IV.A.2 Hydrogen Storage Cost Analysis

Brian D. James (Primary Contact),
Cassidy Houchins, Jennie M. Moton,
Daniel D. DeSantis
Strategic Analysis, Inc.
4075 Wilson Blvd., Suite 200
Arlington, VA 22203
Phone: (703) 778-7114
Email: bjames@sainc.com

DOE Manager: Grace Ordaz
Phone: (202) 586-8350
Email: Grace.Ordaz@ee.doe.gov

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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) 2016 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 pathways to lowering cost.
- Document all analysis results and assumptions.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Fuel Cell Technologies Office (FCTO) 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 2016Accomplishments

- Updated Type IV 700 bar storage system cost status.
- Investigated cost impact of manufacturing and fiber variations.
- Estimated uncertainty in gravimetric and volumetric capacity.
- Investigated strategies to improving carbon fiber utilization as a means of reducing cost.
  - Vacuum infiltration to reduce resin void fraction
  - Analyzed markup versus lower manufacturing variations and faster winding speed tradeoffs for carbon fiber pre-impregnated with resin (pre-preg)
  - Winding pattern improvements and tank boss redesign (as demonstrated by Toyota)
- Evaluated impact of changing integrated valve from 316SS to aluminum.

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INTRODUCTION

The 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 and 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 R&D decisions.

Since the last Annual Progress Report, Strategic Analysis and FCTO issued a joint update to the status of 700 bar type IV hydrogen storage system cost [1] based on advances made in materials and BOP components and included an explicit accounting of manufacturing and fiber variations which result in additional carbon fiber composite used to meet statutory requirements. In addition to the model updates described in Ordaz, et al. [1], a preliminary estimate of the uncertainty in capacity (gravimetric and volumetric) was also analyzed using test results from PNNL and Hexagon Lincoln. Using the status reported in Ordaz, et al. as a baseline for comparison, processs, and design strategies were investigated to explore potential cost savings by decreasing the total amount of carbon fiber composite used.

APPROACH

A Design for Manufacturing and Assembly 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), 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, the National Renewable Energy Laboratory, 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 components 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 non-recurring research, design, engineering, and general expenses such as general and administrative costs, warranties, advertising, and sales taxes.

RESULTS

Updated Type IV 700 bar storage system cost status were based on reductions due to balance of plant component integration, lower cost and lower density resin, and carbon fiber cost reductions from low-cost precursor fiber. Major cost increases in the updated status were due to composite mass increase due to replacing the previously used carbon fiber dome reinforcements with additional helical windings, and increasing the total composite to account for manufacturing and fiber variations per current industrial practice. The baseline system cost is projected to be \$14.8/kWh with a 90% confidence interval of [-\$0.8/kWh, +1.7/kWh] estimated using Monte Carlo error analysis.

In addition to updating the cost status, uncertainty in capacity (gravimetric and volumetric) was estimated and reported for the first time this year. Data provided by PNNL was used to assess the uncertainty in gravimetric and volumetric capacity for the tank while a 10% mass contingency was assumed for the BOP. Based on the PNNL data, the coefficient of variation in tank masses was found to typically be between 1% and 1.5%. Tank-to-tank manufacturing variation in the carbon fiber (CF) mass within a single tank manufacturer is expected to be very small due to tight manufacturing tolerances. On the other hand, the resin mass may vary measurably given its low-viscosity and the likelihood that resin will drip and be squeezed out from the fibers due to tension and compression during the wet-winding process. BOP mass uncertainty data are not available; consequently a ±10% BOP mass uncertainty was assumed as a reasonable approximation. Uncertainty in the volumetric capacities was calculated using the mass variations described above and the density of the respective materials. The resulting uncertainty (±0.04 kWh/kg and ±0.01 kWh/L) represents the best available estimate given the data available, but may understate the uncertainty.

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 and burst pressure to account for both fiber strength and manufacturing process variations in high volume manufacturing. Current design practice is based on a 3σ[1] 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% each. 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. This results in a

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[1] σ= standard deviation = $\sqrt{(COV_{manufacturing}^{2} + COV_{fiber}^{2})}$

combined fiber and manufacturing overdesign of 14% in the baseline design.

