IV.A.2 Hydrogen Storage Cost Analysis

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Overall Objectives

- Identify and/or update the configuration and performance of a variety of H_2 storage systems for both vehicular and stationary applications
- Conduct rigorous cost estimates of multiple H_2 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 future pathways to lower system cost

Fiscal Year (FY) 2015 Objectives

- Update and expand the cost analysis of onboard hydrogen storage in pressurized carbon composite (fiber and resin) pressure vessels
- Incorporate reduced cost, integrated balance of plant (BOP) components into cost model
- Assess cost and performance impact of Pacific Northwest National Laboratory (PNNL) enhanced materials and design concepts for pressurized hydrogen storage
- Identify cost drivers and future pathways to lower cost
- Document all analysis results and assumptions
- Continue validation of cost savings from PNNL cold gas storage concept
- Prepare cost estimates of sorbent systems (both the HexCell and modular adsorption tank insert [MATI] concepts)

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:

(B) System Cost

(H) Balance of Plant (BOP) Components

(K) System Life-Cycle Assessments

Technical Targets

This project conducts cost modeling to attain realistic, process-based system costs for a variety of H_2 storage systems. These values can inform future technical targets for system storage cost.

- System Storage Cost: <$12/kWh net (2017 target)

FY 2015 Accomplishments

- Updated the cost analysis of 700 bar Type IV compressed H_2 storage systems to reflect recent technological advances
  - Low cost, low density resin advances from PNNL
  - Carbon fiber cost reductions enabled by replacing a low volume precursor process with a high volume process used in the textile industry that was identified and adapted to high tensile strength carbon fiber by Oak Ridge National Laboratory (ORNL)
  - Completed analysis of an integrated pressure regulator block to reduce the cost of the BOP
  - Added explicit accounting for manufacturing and fiber variations into the cost model
  - Further refined assumptions and analysis based on expert feedback
  - Projected the cost of 700 bar Type IV compressed H_2 storage system to be $14.69/kWh at a manufacturing rate of 500,000 systems/year

- Completed a cost analysis of the MATI and HexCell sorbent H_2 storage systems (based on an Hydrogen Storage Engineering Center of Excellence [HSECoE] design and demonstrated in lab-scale systems[1])
  - Projected the cost of the MATI sorbent system to be $13.34/kWh at a manufacturing rate of 500,000 systems/year
  - Projected the cost of the HexCell sorbent system to be $12.79/kWh at a manufacturing rate of 500,000 systems/year
- Continued validation of the PNNL cold-gas H_2 storage system and confirmed cost savings made possible by the noncryogenic tank aspects

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INTRODUCTION

The Fuel Cell Technologies Office (FCTO) has identified H_2 storage as a key enabling technology for advancing H_2 and fuel cell technologies and has established goals of developing and demonstrating viable H_2 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 the DOE to compare the cost impact of new components, etc., to the overall 2017 and ultimate DOE cost targets. The cost breakdown of the system components and manufacturing steps can then be used to guide future research and development decisions.

During 2015, the 700 bar type IV H_2 storage system analysis was updated based on advances made in materials and BOP components. In addition to the 700 bar Type IV compressed H_2 storage system analysis, two sorbent systems were analyzed: the MATI system and the HexCell systems. Both have been extensively studied by HSECOE.

APPROACH

A Design for Manufacturing 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), members of the HSECoE, and internal analysis. This data was used to develop a mechanical design of each component, including materials, scaling, and dimensions. 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, machine rate of the equipment, equipment tooling amortization, material costs, and other 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, National Renewable Energy Laboratory (NREL), and industry partners to obtain feedback and further refine the model.

The analysis explicitly includes fixed factory expenses such as equipment depreciation, tooling amortization, utilities, and maintenance as well as variable direct costs such as materials and labor. However, because this analysis is intended to model manufacturing costs, a number of costs that usually contribute to the original equipment manufacturer price are explicitly not included in the modeling. These costs are excluded in this analysis: profit and markup, one-time costs such as nonrecurring research/design/engineering, and general expenses such as general and administrative costs, warranties, advertising, and sales taxes.

