Hydrogen Storage Cost Analysis

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Subcontractors:
- Argonne National Laboratory, Lemont, IL
- Pacific Northwest National Laboratory, Richland, WA

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Project End Date: September 30, 2020

Overall Objectives

- Identify and/or update the configuration and performance of a variety of hydrogen storage systems for both vehicular and stationary applications.
- Conduct rigorous cost estimates of multiple hydrogen storage systems to reflect optimized components for the specific application and manufacturing processes at various rates of production.
- Explore cost parameter sensitivity to gain understanding of system cost drivers and pathways to lowering system cost.

Fiscal Year (FY) 2018 Objectives

- Examine hydrogen storage options for buses utilizing 350–700 bar cryo-compressed hydrogen (CcH_2) and 350 bar compressed hydrogen (cH_2).
- Examine the system cost of a hybrid metal hydride storage system.
- Explore the cost impacts of recent, novel ideas for improving the performance or reducing the cost of hydrogen storage systems, such as replacing wet winding carbon fiber with advanced fiber placement of a carbon fiber tape.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan[1]:

(B) System Cost

(H) Balance of Plant (BOP) Components

(K) System Life-Cycle Assessments.

FY 2018 Accomplishments

- Completed analysis comparing thermoplastic carbon fiber tape with advanced fiber placement against wet fiber layup.
- Completed an analysis of several fuel cell electric bus hydrogen storage options: 350, 500, and 700 bar CcH_2 and 350 bar cH_2.
- Performed a cost tradeoff analysis between light-duty vehicle regulators and fuel cell system cost for different pressures delivered to the stack.
- Completed a first-step baseline system cost analysis of a hypothetical hybrid 350 bar metal hydride hydrogen storage system.

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[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

INTRODUCTION

The Fuel Cell Technologies Office (FCTO) has identified hydrogen storage as a key enabling technology for advancing hydrogen and fuel cell technologies and has established goals of developing and demonstrating viable hydrogen storage technologies for transportation and stationary applications. The cost assessment described in this report supports the overall FCTO goals by identifying the impact of components, performance levels, and manufacturing/assembly techniques on storage system cost at a variety of annual manufacturing rates. The results of this analysis enable DOE to compare the cost impact of new components, etc., to the overall 2018 and ultimate DOE cost targets. The cost breakdown of the system components and manufacturing steps can then be used to guide future R&D decisions.

APPROACH

A Design for Manufacture and Assembly (DFMA)-style cost analysis methodology was used to assess the materials and manufacturing cost of hydrogen storage systems and components. Key system design parameters and engineering system diagrams describing system functionality and postulated manufacturing process flows were obtained from a combination of industry partners, Argonne National Laboratory (ANL), Pacific Northwest National Laboratory (PNNL), and internal analysis. This data was used to develop a mechanical design of each component, including materials, dimensions, and physical construction. Based on this design, the manufacturing process train was modeled to project the cost to manufacture each part. Cost was based on the capital cost of the manufacturing equipment, operating cost of the machinery, equipment tooling amortization, material costs, and financial assumptions. Once the cost model was complete for the system design, sensitivity data for the modeled technology was obtained by varying key parameters. Results were shared with ANL, PNNL, and industry partners to obtain feedback and further refine the model.

RESULTS

Type 4 Compressed Natural Gas Analysis

In support of the Institute for Advanced Manufacturing Composites Innovation (IACMI), our 700 bar Type 4 hydrogen storage system model was adapted to provide a cost estimate for two commercially available compressed natural gas (CNG) pressure vessels. In consultation with DOE, two Hexagon TUFFSHELL tanks—a 64.4 L light-duty vehicle tank and a 537.5 L heavy-duty tank—were selected as model systems. Baseline results were discussed in the 2017 Annual Progress Report. The total composite mass for the CNG tanks was estimated from a derived performance factor for 700 bar tanks modeled by ANL and calibrated to Hexagon tanks that were burst tested at PNNL [1]. The modeled 2017 baseline tank mass (boss, liner, and composite) was within ±5% of a commercial comparison system, inspiring confidence that our model adequately represents realistic composite mass for mass-produced tanks.