Strategies to reduce cost by improving carbon fiber utilization and increasing winding speed were investigated. Tank winding is a time-consuming step, projected to take as long as five hours per tank in the current model using an average winding speed of 26 meters of carbon fiber per minute. Figure 1 shows the manufacturing cost (the amortized cost of the winding machinery, electricity, and labor cost) of winding a single 5.6 L 700 bar pressure vessel as a function of winding speed. At the baseline 26 m/min, the total winding manufacturing cost is $0.80/kWh or a little more than 5% of the total system cost. The current cost model assumes a winding speed of 40 m/min for carbon fiber pre-impregnated with resin (pre-preg); however, some have suggested pre-preg winding speeds of 90 m/min may be possible which is projected to reduce the winding manufacturing cost to around $0.20/kWh or ~1% of the total system cost.

In addition to investigating potential cost reductions from increasing the winding speed, tradeoffs between faster winding time and manufacturer's markup on pre-preg were investigated. Compared to wet-winding, and in addition to faster winding speeds, pre-preg is expected to achieve lower resin wastage and may achieve a lower manufacturing coefficient of variation ($\mathrm{COV}_{\mathrm{manufacturing}}$) resulting in lighter tanks. To understand these tradeoffs, we parametrically analyzed the cost of materials and manufacturing for pre-preg and compared them at multiple markup rates against the cost of wet winding. Figure 2 shows a parametric examination of the total material (carbon fiber and resin) and manufacturing cost of pre-preg as a function of winding speed and manufacturer's markup (a percentage multiplier). The red line marks the cost of wet winding materials and manufacturing (at 26 m/min). Where the grey dashed lines cross the red line is where the cost of pre-preg is expected to be at cost parity with wet winding for a given markup. This analysis suggests that pre-preg would be an economical choice for markups below around 9% assuming winding speeds are faster than wet winding. For instance, the average winding speed would need to be around 50 m/min to reach cost parity with wet winding for an 8% markup. Pre-preg is not used by most tank vendors, presumably due to the current high cost of pre-preg (>9% markup) which may result from low production volume.

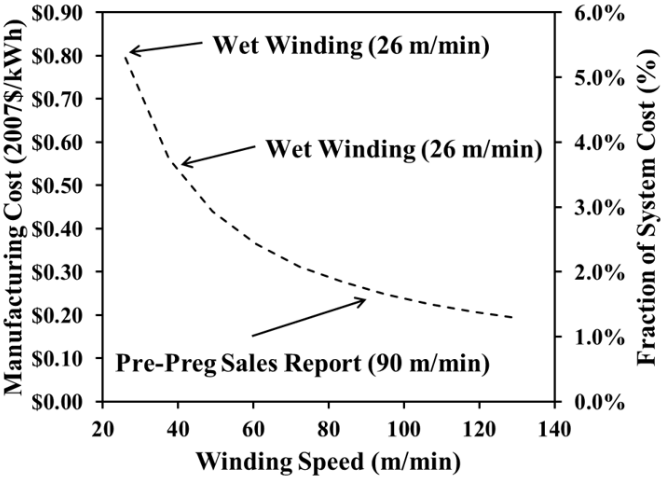

FIGURE 1. Manufacturing cost of pressure vessel winding as a function of winding speed

Toyota has reported Type IV tank designs that result in lower carbon fiber usage by using alternate liner geometry to eliminate high-angle helical winding, an alternate winding scheme, a smaller diameter boss with a longer flange, and high strength T-720 carbon fiber. In the Toyota two-tank configuration, the front tank has an aspect ratio (length/diameter) of 2.8 while the rear tank has an aspect ratio of 1.7. ANL finite element analysis model results predict a 4.8% CF mass reduction for the high aspect ratio (2.8) tank using T-700 carbon fiber and the PNNL lower cost, low density resin; however, no CF mass reductions is predicted for the low aspect ratio (1.7) tank. Additional mass savings are possible by switching to higher strength T-720 CF but there is insufficient data on T-720 price to project accurate system cost results. When the Toyota CF reductions are applied to the Strategic Analysis single and two-tank configurations, cost is reduced around $0.50/kWh as shown in Table 1.

