III.1 Hydrogen Delivery Infrastructure Analysis

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

Overall Objective

Evaluate hydrogen delivery and refueling concepts that can reduce hydrogen delivery cost towards meeting the delivery cost targets

Fiscal Year (FY) 2015 Objectives

- Develop and publish Hydrogen Refueling Station Analysis Model (HRSAM) with today's station configurations, utilization, and cost information
- Update and publish Hydrogen Delivery Scenario Analysis Model (HDSAM) with recent/current station configurations, market data, and cost information of delivery components for near-term and long-term markets

Technical Barriers

This project directly addresses Technical Barriers A, B, C, and E in the Hydrogen Delivery section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDD).

(A) Lack of Hydrogen/Carrier and Infrastructure Options Analysis

(B) Reliability and Costs of Gaseous Hydrogen Compression

(C) Reliability and Costs of Liquid Hydrogen Pumping

(E) Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

Technical Targets

- Develop HRSAM to evaluate alternative refueling station components for near-term/current market scenarios and component costs
- Update HDSAM with recent/current market data, component cost data for near-term and long-term markets (with varying market penetration), station configuration options, and utilization scenarios

Contribution to Achievement of DOE Hydrogen Delivery Milestones

This project contributes to the following DOE milestones from the Hydrogen Delivery section of the FCTO MYRDD Plan:

- Milestone 1.5: Coordinating with the H_2 Production and Storage sub-programs, identify optimized delivery pathways that meet a H_2 delivery and dispensing cost of <\$2/gge for use in consumer vehicles. (4Q, 2020)
- Milestone 6.1: Define potential RD&D activities for other long-term market fueling/terminal needs. (4Q, 2015)
- Milestone 6.3: By 2020, reduce the cost of hydrogen delivery from the point of production to the point of use in consumer vehicles to <\$2/gge of hydrogen for the gaseous delivery pathway. (4Q, 2020)

FY 2015 Accomplishments

- Developed and published the HRSAM
- Studied the impact of various parameters including station design capacity, utilization rate, and station configuration on the hydrogen refueling cost component
- Updated HDSAM with recent market data, cost indexes, and alternate liquid delivery station configurations, as well as projections of the cost reductions expected at different market penetrations

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INTRODUCTION

Initiated as part of the Hydrogen Analysis (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 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 (summed over all components) of hydrogen delivery, accounting for losses and tradeoffs among the various component costs. Users of HDSAM can specify the values of model inputs, or select the default inputs, which are based on data from literature, vendors, other stakeholders, or basic engineering calculations. The quality of the data and the direction of the analysis are vetted by partners at other national laboratories, independent consultants, and briefings to the Hydrogen Delivery Technical Team (HDTT). Argonne National Laboratory (ANL) also developed HRSAM, which calculates the cost of hydrogen refueling as a function of various fueling station capacity values and design configurations. HRSAM is an abbreviated version of HDSAM that focuses solely on near-term refueling station costs.

APPROACH

In this project, HDSAM was adapted to build HRSAM, a model that studies station economics, excluding all upstream costs (hydrogen production and delivery to the station). Cost formulas developed using current cost and design data of the refueling and delivery components have been embedded in the model. The station configurations represent the stations being installed in California today, and projected utilization rates are based on estimates from the California Air Resources Board. HRSAM outputs the annual and cumulative cash flows, total capital investment, cost of refueling per kilogram of hydrogen (which has an energy approximately equal to that in a gallon of gasoline), years required to break even on capital investment, and land area required by a given station. Figure 1 shows the inputs (can be user-specified or default values) and outputs of the HRSAM model.

The HDSAM model was also updated with recent market data, including key statistics of urban population, vehicle ownership rate, annual vehicle miles traveled, and average vehicle fuel economy, that enable calculations of market demand. Cost formulas for all dispensing equipment were also updated based on quotations received for today's technologies. Additionally, projections were made on the reductions in cost that can be expected in various market penetration scenarios due to learning, technology advancement, and economies of scale. The model was then updated to include these cost reduction factors as inputs. The model was also updated to include an option to define a utilization scenario for hydrogen refueling stations over the project period. Finally, the cost of refueling station precooling equipment was updated to simulate an advantageous configuration identified in a separate DOE-funded project (Hydrogen Fueling Station Pre-Cooling Analysis).

