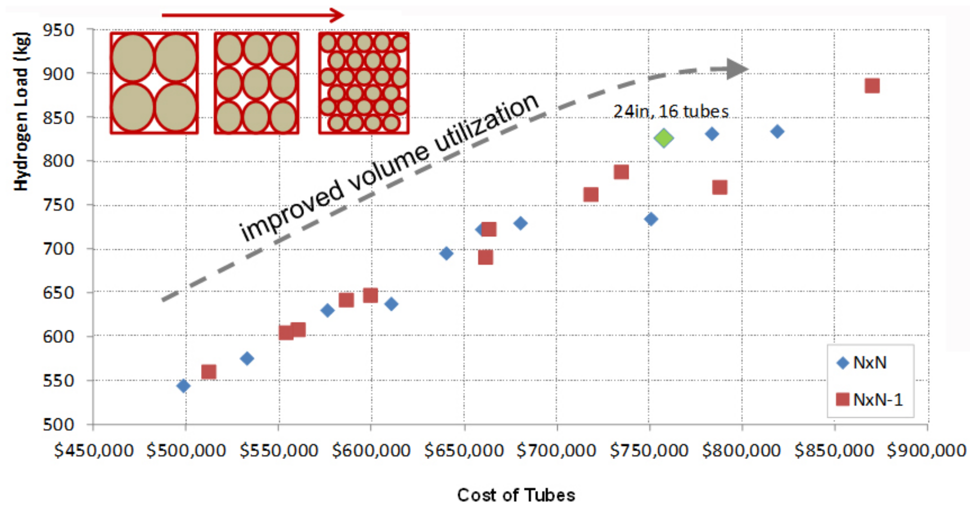

FIGURE 2. Cost of High-Pressure Composite Tubes (250 bar) as a Function of Payload

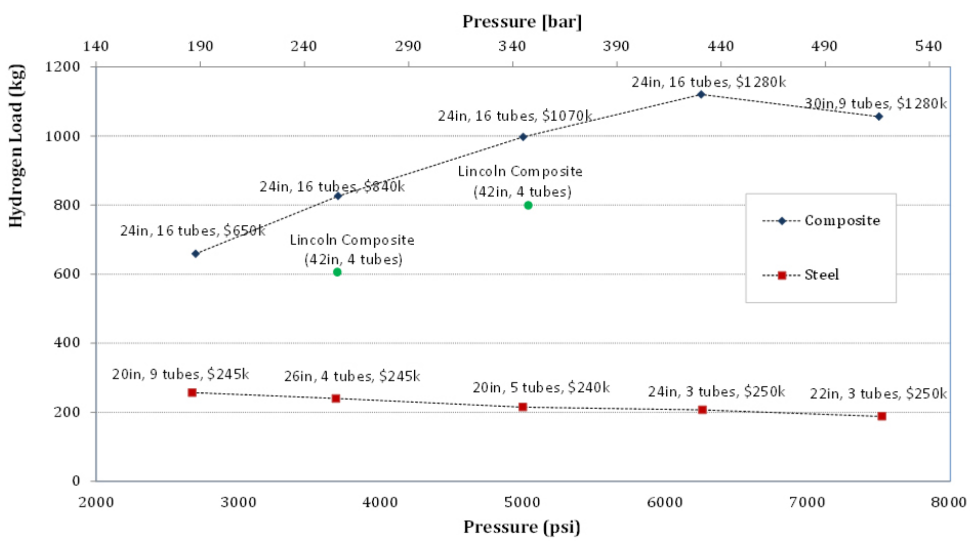

FIGURE 3. Effect of Hydrogen Loading Pressure on Tube Trailer Payload

Hydrogen Delivery for Forklift Applications

Hydrogen delivery for forklift applications was examined to identify potential synergies with hydrogen delivery for vehicle fueling. Table 1 presents selected results (i.e., capital cost, the cost contribution per kg of dispensed hydrogen, and the monthly lease of installed refueling equipment) for two levels of daily forklift refueling demand. With the cost contribution of refueling equipment dropping from $2.50 to $2.00 per kg of dispensed hydrogen, results show some economies of scale with increases in daily demand for hydrogen refueling. This is in addition to a $6 per kg “delivery charge” for producing, liquefying and delivering hydrogen for onsite use.