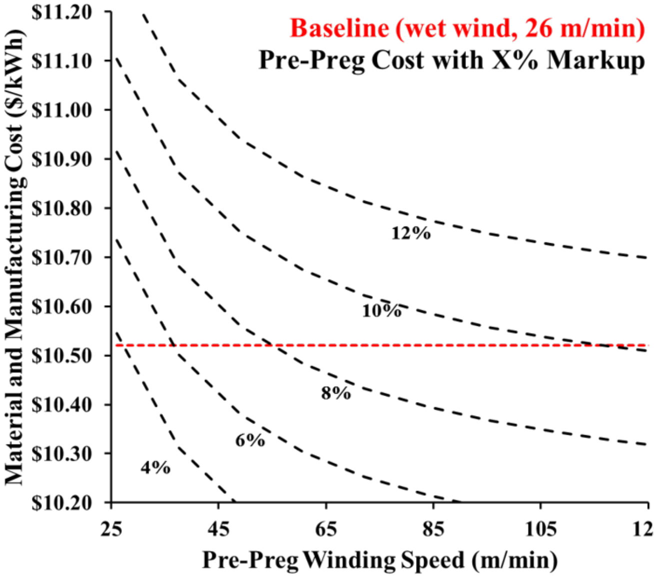

FIGURE 2. Comparison of material and manufacturing costs as a function of winding speed for pre-preg at multiple markups. Dashed black lines represent cost curves for pre-preg at the indicated markup (e.g., the upper curve has a 12% markup applied; the next curve has a 10% markup). The red dashed line marks the cost for wet winding at 26 m/min. The analysis is based on a 1.6% $\mathrm{COV}_{\mathrm{manufacturing}}$ for pre-preg and 3.3% $\mathrm{COV}_{\mathrm{manufacturing}}$ for wet winding.

A final avenue of investigation into reducing cost by decreasing carbon fiber usage is vacuum resin infusion being investigated by Materia [3]. To understand the cost impact of the Materia process, the cost of the composite (materials and manufacturing) was analyzed as a sensitivity study against a case with no composite reduction. Figure 3 presents a summary tornado chart of these results. If there is no composite mass reduction for the Materia process, the cost of the composite material, winding, and resin application at 500,000 systems/year would be $12.03/kWh compared to $10.52/kWh for the baseline storage vessel. The higher cost is due largely to the higher resin cost: $13.5/kg for dicyclopentadiene with Grubb's catalyst compared to $4.52/kg for vinyl ester used in the baseline tank. The additional processing cost associated with the vacuum infiltration process itself also contributes an additional $0.51/kWh. In order to offset these additional costs and reach cost parity with wet winding, a 14% composite mass reduction would need to be realized. If Materia meets the 30% composite mass reduction project objective, these results project a system cost savings of $1.79/kWh.

CONCLUSIONS AND FUTURE DIRECTIONS

Based on work completed this year the major conclusions are:

- 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).
- Addition improvements have been analyzed.

TABLE 1. Projected system cost savings for single and two tank configurations using the Toyota winding patterns compared with current winding patterns. System costs are modeled assuming aluminum valve and regulator bodies, assuming a 3.3% COV_{Fiber} for the Oak Ridge National Laboratory polyacrylonitrile with methyl acrylate fiber, and PNNL lower cost, low density resin.