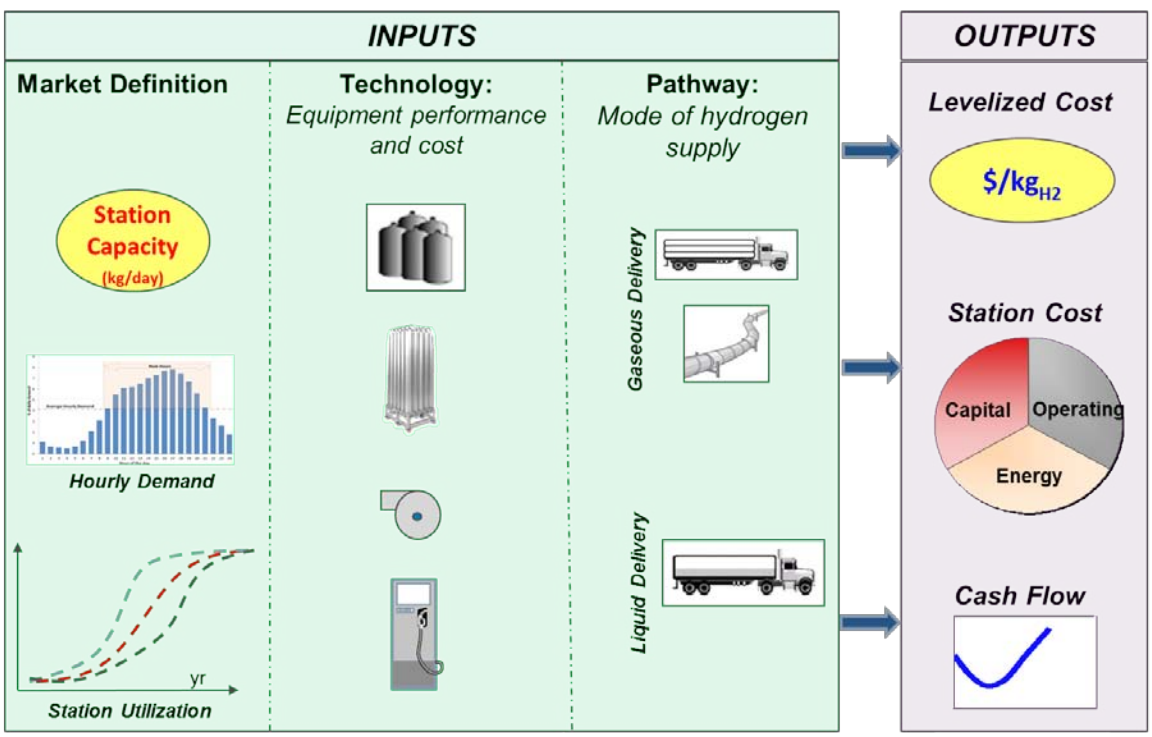

FIGURE 1. HRSAM overview

RESULTS

Hydrogen Refueling Station Analysis Model

HRSAM was developed to enable studies of the impact station design has on station economics. By ignoring the costs of hydrogen production and delivery to the station, HRSAM highlights the operating costs, capital costs, levelized costs, and cash flows of the refueling stations themselves. The model was used in the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project's Reference Station Design Task to rapidly screen 160 station designs and identify the 15 with the most favorable economics. The model is also used for the generation of default inputs in Hydrogen Financial Analysis Scenario Tool (H2FAST), a model developed at the National Renewable Energy Laboratory in 2015. H2FAST is a web-based tool that provides detailed financial analyses of stations using an interface targeted for the financial community. Finally, HRSAM was used in 2015 by ANL to conduct several sensitivity analyses of the impacts of key variables on economics, as is discussed below.

