# 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 Objectives

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

## Fiscal Year (FY) 2013 Objectives

- Incorporate SAE International (SAE) J2601 refueling protocol in the modeling of various hydrogen refueling station (HRS) configurations.
- Evaluate the role of high-pressure tube trailers in reducing hydrogen refueling station capital investment and operation cost.

## Technical Barriers

This project directly addresses Technical Barriers A, B and E in the Hydrogen Delivery section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. These barriers are:

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

(B) Reliability and Costs of Gaseous Hydrogen Compression

(E) Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

## Technical Targets

The project employs a simulation tool to investigate current and novel hydrogen delivery technologies and pathway options with the potential to meet the cost targets specified in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, and to assist with defining R&D areas that can bridge current and targeted performance and cost of major delivery and refueling components.

## Contribution to Achievement of DOE Hydrogen Delivery Milestones

This project contributes to achievement of the following DOE milestone from the Hydrogen Delivery section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

- Task 2.2: Down-select two to three H2 pressurization and/or containment technologies that minimize delivery pathway cost for near-term markets. (2Q, 2013)

## FY 2013 Accomplishments

- Developed a simulation tool that sizes HRS equipment according to SAE J2601 fueling protocol and tracks mass, temperature and pressure across delivery components. The tool's predictions were validated against measurement data published in the literature.
- Identified optimum cascade storage configurations for maximum storage utilization with lowest compression capacity and minimum combined storage and compression cost. The optimum configuration employs cascade buffer storage with capacity that equals 24% of the station daily dispensing capacity and compression throughput that equals 180% of the station average daily dispensing rate (as defined by the peak to average hourly demand ratio).
- Investigated the role of high-pressure tube trailers in reducing station capital investment. High-pressure tube trailers delivering hydrogen at 350 bar can decrease the station cost by 20% when used for initial vehicle fill.

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## 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 infrastructure components to hydrogen delivery cost, energy use, and greenhouse gas emissions. The model links individual components for specific market conditions to develop capacity/flow parameters for a complete hydrogen delivery infrastructure. 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. The quality of the data and the direction of the analysis are vetted via presentations to experts in the Hydrogen Delivery Technical Team and other U.S. DRIVE partnership technical teams, and through formal interaction with independent consultants and researchers from other national laboratories.

From previous HDSAM analyses, the refueling station was found to contribute approximately half of the total delivery cost in a mature fuel cell electric vehicle (FCEV) market. Furthermore, the under-utilization of the HRS capital investment in early markets of FCEVs negatively impacts the economic viability of refueling infrastructure. It is suggested that delivery concepts that reduce refueling station capital investment may partially offset the adverse economics in early markets. Thus, the delivery analysis in FY 2013 was focused on identifying delivery concepts that can reduce HRS capital investment and operation cost. Compressing hydrogen to high pressures in tube trailers (at terminals upstream of the HRS) can reduce compression requirement at the station. Since compression and storage were shown to constitute the bulk of HRS capital cost, delivering high-pressure hydrogen in tube trailers to HRS can reduce the station's capital investment significantly.

## APPROACH

Hydrogen refueling station components are sized to meet a specific demand profile while satisfying the SAE J2601 refueling protocol. A simulation tool was developed from first principles to model the physical laws of thermodynamics, mass, energy, momentum and heat transfer, and to solve for the temperature, pressure, and mass flow through hydrogen refueling components and FCEV onboard storage system. The simulation tool identifies the combination of compressor size and buffer storage capacity for minimum total capital and operation cost. The role of tube trailers in reducing HRS capital investment and operation cost was examined by simulating two possible operation scenarios in a typical hydrogen refueling station. In Scenario 1, the tube trailer is merely used to supply hydrogen to a compressor that replenishes a cascade buffer storage system. In Scenario 2, the high-pressure tube trailer directly fills the vehicle's tank during the early dispensing period, in addition to supplying hydrogen to a compressor for replenishing the cascade buffer storage system. Figure 1 shows the refueling station operation strategies for Scenarios 1 and 2.