TABLE 1. Forklift Refueling Cost Estimates

Daily Refueling Demand	150 kg/day	300 kg/day
Total installed capital	$850,000	$1,300,000
Other Capital (including site preparation)	$200,000	$400,000
Cost contribution of refueling	$2.5/kg$_{H2}$	$2/kg$_{H2}$
Monthly Lease of installed equipment (recover investment in 7 years)	$15,000	$20,000
Monthly Lease of installed equipment (recover investment in 10 years)	$10,000	$15,000

The following are some lessons learned from studying fuel cell forklift fueling:

- Hydrogen is available and can be delivered at a cost of ~$6/kg
- Current technology favors high volume delivery in liquid form
- There is a business case for demand volumes >150 kg/day
- The desired delivery frequency is ~2-3 deliveries/month
- Lease of the installed equipment is a preferred option

However, there are profound differences between refueling forklifts and FCVs. The incumbent technology for fuel cell forklifts is the battery-operated forklift, while FCVs compete against gasoline internal combustion engine vehicles. The refueling frequency for forklifts is every 4-6 hours with relatively flat hourly demand, while vehicles refuel every 300-400 mi with wide variations in desired refueling times (and locations for vehicles that do not return to base each day). FCVs also require high pressure fills at 700 bar with -40°C precooling, while fuel cell forklifts typically refuel at 350 bar with no precooling requirements. Finally, the utilization of the refueling capital investment is expected to be much lower for early deployment of FCVs as compared with a forklift fleet refueled in a central location. All of these differences provide additional challenges with respect to the cost of refueling FCVs.

Conclusions and Future Directions

The hydrogen delivery infrastructure for refueling FCVs as well as forklifts in early markets has been examined. The analysis identified synergies and differences between these two fuel cell applications. Hydrogen is available and can be delivered to these two markets at a reasonable cost when refueling demand exceeds 150 kg/day. The preferred delivery mode for volume deliveries is trucking hydrogen in liquid form. However, liquefying hydrogen suffers from a high electric energy requirement for liquefaction, with potentially high greenhouse gas emissions if the electricity generation mix relies on fossil sources. Our analysis shows that underutilization of refueling capital and the cost of high-pressure dispensing present major challenges to reducing the cost of hydrogen for FCVs. The need for high-pressure (700 bar) hydrogen for dispensing into FCVs exacerbates the compression requirement at the refueling sites, which is the single most significant contributor to refueling cost. High-pressure tube-trailers can deliver hydrogen with up to 1,000 kg of payload of may reduce the compression requirement at the refueling stations in early markets.

For the remainder of FY 2012, efforts will be directed toward further study of fueling compressor options (the most costly of all refueling components), particularly large throughput compressors. The cost and performance of large throughput compressors will be examined for loading tube trailers and for storing and dispensing hydrogen at large refueling stations. Liquid delivery, today's most favored mode, will also be examined in detail. HDSAM will be updated and employed to examine the impact of these delivery options for early and future markets. Strategies to optimize refueling station and pathways with the greatest potential to achieve significant cost reductions for hydrogen delivery and refueling will be identified for both automotive and non-automotive fuel cell applications.

FY 2012 Publications/Presentations

1. Elgowainy, A., M. Mintz, and M. Gardiner (2012) *Hydrogen Delivery Infrastructure: Analysis of Conventional Delivery Pathway Options*, in Handbook of Hydrogen Energy, CRC Press, S.A. Sherif, D.Y. Goswami, E.K. Stefanakos and A. Steinfeld, eds., ISBN: 9781420054477.

2. Elgowainy, A., M. Mintz, D. Steward, O. Sozinova, D. Brown and M. Gardiner (2011) *Liquid Hydrogen Production and Delivery from a Dedicated Wind Power Plant*, Argonne National Laboratory Report ANL-11/33, Oct.

3. Paster M.D., R.K. Ahluwalia, G. Berry, K. Day, A. Elgowainy, S. Lasher, K. McKenney, M. Gardiner, (2011) *Hydrogen Storage Technology Options for Fuel Cell Vehicles: Well-to-Wheel Costs, Energy Efficiencies, and Greenhouse Gas Emissions*, Intl. J. of Hydrogen Energy, doi:10.1016/j.ijhydene.2011.07.056.