Hydrogen Storage Cost Analysis

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- Argonne National Laboratory, Argonne, IL
- Pacific Northwest National Laboratory, Richland, WA

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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) 2019 Objectives

- Analyze storage system sizing requirements and system specifications for medium- and heavy-duty fuel cell electric vehicles.
- Update 700-bar Type 4 light-duty vehicle system costs.

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[1]:

- (B) System Cost
- (H) Balance of Plant Components
- (K) System Life-Cycle Assessments.

FY 2019 Accomplishments

- Completed a scoping analysis of medium- and heavy-duty fuel cell electric truck requirements and a preliminary cost analysis of 350-bar Type 3, 500-bar cryo-compressed, and 700-bar Type 4 storage systems for multiple storage system packaging strategies.
- Modeled high-volume carbon fiber prices and compared results with industry-provided T700S price quotes.
- Updated 700-bar Type 4 light-duty vehicle storage system costs, including updates to carbon fiber prices and low-volume balance of plant component costs.

INTRODUCTION

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 advances in components, materials, and manufacturing to cost targets. Results from the detailed cost models reported under this project help guide future R&D decisions by providing insight into which components and cost have the greatest potential to reduce system cost.

APPROACH

A Design for Manufacture 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

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

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

Medium- and Heavy-Duty Vehicles

Medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs) are an increasingly important market sector of fuel cell vehicles. According to the 2016 Vehicle Technologies Market Report [1], annual vehicle sales of these two broad classes of vehicles was expected to be around 400,000 vehicles in the U.S. with 97% being produced domestically. In general, the on-board hydrogen storage requirements are significantly higher for fuel cell MDVs and HDVs than for light-duty vehicle (LDV) applications to meet the range and vehicle power requirements dictated by the vehicle's vocation [2].

Drive cycle analyses of multiple vocations typical of MDVs (e.g., refuse trucks, package delivery vehicles, and buses) and HDVs (e.g., line-haul and tractor trailers) show that most vocations fall into two groups with respect to hydrogen on-board storage requirements. One group has a range of 10–30 kg H_2 centered around 20 kg H_2 and covers the MDV vocations. The other group, covering the HDV vocations, spans a range from 60–100 kg H_2. There are three typical locations for storing compressed gaseous fuels, particularly compressed natural gas, on-board MDVs and HDVs: behind the cab, on the frame, and on the roof. The choice of where to mount the tanks and how many will vary by system integrator and will depend on various considerations such as cost, available space, and range requirements.

Table 1 compares several system configurations (size and number of tanks, composite mass, location, pressure, and state). Preliminary system costs reveal trends that are similar to our analysis of fuel cell electric bus storage options [3]. Cryo-compressed storage appears to have the advantages of lower capital cost and higher gravimetric capacity; however, preliminary total cost of ownership analysis suggests 700-bar and 500-bar cryo-compressed systems are less expensive than 350-bar compressed and are at parity with each other when refueling costs are included. Compared with LDV system costs, 700-bar Type 4 MDV and HDV systems are dominated by the composite cost at all volumes investigated (10,000–200,000 systems/year) because the composite mass of MDV and HDV tanks is in the range of 200–1,000 kg/system.

Table 1. Summary of System Capacities and Carbon Fiber Requirements for MDV and HDV Storage Systems

Location	Number of Tanks	Interior Tank Length (inches)	Interior Tank Diameter (inches)	Usable H_2 (kg H_2/tank)			Composite Mass (kg carbon fiber/tank)		
				350-bar cH_2	500-bar CcH_2	700-bar cH_2	350-bar cH_2	500-bar CcH_2	700-bar cH_2
BTC	2–4	80	16	5.7	17.4	9.7	61.0	93.8	152.0
	2–4	80	21	9.6	29.6	16.3	107.2	152.8	257.5
RM	4	80	16	5.7	17.4	9.7	61.0	93.8	152.0
	4	96	16	6.9	21.1	11.7	73.6	113.3	182.8
	4	97	12	4.0	12.1	6.7	50.1	68.0	108.5
FM	1–2	60	21	7.0	21.4	11.9	79.3	112.7	190.9
	1–2	80	21	9.6	29.6	16.3	107.2	152.8	257.5
	1–2	120	21	14.9	45.8	25.3	163.0	232.9	390.8
	1–2	60	26	10.3	31.8	17.5	120.4	165.7	288.2
	1–2	80	26	14.4	44.1	24.4	161.8	224.9	386.7
	1–2	90	26	16.4	50.4	27.8	182.5	254.6	436.0
	1–2	120	26	22.4	68.9	38.1	244.7	343.4	583.8