## RESULTS

### Cascade Storage and Compression Optimization

The number of cascade pressure levels that ensures maximum back-to-back vehicle fills with lowest cost depends on the size of the vessel. The combination of compressor and cascade storage, when considered together, identify the potential lowest cost configuration at HRSs. Figure 2 shows the cascade system capital cost (shown on the left vertical axis), the hydrogen utilization (shown on the right vertical axis and defined as the ratio of total amount of hydrogen dispensed to the total amount hydrogen stored in the cascade system), and an economic index (shown on the left vertical axis and defined as the cascade system cost divided by the

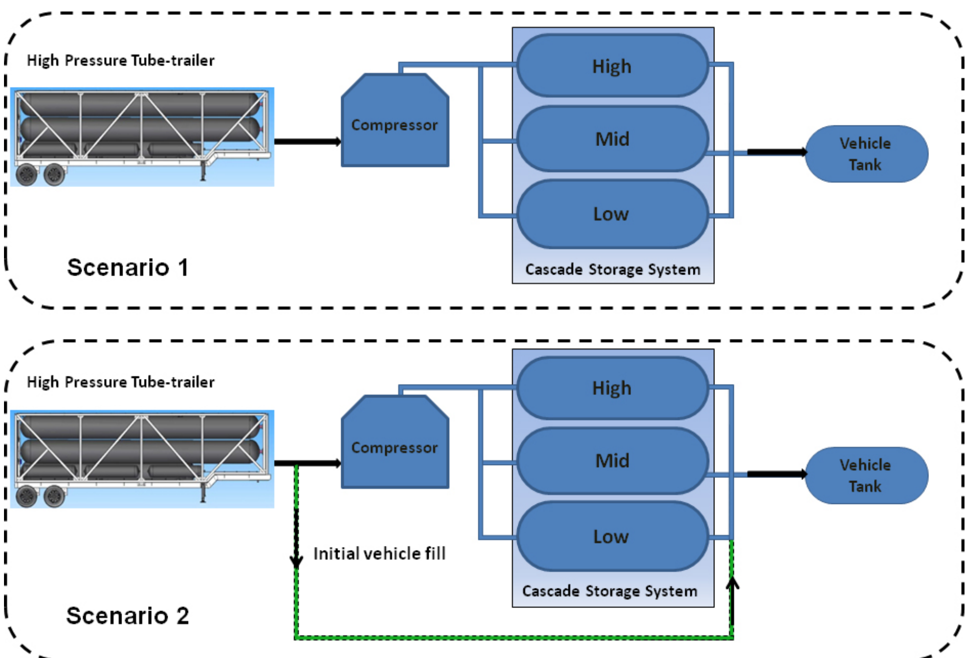
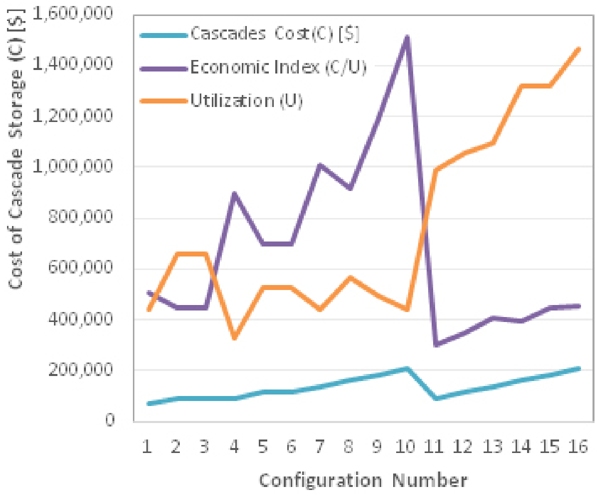



**FIGURE 1.** Operation Scenarios for High Pressure Tube Trailers at Refueling Stations




| Configuration Number | Configuration (High-Medium-Low) |
|---|---|
| 1 | 1-1-1 |
| 2 | 1-1-2 |
| 3 | 1-2-1 |
| 4 | 2-1-1 |
| 5 | 2-2-1 |
| 6 | 1-2-2 |
| 7 | 2-2-2 |
| 8 | 2-2-3 |
| 9 | 2-3-3 |
| 10 | 2-3-4 |
| **11** | **1-1-1-1** |
| **12** | **1-1-1-1-1** |
| 13 | 1-1-1-1-1-1(6) |
| 14 | 1-1-1-1-1-1-1 (7) |
| 15 | 1-1-1-1-1-1-1-1(8) |
| 16 | 1-1-1-1-1-1-1-1-1 (9) |