RESULTS

In FY 2015, SA updated the cost analyses for 700 bar Type IV H_2 storage systems to reflect recent materials and design advancements. Major changes to the 700 bar pressure vessel include use of a lower cost carbon fiber precursor based on high volume textile processing from ORNL, integration of BOP components to reduce the number of fittings, and use of a low cost, low density resin identified by PNNL. The analysis this year also explicitly accounted for costs associated with manufacturing design changes suggested by industry, including the removal of strips of carbon fiber composite used for local endcap reinforcement (referred to as doilies) and increased composite layer thickness to account for a more robust assessment of manufacturing variations. The relative impact of each component change computed versus the 2013 baseline system cost [1] is presented in the waterfall chart in Figure 1. Note that cost reductions in this figure are the result of single variable sensitivity analyses while the 2015 system cost is a result of the cumulative impact of all the changes. The waterfall chart is meant to capture qualitatively how the manufacturing cost was reduced from the 2013 baseline. To achieve this, the single variable changes reported in Figure 1 were scaled so that the relative percent adds up to the 12% reduction calculated for the 2015 tank. The assumptions used for each of the changes are described in further detail below.

In FY 2014 and FY 2015, SA examined the potential for compressed H_2 storage system cost reduction through use of

[1] Note that, whereas the 700 bar pressure vessels has been validated against commercially available compressed natural gas tanks, the sorbent systems represent lab-demonstrated technology and are therefore at a much lower technology readiness level and carry substantially increased performance and cost uncertainty.

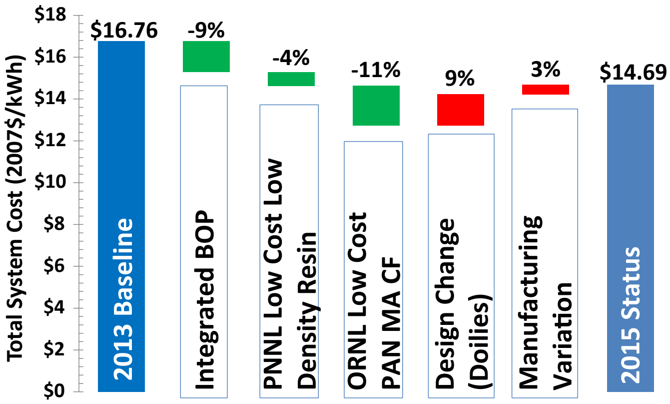

FIGURE 1. 700 bar Type IV pressure vessel storage system cost update for 2015 showing approximate cost impact of multiple simultaneous changes since 2013

a lower cost carbon fiber developed at ORNL. The ORNL developed carbon fiber is a replacement for the baseline Toray T-700S carbon fiber and is based on a polyacyrlonitrile with methacrylate (PAN-MA) precursor used in high volume textile manufacturing. ORNL identified significant cost savings enabled by switching to the PAN-MA precursor. Upon further analysis, SA applied factors to account for cost savings due to high volume carbon fiber manufacturing based on results from the Kline report [2] resulting in a total savings of 18.3% for PAN-MA over Toray T-700S carbon fiber.

System cost using the ORNL textile PAN-MA fiber is projected to be $15.03/kWh vs. $16.76/kWh for the 2013 baseline system using T-700S carbon fiber (both at 500,000 systems/year, in 2007$) or a reduction of $1.73/kWh. However, there is uncertainty in the ultimate tensile strength (UTS) which is the primary performance parameter for carbon fiber for pressure vessel applications. While only 653 KSI UTS was reported by ORNL in 2014, significantly higher performance has been observed in unpublished laboratory fabricated fibers. A preliminary tensile strength of 711 KSI was selected for the cost analysis to match the T-700 specification. When the upper limit of textile PAN-MA carbon fiber UTS is further documented and validated at production scale, the cost projections will be updated.