350-bar Type 3 compressed (350-bar cH2), 500-bar cryo-compressed (500-bar CcH2), and 700-bar Type 4 compressed (700-bar cH2) hydrogen storage systems are considered. Storage system dimensions are taken from A-1 electric (http://www.a1autoelectric.com/alternative-home/fuel-systems-integration/). Three package options were considered: behind the cab (BTC), roof-mounted (RM), and frame-mounted (FM). The composite masses were calculated by ANL.

Carbon Fiber Price

Based on input from industry experts, the current 2019 market price for T700S carbon is about 9% lower compared to 2010. Based on discussions with carbon fiber purchasers, the intermediate modulus carbon fiber market follows Toray's pricing due to Toray's dominant market position. An implicit assumption of our modeled carbon fiber price is that a larger vehicle market will lead to a more competitive carbon fiber market, more efficient precursor processing plants, and larger, more efficient carbonization plants. For example, at an annual production rate of 100,000 fuel cell vehicles the current intermediate modulus carbon fiber would be doubled [4]. We believe that a market of this size would induce increased investment and put pressure on suppliers to realize the process improvements from larger, more efficient plants.

Building on the work of Das [5] and Kline [6], we modeled carbon fiber costs to better understand the underlying capital costs and operating costs and so that inputs could be adjusted as appropriate. A schematic of carbon fiber manufacture with key assumptions is shown in Figure 1.

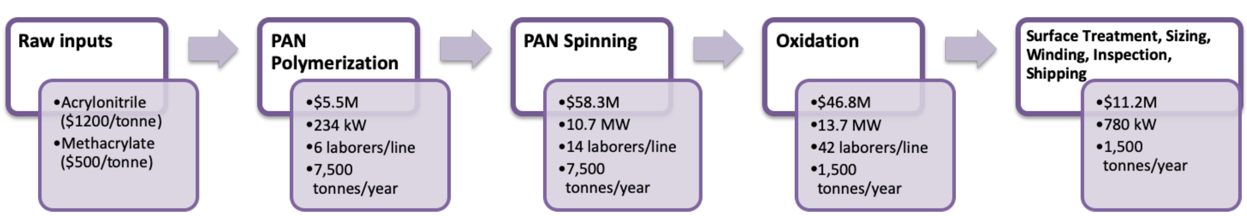

Figure 1. Modeled carbon fiber cost assumptions

The oxidation plant capital cost and operating conditions are based on discussions with suppliers. Our modeled costs are consistent (within ~$1/kg) with both Das and Kline. We explicitly assume that the composite material properties are equivalent to T700S in our pressure vessel cost model; the material properties primarily impact the carbon fiber mass. Figure 2 shows the Strategic Analysis (SA) modeled carbon fiber cost at current oxidation line capacities (1,500 tonnes per year) compared with T700S price quotes. It is difficult to say what the T700S markup is, so we estimate the carbon fiber price at high volume by scaling the T700S price by our projected high- and low-volume costs. Two high-volume savings are accounted for in our model: one from the low-cost high-volume precursor (PAN-MA) investigated by ORNL [5], and the other from process improvements reported by Kline [6] and confirmed by discussions with oxidation plant suppliers. Applying these two savings to our cost model reduces the processing cost by $6/kg (or 6/25 = 24%). The projected price at high volume is 76% of the low-volume T700S price (or $26/kg x 76% = $20/kg) as shown at the right in Figure 2.