In 2018, the model was modified to compare system costs using a novel thermoplastic tape applied using Advanced Fiber Placement (AFP), a process developed by DuPont and Steelhead Composites. In the modified manufacturing process, a tape of Panex-35 carbon fiber in a polyamide (PA-6) thermoplastic matrix is applied to the vessel by AFP. The thermoplastic tape is cured[2] in place, which eliminates the need for the two oven curing steps used in conventional wet-composite layup systems. The AFP capital cost was estimated from a buildup of component costs, and the composite tape price is estimated to have a similar cost per kilogram as T-700S/epoxy in the preliminary analysis. The estimated cost of the AFP system ($1.5 million) is substantially higher than the ~$350,000 for conventional wet composite layup. However, AFP eliminates the need for down-process curing ovens by curing in place. The fiber lay-down speed of AFP is assumed to be comparable to that of wet winding, although faster speeds may be possible with optimization according to discussions with some component suppliers. While spooled fibers and resin are used as inputs to the wet winding process, the AFP requires the fibers and thermoplastic matrix to be pre-processed together into a tape prior to use

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[2] This process is commonly referred to as "cure in place" although technically it is not curing, as a thermoplastic matrix is used rather than a thermoset matrix.

(analogous to a pre-preg tape). The DuPont material is based on a Panex-35 (600 ksi) fiber in a polyamide (PA-6) matrix. Tape cost at high volume manufacture is estimated to be $22.83/kg and is, coincidentally, very close to the $23/kg estimate of the much higher strength T-700S (711 ksi) carbon fiber used in the baseline tank system. Interestingly, the relatively high price of the thermoplastic tape is not due to processing but rather to the 50% markup assumption suggested by vendor input. Should the tape become a commodity material with multiple comparable vendors, the markup is expected to go down. The higher AFP capital cost and the lower strength at comparable material cost Panex-35 led to an overall increase in the tank cost as shown in Figure 1.

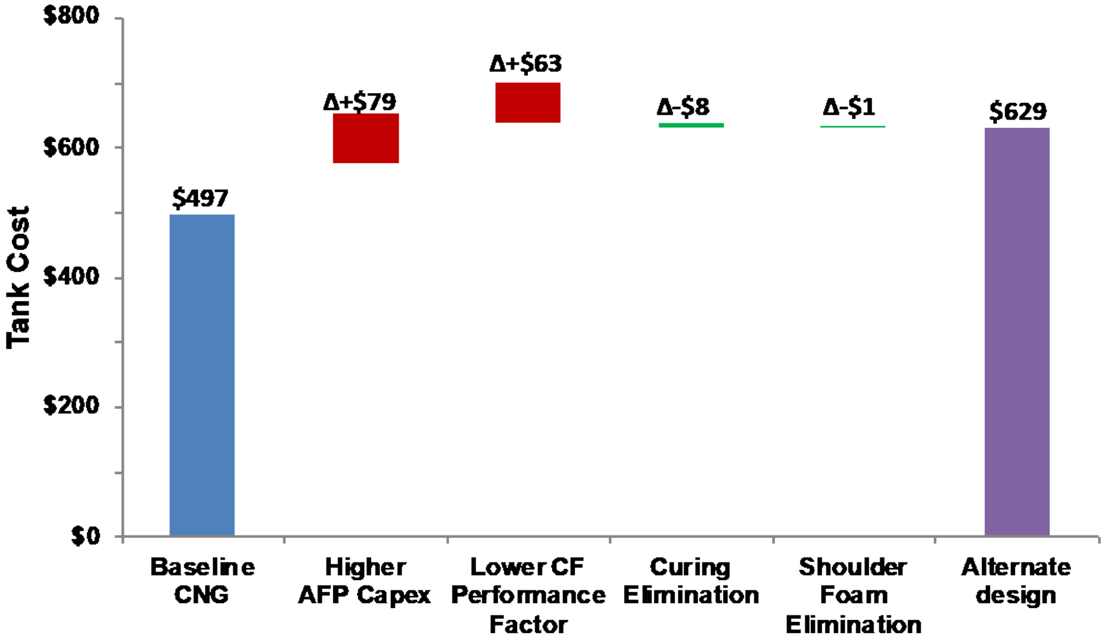

Figure 1. Waterfall chart comparing baseline wet fiber layup CNG tank cost with an alternate design using Panex-35/PA-6 thermoplastic tape applied by advanced fiber placement. Costs are for a 65 L tank and annual production of 500,000 tanks per year.