Gaseous Compression vs. Liquid Pumping at Hydrogen Refueling Stations

At liquid hydrogen stations, gaseous cryo-compression is advantageous over liquid pumping when the station utilization is low (e.g., in early markets) or the capacity is small (even if utilization is high). Under-utilized hydrogen refueling stations with liquid pumping lose about 50 kg/day to boil-off because the pump and piping heat up when not being utilized. Additionally, if stations are small or under-utilized, the impact of boil-off loss on hydrogen cost becomes very large. On the contrary, liquid pumping may be beneficial over gaseous compression for stations with capacity greater than approximately 500 kg/day, as shown in Figure 2. The impact of overhead liquid boil-off losses on refueling cost becomes small when distributed over the much greater quantity of hydrogen dispensed at these large stations.

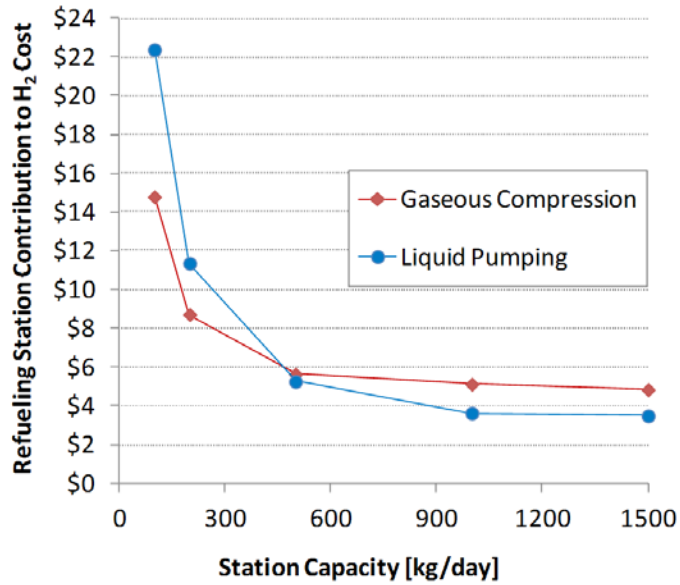

FIGURE 2. Refueling cost for various station capacities with gaseous compression and liquid pumping

Impact of Station Capacity and Utilization Ramp-Up Rate

As shown in Figure 3, large hydrogen refueling stations (HRSs), in spite of high capital investment, enable low refueling cost of hydrogen by taking advantage of the economies of scale. It is important to note, however, that

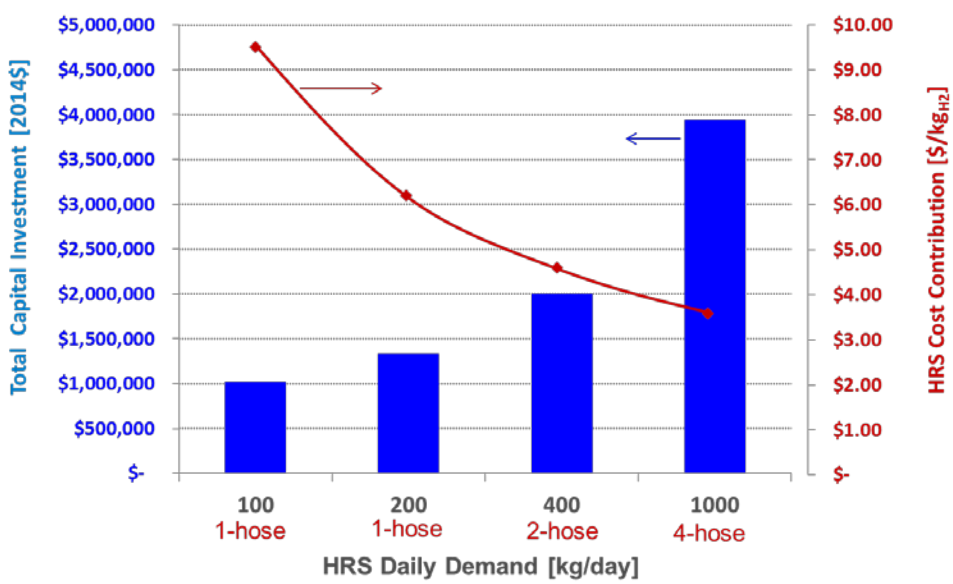

FIGURE 3. Station capital investment and cost contribution for different station capacities