	Available H_2 (kg)	L/D	CF Reduction (%)	System Cost Reduction ($/kWh)
Baseline (single tank)	5.6	3	--	--
Single tank w/Toyota winding pattern	5.6	3	-4.8%	0.50
Two-Tank Configuration	5.6	3	--	--
Two-Tank w/Toyota winding pattern	5.6	3	-4.8%	0.49

L - Length; D - Diameter

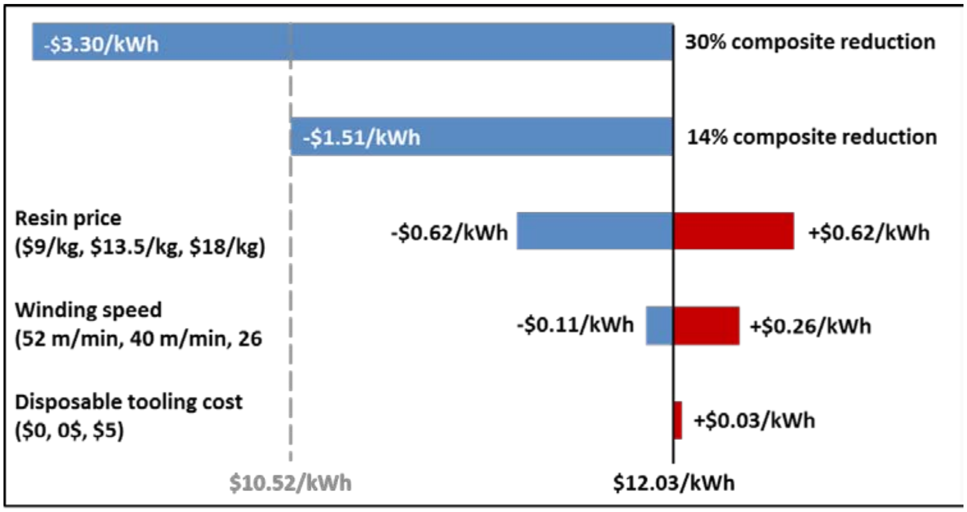

FIGURE 3. Single variable sensitivity analysis of the Materia vacuum infiltration process for a single 147 L tank with 5.6 kg usable H_2 produced at 500,000 systems per year. The black line ($12.03/kWh) shows the modeled tank cost using the Materia process with no carbon fiber reduction. The grey dashed line ($10.52/kWh) is the baseline tank cost.

  - Replacing stainless steel BOP components result in a reduction of $0.16/kWh.
  - Tank design and winding patterns demonstrated by Toyota suggest additional savings of around 3%.

Based on results from this year, Strategic Analysis plans to:

- Further investigate and validate the Toyota tank design.
- Track and model improvements from current DOE funded projects looking at lower cost materials, sorbents, and strategies to reduce carbon fiber usage as appropriate.
- Re-evaluate commercially available BOP components to validate current BOP costs and to investigate further price reductions.

FY 2016 PUBLICATIONS/PRESENTATIONS

1. Ordaz, Grace, Cassidy Houchins, and Thanh Hua. "Onboard Type IV Compressed Hydrogen Storage Systems-Cost and Performance Status 2015." U.S. Department of Energy, 2015.

2. Brian D. James, Cassidy Houchins, Daniel DeSantis, Jennie Huya-Kouadio, "Cost of On-Board Hydrogen Storage Systems: Status and Technical Challenges" Hydrogen Storage Technical Team Meeting, USCAR, Southfield, MI, March 17, 2016.

3. Brian D. James, "Hydrogen Storage Cost Analysis" 2015 DOE Hydrogen and Fuel Cells Program Review, Arlington, VA, June 8, 2016.

REFERENCES

1. Grace Ordaz, Cassidy Houchins, and Thanh Hua. "Onboard Type IV Compressed Hydrogen Storage Systems-Cost and Performance Status 2015." U.S. Department of Energy, 2015.

2. Scott McWhorter and Grace Ordaz, "Onboard Type IV Compressed Hydrogen Storage Systems-Current Performance and Cost." U.S. Department of Energy, 2013.

3. Brian Edgecombe, "Next Generation Hydrogen Storage Vessels Enabled by Carbon Fiber Infusion with a Low-Viscosity, High-Toughness Resin System." 2016 DOE Hydrogen and Fuel Cells Program Review, Washington DC, June 9, 2016.