Fuel Cell Electric Bus Hydrogen Storage Options

Three different storage systems were analyzed this year for fuel cell electric bus applications: (1) 350–700 bar, <100 K CcH_2, (2) 500 bar 200 K cold compressed hydrogen (Cold-cH_2), and (3) 350 bar ambient temperature compressed hydrogen. Cryo-compressed systems are characterized by hydrogen storage in insulated Type 3 pressure vessels at cryogenic temperatures (typically 70–200 K) and elevated pressure (typically 100–500 bar). The benefits of CcH_2 storage include higher effective storage density of hydrogen (and reduced system size) without incurring the energy and cost of a full hydrogen liquefaction, and a long driving range after a full boil-off event. Hydrogen density at 700 bar and 288 K is the same as hydrogen at 500 bar and 200 K. However, the carbon fiber required for the lower-pressure cold compressed tank is approximately 71% of the carbon fiber required for the tank at 700 bar, and yet the gas temperature of the cold compressed tank is not so low to require a metal liner. For comparison, a conventional 350 bar Type 3 compressed gas storage system was analyzed. The cost results of the fuel cell electric bus analysis shown in Table 1 demonstrate that cryo-compressed storage has the potential to significantly reduce the storage cost for fuel cell electric bus applications compared to 350 bar compressed storage. The anticipated savings in carbon fiber from the higher-density cold-compressed system, however, is offset by the higher cost of insulation and the containment vessel, leading to a higher overall cost system compared to the baseline.

Table 1. System Cost Comparison

	350 bar CcH_2	500 bar CcH_2	700 bar CcH_2	350 bar cH_2	Cold-cH_2
Liner	$1.03	$1.01	$0.99	$0.21	$1.58
Composite	$3.25	$4.70	$7.12	$9.79	$8.86
Insulation and Containment Vessel	$3.48	$3.21	$2.92	$0.00	$3.05
BOP	$3.84	$3.85	$3.85	$3.25	$3.45
Assembly and Other	$0.04	$0.04	$0.04	$0.12	$0.04
System Cost (2007$/kWh)	$11.65 [-2.32, +2.90]	$12.82 [-2.32, +2.90]	$14.92 [-2.78, +3.61]	$13.38 [-3.44, +5.73]	$16.97 [-0.81, +1.59]

700 bar System Update

The baseline 700 bar Type 4 storage system design implicitly assumes a 15 bar pressure differential between the regulator inlet and outlet is required to deliver 5.6 kg hydrogen at flow (0.02 g/s/kW) for peak power fuel cell stack operations (80 kW). This assumption led to an effective empty tank pressure of 20 bar in the 2015 baseline system [1] to deliver 5 bar to the fuel cell system at full flow. However, higher fuel cell system delivery pressure allows lower-cost hydrogen recirculation components, which leads to an overall lower system cost. Cost tradeoffs comparing the combined storage system composite cost plus the fuel cell system recirculation cost are shown in Figure 2. The bottom green curve shows how composite cost scales with the storage vessel minimum empty pressure, and the two top curves sum the composite and recirculation costs (blower vs. pulsed-ejector with bypass), which determines the lowest minimum empty tank pressure. A recirculation system with a blower can function with only 5 bar to the fuel cell system and thus requires at least a 15 bar minimum tank pressure (assuming a pressure regulator drop of 10 bar). Alternately, the pulsed-ejector with bypass system requires 10 bar pressure to the fuel cell system and thus requires a minimum empty pressure of 20 bar. While the pulsed-ejector system results in a higher storage system cost of $18 ($0.10/kWh), the vehicle cost is actually $322 less per system.

An alternate pathway to lower minimum empty tank pressure was recently suggested by ANL [2]: switching from a single-stage regulator to a two-stage regulator to reduce regulator pressure drop while maintaining peak flow rates. Analysis of one- and two-stage regulators suggests two-stage regulators can be as much as 50% higher cost; this added cost may not be justified merely to maintain full flow at near-empty tank conditions [3] when the gas density is low as it represents only a few percent of the total full fill mass. In 2019, balance of plant components will be updated with a goal of further consolidation and cost reduction.