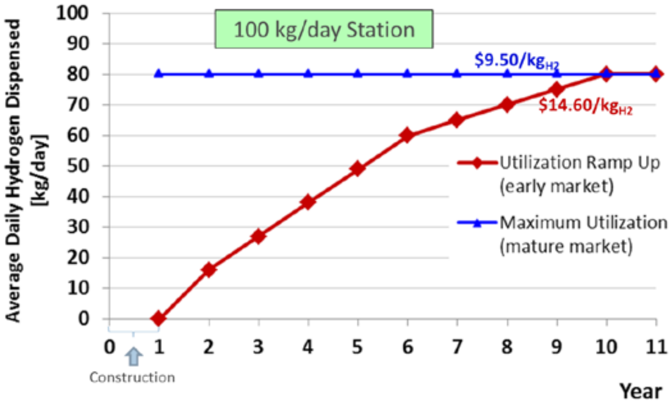

FIGURE 4. Impact of station utilization ramp-up on the refueling cost

this advantage diminishes when stations are under-utilized. Station utilization rate was identified as one of the most significant variables impacting dispensing cost. Figure 4 shows an example of a station utilization ramp-up scenario and the corresponding refueling cost for a 100 kg/d station.

CONCLUSIONS AND FUTURE DIRECTIONS

With liquid hydrogen supply, gaseous compression at the station is beneficial for early markets when the station utilization is low, and also for small stations irrespective of their utilization. On the other hand, liquid pumping is more advantageous for stations with large capacity and high utilization rates. The vehicle deployment rate significantly influences the success of hydrogen stations in the marketplace because the number of deployed vehicles is critical to the utilization of the station capacity, and therefore its economics. Under-utilization of station capital results in a significant increase in hydrogen refueling cost. For the remainder of FY 2015, efforts will be directed toward reviewing, documenting, and publishing the update of HDSAM.

As stations are deployed, HDSAM will continue to be updated with the most recent cost data and simulation of emerging technologies. The model will also continue to be used to evaluate refueling concepts and identify technology configurations with the potential to lower the cost or improve the performance of delivery technologies.

PUBLICATIONS

1. Reddi, K., Mintz, M., Elgowainy, A., Sutherland, E., “Challenges and opportunities of hydrogen delivery via pipeline, tube-trailer, liquid tanker and methanation-natural gas grid,” Wiley (in press).

2. Reddi, K., Mintz, M., Elgowainy, A., Sutherland, E., “Building a hydrogen infrastructure in the United States,” Compendium of Hydrogen Energy, Vol. 4 Hydrogen Use, Safety and the Hydrogen Economy, Woodhead Publishing, ISBN: 9781782423645.

3. Elgowainy, A., Reddi, K., Sutherland, E., and Joseck, F., 2014. Tube-trailer consolidation strategy for reducing hydrogen refueling station costs. *International Journal of Hydrogen Energy,* **39**(35), pp. 20197-20206.

4. Reddi, K., Elgowainy, A., and Sutherland, E., 2014. Hydrogen refueling station compression and storage optimization with tube-trailer deliveries. *International Journal of Hydrogen Energy,* **39**(33), pp. 19169-19181.

5. Pratt, J., Terlip, D., Ainscough, C., Kurtz, J., and Elgowainy, A., 2015. H2FIRST Reference Station Design Task Project Deliverable 2-2. Golden, CO: NREL/TP-5400-64107.