**FIGURE 2.** The Cost and Utilization of Different Cascade Configurations

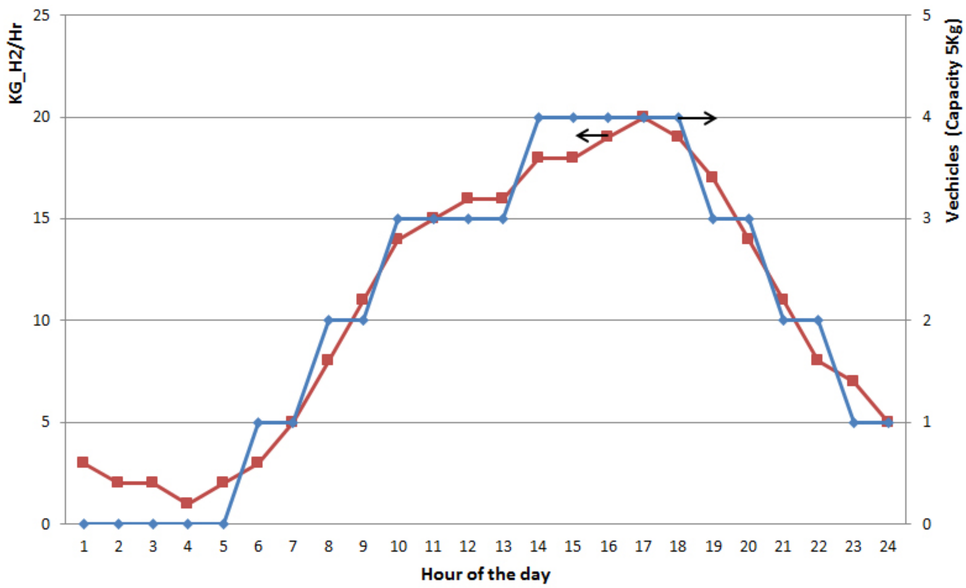



**FIGURE 3.** Hydrogen Demand (kg) and Number of Vehicles Per Hour

hydrogen utilization). The economic index is noteworthy since it represents the contribution of the cascade system to the cost of dispensed hydrogen. Since the primary goal is to achieve maximum back-to-back vehicle fills at lowest possible cost, it is desirable to minimize the economic index. The cost estimates reflect a 250 kg/day HRS with the hourly demand profile shown in Figure 3. Figure 2 shows that (for a vessel volume of 250 liters) the most economic option for this HRS is a cascade system with four pressure (i.e., cascade) levels (configuration# 11).

### High-Pressure Tube Trailer Operation Strategy

Figure 4 shows the capital cost estimates for the combined compressor and cascade storage system (left vertical axis) and the required compressor capacity (right vertical axis) for different HRS operation scenarios. Using the tube trailer to initially fill the vehicle tank (Scenario 2) reduces the demand for compression and cascade storage at the refueling station. Furthermore, returning the tube trailer at a higher pressure further reduces the demand for compression at HRS, thereby reducing the initial capital investment and operation cost.

### Cost Contribution of Station Components

The HRS compression and cascade buffer storage system was optimized for three sizes: 250, 500, and 1,000 kg/day. Figure 5 shows the total capital cost of the refueling station as a stacked bar of individual component cost (left vertical