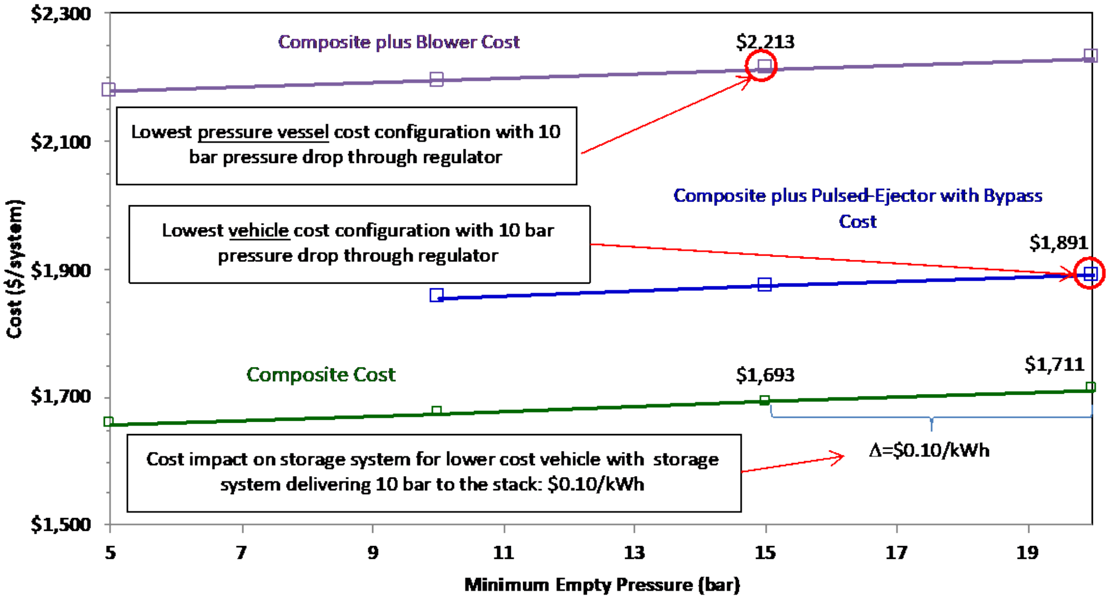

Figure 2. Cost tradeoffs between storage system minimum empty pressure and fuel cell system hydrogen recirculation cost

Metal Hydride Reverse Engineering

Strategic Analysis completed a baseline 350 bar Type 4 hybrid metal hydride storage system cost analysis based on a system proposed by ANL [4]. The system modeled is based on ANL's proposed storage system using onboard fuel cell stack coolant to heat the metal hydride bed and offboard station coolant to cool the bed during refueling. The projected system cost is $13/kWh at 500,000 systems per year as summarized in Table 2. While the system enables a significant reduction of composite weight compared with the 700 bar compressed gas system, the additional materials and internal heat exchanger present significant cost and technical challenges. Additionally, the feasibility of a high density polyethylene (HDPE) liner for this system is questionable. The next step for this analysis is to investigate which further material and system constraints are needed to achieve the DOE cost and performance targets and to evaluate a Type 3 tank. We anticipate that the total tank volume and pressure need to be reduced to achieve the cost targets.

Table 2. Hybrid 350 bar Type 4 Metal Hydride Storage System Cost Breakdown. System Costs are Reported in 2007$.

	Est. @500,000/yr	Notes
Type 4 pressure vessel (boss, liner, composite)	$6/kWh	51 kg carbon fiber composite Aluminum bosses HDPE liner (blow mold only; cost for friction welding not included)
Fill receptacle	$0.30/kWh	Based on high volume quote for 350 bar compressed gas receptacle. Cost for offboard heat transfer fluid not yet included.
Integrated regulator block	$1.75/kWh	Analysis complete
In-tank valve	$0.89/kWh	Analysis complete
In-tank HX	>$1/kWh	Based on high volume tube quotes with a single bend, but does not yet include assembly or the coolant manifolds
MH/EG	$2.70/kWh	ANL assumes 5.6% MH hydrogen capacity and 45.9 kg MH with 4.6 kg EG. Goal of this analysis is to set cost-driven targets on this parameter. Current cost assumption is $10/kg for the MH/EG.
Other BOP	To be determined	Additional costs for storage-side coolant pump, valve, and plumbing
Total	~$13/kWh	Compared to DOE 2020 target of $10/kWh ($8/kWh ultimate)

HX – heat exchanger
MH – metal hydride
EG – expanded graphite

CONCLUSIONS AND UPCOMING ACTIVITIES

- Completed analysis comparing thermoplastic carbon fiber tape with advanced fiber placement against wet fiber layup.
- Completed an analysis of several fuel cell electric bus storage options: 350, 500, and 700 bar CcH_2 and 350 bar cH_2.
- Performed a cost tradeoff analysis between light-duty vehicle regulators and fuel cell system cost for different fuel cell system delivery pressures.
- Completed a first-step baseline system cost analysis of a hypothetical hybrid 350 bar metal hydride system.