BOP improvements from last year were further refined by analysis of an integrated pressure regulator block. Component integration is a key cost reduction strategy and was suggested by the Storage Tech Team after a review of the number of fittings within the system. A DFMA® analysis was conducted based on a SS316 integrated pressure regulator block that is forged then machined with tight tolerances to allow proper fitting connections to components. O-rings provide a proper seal for attachment. Figure 2 shows a diagram of the integrated pressure regulator valve, bringing together six low pressure components (downstream of the pressure regulator). By combining the components into one unit, the integrated pressure regulator block body adds a component to the BOP list but reduces overall cost by eliminating piping and fittings. The combined cost reduction of the fitting component costs (2014) and the integrated pressure regulator (2015) is $1.34/kWh from the 2013 baseline tank at 500,000 systems per year. Further cost reductions are anticipated by replacing the SS316 with aluminum.

In FY 2015, SA worked with PNNL to assess their experimental efforts and to incorporate advances identified at PNNL into the baseline 700 bar storage system and cost model. A key element PNNL identified was to replace the epoxy resin used with carbon fiber to make carbon composite with a low cost, low density (vinyl ester) resin. The new resin reduced the total composite cost by lowering the total mass

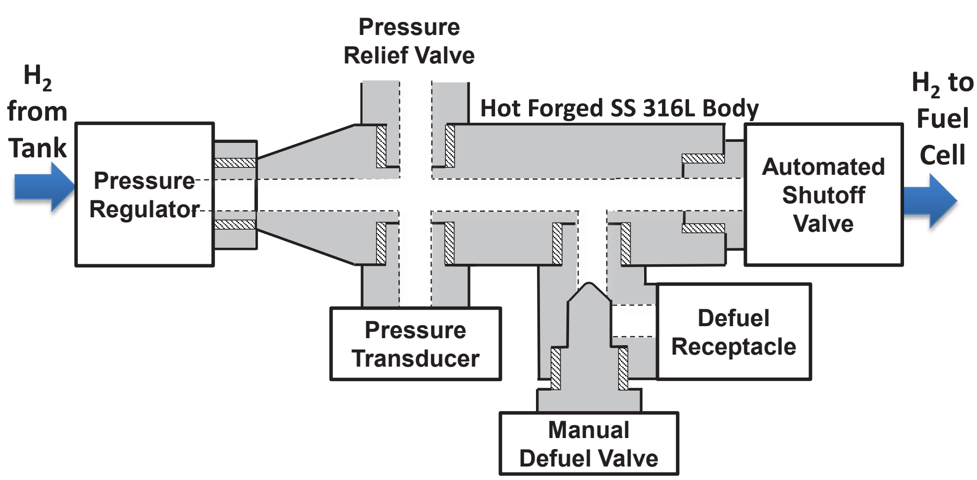

FIGURE 2. Cross-section of integrated pressure regulator block that combines six low pressure components

of resin required as well as using a less expensive resin. The total mass of composite required to meet the design bursts pressure was reduced by ~10% while the material cost of the resin was reduced by ~36%. This results in a reduction of $0.59/kWh over the 2013 baseline system at 500,000 systems per year.

Discussions with vessel manufacturers and ANL led to removal of the doilies previously used in the 2013 baseline tank system [1]. Analysis at ANL suggested that the 2013 baseline tank would require 102 kg composite, up from 91 kg, to meet the same burst pressure without doilies. This change results in an increase of $1.36/kWh from the 2013 baseline.

High volume manufacturing of composite pressure vessels with an extended service life requires some level of overdesign to ensure safety and statutory requirements. Consequently, vessels are designed with enhanced wall-thickness/burst-pressure to account for both fiber strength and manufacturing process variations in high volume manufacturing. Current design practice is based on a 3σ overdesign which is consistent with burst testing of every 200th tank. Based on conversations with tank manufacturers, typical coefficients of variation (COV) for manufacturing and fiber variation are around 3%. In previous analyses, ANL included a 10% increase in composite mass to account for variations in fiber strength: this is approximately equivalent to a 3σ overdesign and a fiber COV of 3.3%. In order to explicitly account for manufacturing variability and to be consistent with current manufacturing practices, a manufacturing COV of 3.3% was assumed for the 2015 tank. This results in a combined fiber and manufacturing overdesign of 14%. The cost impact relative to the 2013 baseline tank for including 3.3% manufacturing variation is $0.42/kWh. When all changes are applied to the model (the ORNL low cost carbon fiber, PNNL low cost resin, integrated BOP, design change, and manufacturing variation) the 2015 tank cost is $14.69/kWh or a reduction of $2.07/kWh from the 2013 baseline tank.