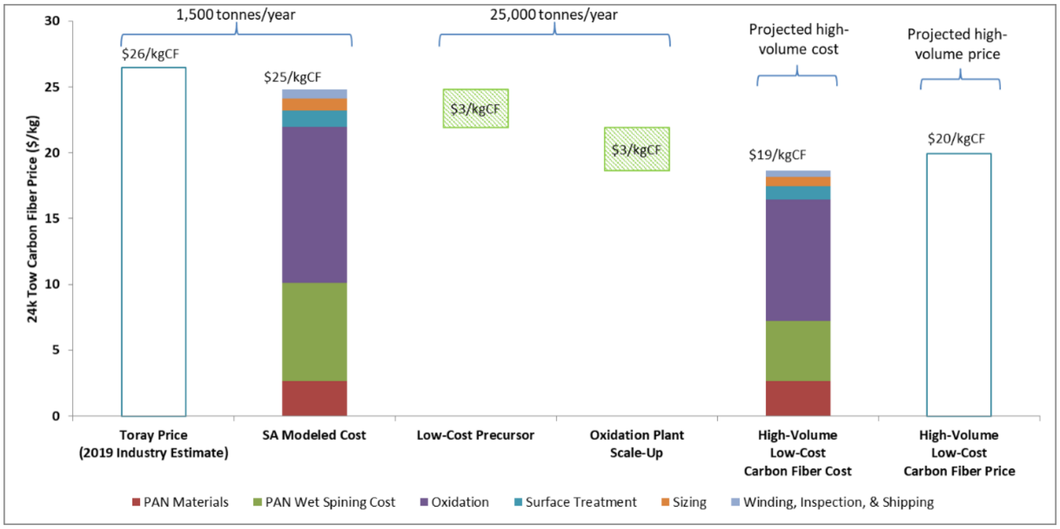

Figure 2. Comparison of current T700S *prices* with projected high-volume carbon fiber (CF) *prices*. The ratio of modeled carbon fiber *cost* at low (1,500 tonnes per year) and high (25,000 tonnes per year) volume are used to scale the quoted low-volume T700S to a projected high-volume carbon fiber *price* assuming processing *cost* savings from the low-cost precursor and oxidation plant are realized. PAN – polyacrylonitrile

700-bar Type 4 LDV Analysis

Compressed gas storage, while falling short of the DOE gravimetric and volumetric storage targets, is becoming the standard in light-duty applications. Fueling infrastructure to support 350-bar and 700-bar compressed gas storage is emerging in parts of the United States (particularly California as a result of Assembly Bill 8 [7]), Europe, and Japan. Meanwhile, Nikola and Nel have partnered to build fueling infrastructure to support fuel cell electric long-haul trucking in the United States.

In this analysis year, an update of the 700-bar Type 4 light-duty vehicle storage model was completed. Major changes documented in the program record include:

- Replaced stainless steel balance of plant components with aluminum.
- Reduced storage vessel carbon fiber composite mass by employing a hoop-intensive winding pattern proposed by Yamashita [8] and modeled by Hua et al. [9].
- Adjusted model to:
  - Reduce the in-tank gas temperature assumption from 20°C to 15°C consistent with J2601 [10].
  - Reduce the assumed minimum pressure differential between regulator inlet and outlet pressure from 15 bar to 10 bar. The updated regulator inlet pressure is 15 bar (P_{FC} = 5 bar, DP = 10 bar) compared with the previous assumption of 20 bar at the regulator inlet (P_{FC} = 5 bar, DP = 15 bar).
  - Inflate the modeled material (except for carbon fiber as described in detail below) and capital equipment costs from 2007$ to 2016$ for consistency with and comparison to other FCTO cost analyses.

- Reflect updates to carbon fiber price assumptions described above.
- Reflect price quotes for balance of plant components with equivalent functionality at low volume.