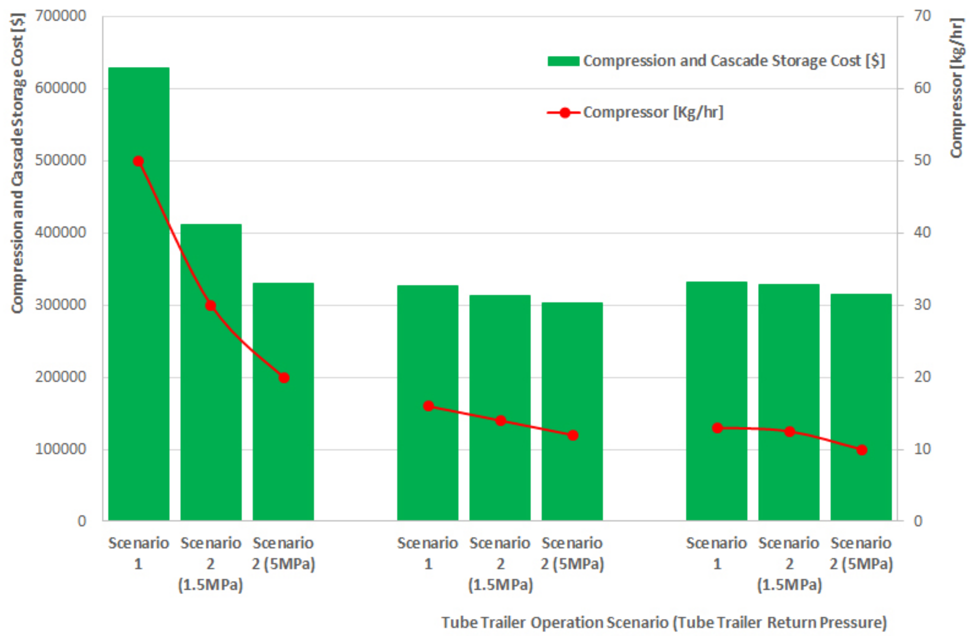



**FIGURE 4.** Combined Compression and Cascade Storage Cost along with Compressor Rating for a 250 kg/day Station

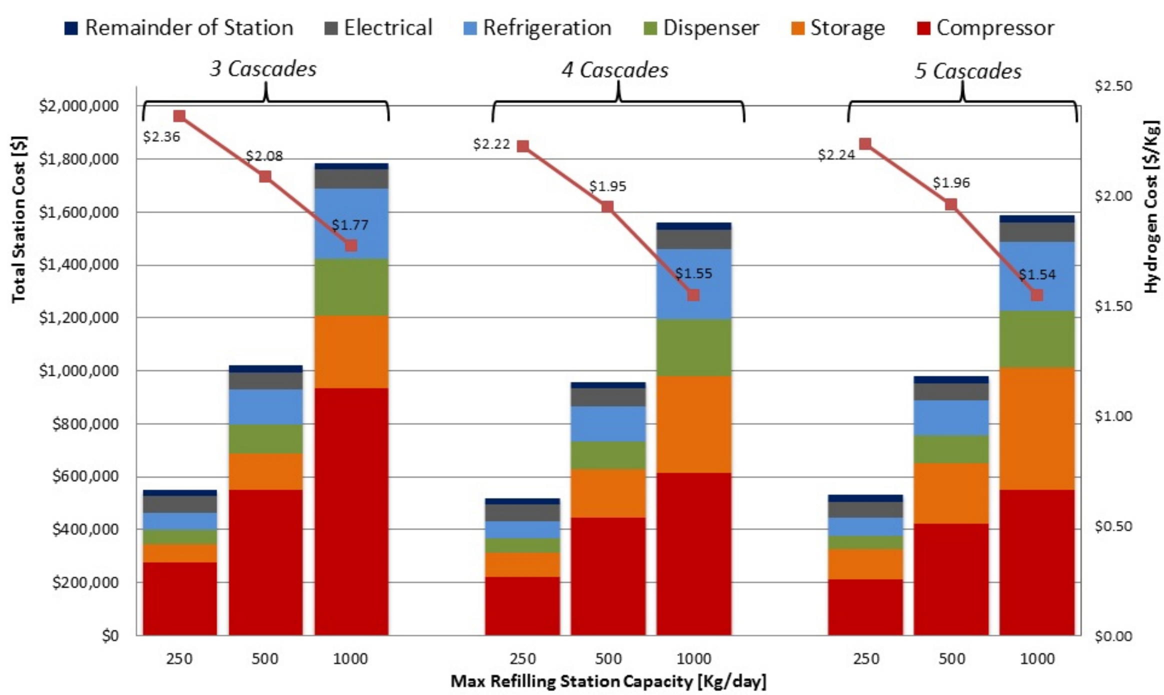



**FIGURE 5.** Capital Cost and Cost Contribution to Dispensed Hydrogen for Different Station Sizes and Configurations

axis). The figure also shows the contribution of the HRS capital cost toward the dispensed cost of hydrogen in $/kg (right vertical axis). The cost per kg of hydrogen for larger refueling stations is lower despite the larger capital cost due to the economies of scale associated with employing larger components. Figure 5 shows similar refueling hydrogen cost per kg for both 4-cascade and 5-cascade systems due to the tradeoff between lower capital cost for the 4-cascade system and lower operation cost for the 5-cascade system.

## CONCLUSIONS AND FUTURE DIRECTIONS

FCEVs with 700 bar onboard storage systems require significant compression which is the single most significant contributor to HRS capital cost. High-pressure tube trailers can reduce the compression requirement at HRS when operated to initially fill the vehicle and returned at a higher pressure. The compression can further be reduced by optimizing the combined compressor capacity and cascade storage size for any particular hourly demand profile, station daily demand, cascade vessel size, and vehicle tank capacity.

For the remainder of FY 2013, effort will be directed at documenting and publishing the results and analysis, and at investigating other tube trailers operation strategies for further reduction of compression requirement at HRS.