In addition to analyzing the high volume manufacturing cost of 700 bar pressure vessels, SA also conducted a DFMA® analysis of two sorbent based onboard H_2 storage systems: the MATI and HexCell concepts as conceptualized by the HSECoE. Both systems use a sorbent (modeled as MOF-5) to store gaseous H_2 at cryogenic temperatures. The MATI system uses liquid nitrogen (LN_2)-heated H_2 gas flowing through an internal heat exchanger to provide the heat of adsorption/desorption, whereas the HexCell system relies on conduction from a static heat exchange insert to transfer heat to the outer shell (which is jacketed by LN_2). The HexCell system manufacturing cost at 500,000 systems per year is $12.79/kWh while the MATI system cost is $13.34/kWh, as shown in Figure 3. The MATI system was anticipated to be more expensive than the HexCell system due to the greater mass of MOF-5 (41 kg/system at $8.44/kg [in 2007$ at 500,000 systems per year]) compressed into discs and a more

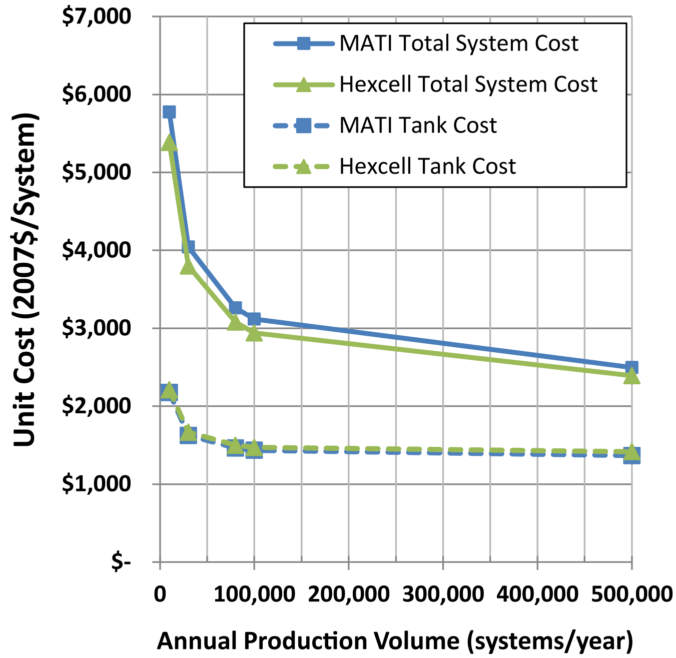

FIGURE 3. Total system and tank costs for both the HexCell and MATI sorbent systems at all manufacturing rates

extensive BOP. Figure 4 compares the breakdown in cost of the two systems at 500,000 systems per year. These cost results were vetted by HSECOE and the Hydrogen Storage Technical Team. Thus both systems are quite similar in cost, and slightly less than the 700 bar compressed pressure vessel system. Whereas the 700 bar pressure vessels have been validated against commercially available compressed natural gas tanks, the sorbent systems represent lab-demonstrated technology and are therefore at a much lower technology readiness level and carry substantially increased performance and cost uncertainty.

CONCLUSIONS AND FUTURE DIRECTIONS

Based on work completed this year the major conclusions are as follows:

- System cost for the single tank 700 bar pressure vessel system has come down by 12% over the 2013 baseline system (at 500,000 systems per year).
  - BOP costs were reduced by integrating components and reducing the total number of fittings leading to a cost reduction of ~9%.
  - Lower cost carbon fiber based on high volume textile processing replaced the conventional carbon fiber reducing the costs ~11%.
  - Low cost, low density resin resulted in a price reduction of ~4%.