Figure 3 summarizes the changes to the system at an annual rate of production of 500,000. The basis year was updated from 2007$ to 2016$ this year to provide a consistent basis for comparison with other program offices. Materials and equipment were adjusted where appropriate using the Producer Price Index: Finished Goods [11]. The inflation factor between 2007 and 2016 is ~20%, and with the exception of the composite materials, all other inputs (material, purchased components, labor, electricity, and equipment) were inflated to 2016$. Based on feedback from tank manufacturers and original equipment manufacturers, the stainless-steel valve and regulator bodies were replaced with aluminum, leading to lower material and manufacturing costs. Changes to the gas temperature assumption, regulator performance, and the hoop intensive winding pattern discussed above led to lighter and lower cost tanks. Finally, carbon fiber prices were updated based on feedback from tank manufacturers.

The carbon fiber price is based on a projected market price of carbon fiber manufactured using low-cost high-volume precursors [5] and a high-volume oxidation plant [12]. Savings from the low-cost precursor and oxidation plant scale up are applied to the current market price of T700S as a percent reduction. The baseline T700S market price was reported confidentially to Strategic Analysis by tank manufacturers and original equipment manufacturers. In 2019, the cost of T700S is ~9% lower than in 2010 at all purchase quantities. Figure 3 shows the impact on system cost of the updated carbon fiber price broken down by the high-volume, low-cost precursor and for the oxidation plant scale-up when these savings are applied to the updated T700S price. Figure 4 shows a comparison of storage system cost statuses in each of the years it has been reported. Costs are reported in both 2007$ and 2016$. This comparison highlights the steady progress made toward reducing the cost of 700-bar compressed hydrogen storage.

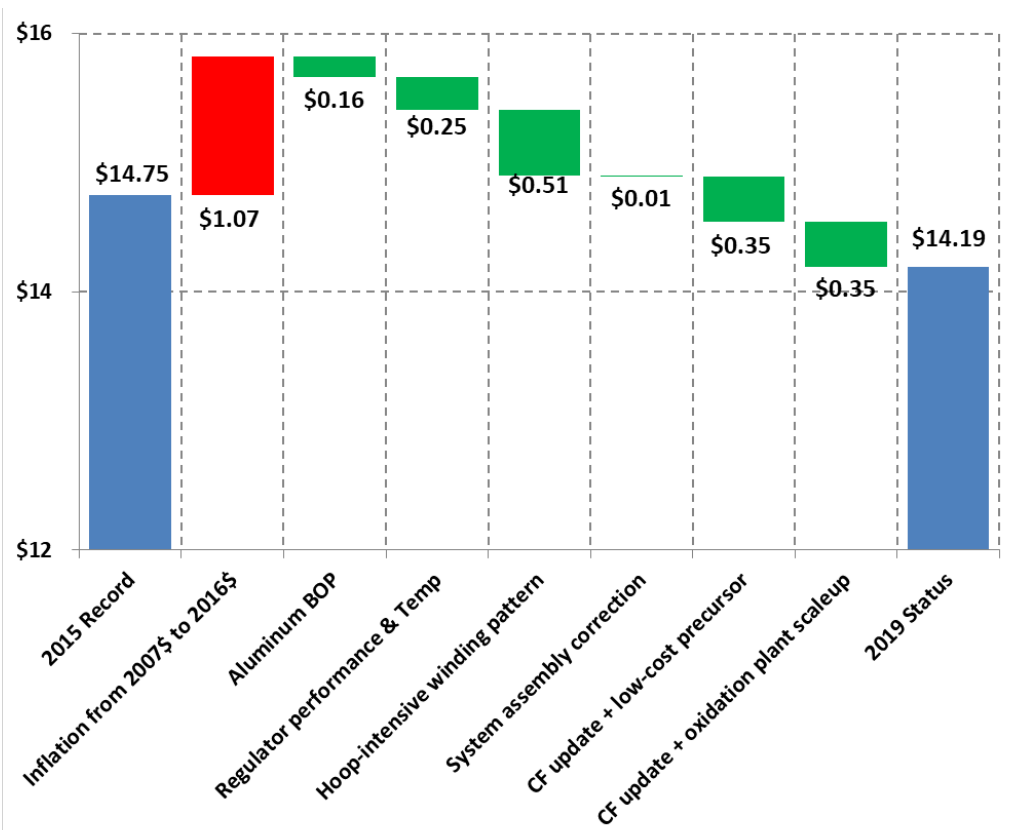

Figure 3. Summary of changes to the high-volume manufacturing (500,000 units/year) system cost from 2015 to the present update