Type 4 CNG Analysis

- Completed an analysis of thermoplastic tape applied by advanced fiber placement. These results show that the higher capital cost of advanced fiber placement and the lower tensile strength of the Panex-35 based thermoplastic tape lead to a higher storage system cost. Reductions in the carbon fiber mass and capital equipment cost are needed for this technology to be cost competitive with wet fiber layup.
- This analysis task was completed at the end of FY 2018.

Fuel Cell Electric Bus Hydrogen Storage Options

- We evaluated several storage options for fuel cell electric buses, including four cryogenic systems and a conventional compressed gas system. Results of the analysis suggest that 350 bar cryo-compressed storage leads to a 13% cost reduction compared with conventional 350 bar ambient temperature compressed gas storage.

700 bar Hydrogen Storage System Update

- A holistic analysis of 700 bar regulators, the minimum tank pressure, and fuel cell system hydrogen recirculation suggests that higher regulator output pressures, while disadvantageous for storage system cost, leads to a combined storage plus fuel cell system cost reduction.

Metal Hydride Reverse Engineering

- Baseline cost analysis of a 350 bar Type 4 hybrid metal hydride storage system based on material and system properties proposed by ANL led to a system cost of $13/kWh. Further analysis is planned to identify a set of material and system assumptions needed to meet the DOE cost targets of $8/kWh.

Future work by Strategic Analysis includes the following:

- Reevaluate BOP components to identify additional opportunities for consolidation and cost reductions for 700 bar Type 4 storage.
- Perform cost analysis for medium- and heavy-duty vehicle hydrogen storage requirements.
- Continue reverse engineering analysis of metal hydride and sorbent storage systems to identify a set of material and system parameters needed to meet DOE targets.

FY 2018 PUBLICATIONS/PRESENTATIONS

1. C. Houchins, B.D. James, D. DeSantis, and J. Huya-Kouadio, “Cost Trade-Offs in H_2 Storage Design Space: Cryogenic, Cold, and Ambient 40 kg H_2 On-Board Cost Analysis for Fuel Cell Electric Buses (FCEB),” presented at the Fuel Cell Seminar, Long Beach, CA, November 9, 2017.
2. R.K. Ahluwalia, J.K. Peng, H.S. Roh, T.Q. Hua, C. Houchins, and B.D. James, “Supercritical Cryo-compressed Hydrogen Storage for Fuel Cell Electric Buses,” submitted to the International Journal of Hydrogen Energy.
3. B.D. James and C. Houchins, “Milestone #5 Report: System Configuration and Bill of Materials,” submitted to DOE, March 30, 2018.
4. B.D. James and C. Houchins, “Hydrogen Storage Cost Analysis,” presented to the Hydrogen Storage Tech Team, January 18, 2018.

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1. G. Ordaz, C. Houchins, and T. Hua, “Onboard Type IV Compressed Hydrogen Storage Systems-Cost and Performance Status 2015,” DOE Hydrogen and Fuel Cells Program Record #15013, U.S. Department of Energy (2015). https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf.
2. T.Q. Hua, H.-S. Roh, and R.K. Ahluwalia, “Performance Assessment of 700-Bar Compressed Hydrogen Storage for Light Duty Fuel Cell Vehicles,” *International Journal of Hydrogen Energy* 42, no. 40 (2017): 25121–25129. https://doi.org/10.1016/j.ijhydene.2017.08.123.
3. B.D. James and C. Houchins, “Hydrogen Storage Cost Analysis,” presented at the 2018 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Washington, DC, June 14, 2018.
4. R.K. Ahluwalia, J.-K. Peng, and T.Q. Hua, “Bounding Material Properties for Automotive Storage of Hydrogen in Metal Hydrides for Low-Temperature Fuel Cells.” *International Journal of Hydrogen Energy* 39, no. 27 (2014): 14874–14886. https://doi.org/10.1016/j.ijhydene.2014.07.052.