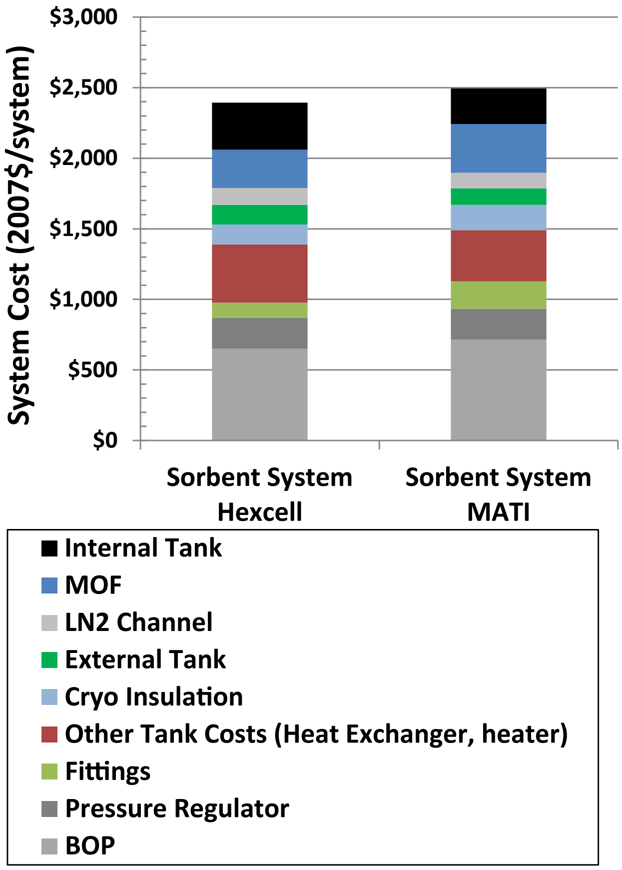

FIGURE 4. Breakdown in total system cost for both the HexCell and MATI sorbent systems

 - Tank design improvements and explicit accounting for manufacturing variation led to a cost increase of ~12%.
- Analyses of the MATI and HexCell sorbent-based onboard H_2 storage systems indicate system costs of ~$13/kWh (at 500,000 systems/year). This is slightly less than the cost of 700 bar compressed H_2 storage; however, there is greater uncertainty in the sorbent systems than for the pressure vessels.

Based on results from this year, SA plans to:

- Re-evaluate pressure vessel winding parameters to assess whether winding speed optimization can lead to lower cost.
- Investigate commercially available cryo-compressed liquid natural gas tanks as a validation case for analysis of the PNNL cyro-gas storage concept.
- As appropriate, track and model improvement from current DOE funded projects looking at lower cost materials, sorbents, and strategies to reduce carbon fiber usage.
- Evaluate alternative, lower cost material selections for the integrated BOP.

FY 2015 PUBLICATIONS/PRESENTATIONS

1. Brian D. James, Jennie A. Moton, Daniel A. DeSantis, "Hydrogen Storage System Cost: Status and Technical Challenges," Hydrogen Storage Summit (PI Workshop), National Renewable Energy Laboratory, Golden, CO, January 29, 2015.

2. Jennie A. Moton, Brian D. James, Daniel A. DeSantis, "Cost of On-Board Hydrogen Storage Systems: Status and Technical Challenges," Hydrogen Storage Technical Team Meeting, USCAR, Southfield, MI, February 19, 2015.

3. Brian D. James, "Hydrogen Storage Cost Analysis," 2015 DOE Hydrogen and Fuel Cells Program Review, Arlington, VA, June 9, 2015.

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1. Scott McWhorter and Grace Ordaz, "Onboard Type IV Compressed Hydrogen Storage Systems--Current Performance and Cost," DOE Program Record 13013 (2013) http://hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf (accessed 14 August 2015).

2. "Cost Assessment of Pan-Based Precursor and Carbon Fiber," Kline and Company, Final Report: Automotive Composites Consortium, 27 November 2007.