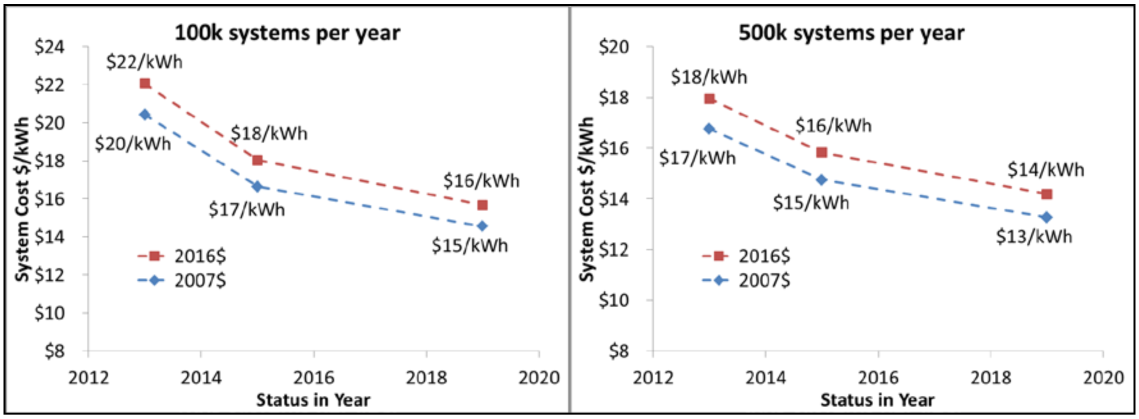

Figure 4. Comparison of storage system cost status in 2007$ and 2016$ as reported in 2013 [13], 2015 [14], and in 2019. Costs are for annual productions of 100,000 units (left) and 500,000 units (right).

CONCLUSIONS AND UPCOMING ACTIVITIES

In FY 2019, we conducted a multi-parameter analysis of hydrogen storage for MDV and HDV applications. In FY 2020, the full cost results will be presented after the assumptions have been reviewed by industry partners. An update to the 700-bar Type 4 LDV analysis has been documented in a DOE program record that is currently under review. There are no major revisions planned for the 700-bar system. Additional topics selected for analysis in FY 2020 include bulk low-pressure storage at refueling stations (both gaseous and liquid hydrogen storage) and on-board storage for rail applications.

FY 2019 PUBLICATIONS/PRESENTATIONS

1. B.D. James and C. Houchins, “Hydrogen Storage Cost Analysis,” presented to the Hydrogen Storage Tech Team, Southfield, MI, January 17, 2019.
2. C. Houchins and B.D. James, “Hydrogen Storage Cost Analysis,” 2019 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Arlington, VA, May 1, 2019.
3. C. Houchins, B.D. James, D. DeSantis, J. Huya-Kouadio, and B. Murphy, “Cost Analyses for the Fuel Cell Technologies Office,” presented to the DOE Hydrogen and Fuel Cells Working Group, Washington, DC, May 24, 2019.
4. J. Adams, C. Houchins, and R. Ahluwalia, “Onboard Type IV Compressed Hydrogen Storage System—Cost and Performance Status,” DOE Hydrogen and Fuel Cell Program Record, submitted.
5. C. Houchins and B.D. James, “Hydrogen Storage Cost Analysis: Summary of FY 2019 Activities,” report submitted to DOE.

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12. Kline and Company, *Cost Assessment of Lignin and PAN Based Precursor for Low-Cost Carbon Fiber: A discussion with Automotive Composites Consortium, Intelligent Insights (TM)* (2007).

13. S. McWhorter and G. Ordaz, "Onboard Type IV Compressed Hydrogen Storage Systems—Current Performance and Cost" (2013), http://hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf.

14. G. Ordaz, C. Houchins, and T. Hua, "Onboard Type IV Compressed Hydrogen Storage Systems-Cost and Performance Status 2015" (2015), https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf.