DOE Hydrogen and Fuel Cells Program Record	
Record #: 19008	**Date: 11/25/2019**
Title: Onboard Type IV Compressed Hydrogen Storage System - Cost and Performance Status	
Update to: Record 15013	
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Item

The projected cost, gravimetric capacity, and volumetric capacity of 700 bar Type IV compressed hydrogen storage system for light duty automotive applications have been updated to reflect the current status as follows:

- System Cost:
    - $14.2/kWh [-$0.5/kWh, +$1.5/kWh] (2016$) when manufactured at 500,000 systems per year
    - $15.7/kWh [-$0.6/kWh, +$1.5/kWh] (2016$) when manufactured at 100,000 systems per year
    - $21.3/kWh [-$0.9/kWh, +$1.8/kWh] (2016$) when manufactured at 10,000 systems per year
    - The projected cost of a 700 bar Type IV compressed hydrogen system has been reduced by ~30% since 2013 from $22.1/kWh to $15.7/kWh (at 100,000 systems per year), due primarily to the development of lower cost carbon fiber and resin, along with integrated balance of plant components.
- Gravimetric Energy Density: 1.48±0.04 kWh/kg system
- Volumetric Energy Density: 0.83±0.01 kWh/L system

Summary

This record summarizes the current status of the projected hydrogen storage capacity and manufacturing costs of 700 bar Type IV compressed hydrogen storage systems for onboard light-duty automotive applications based on a single-tank configuration storing 5.6 kg of usable hydrogen (H_2). The current projected performance and cost of these systems are presented in Table 1 compared with the DOE Hydrogen Storage System targets (1). Analyses were performed in support of the Hydrogen Fuel R&D Program of the DOE Hydrogen and Fuel Cells Program within the Office of Energy Efficiency and Renewable Energy. For reference to previous records, system costs are reported in both 2007$ and 2016$.

Table 1: Projected cost and performance of 700 bar Type IV compressed hydrogen storage systems compared to Department of Energy technical targets.

	Units	2025 Target (1)	Ultimate Target (1)	2013 Status (2)	2015 Status (3)	2019 Status
Gravimetric Capacity[a]	kWh/kg system	1.8	2.2	1.5	1.40±0.04	1.48±0.04
Volumetric Capacity[a]	kWh/L system	1.3	1.7	0.8	0.81±0.01	0.83±0.01
Cost at 500,000 units/year[b]	2016$/kWh	10	8	18.0 [-0.8, +3.2]	15.8 [-0.9, +1.8]	14.2 [-0.5,+1.5]
	2007$/kWh	10	8	16.8 [-0.8,+3.3]	14.8 [-0.8, +1.7]	13.3 [-0.5,+1.4]
Cost at 100,000 units/year[b,c,d]	2016$/kWh	--	--	22.1	18.0 [-0.9, 1.8]	15.7 [-0.6,+1.5]
	2007$/kWh	--	--	20.4	16.6 [-0.8, +1.7]	14.6 [-0.6,+1.4]

[a] Uncertainty in capacity represents the 90% confidence interval and is described in ref (3).

[b] Uncertainty in cost represents the 90% confidence interval.

[c] Uncertainty was not reported for 100,000 units/year in 2013.

[d] An inflation factor is applied to capital equipment and materials, but is not applied to the carbon fiber as carbon fiber nominal year price has largely been constant.

Accomplishments and Rationale

Argonne National Lab (ANL) and Strategic Analysis, Inc. (SA) conducted analyses to project system performance using finite element analysis and costs using Design for Manufacture and Assembly (DFMA) for 700 bar Type IV compressed hydrogen storage systems based on technology and tank manufacturing improvements. Type IV refers to pressure vessels with a polymer liner wrapped completely with a composite of fiber and resin. This update reflects the following changes in materials and tank design assumptions compared to the 2015 DOE Record design (3):

- Replaced stainless steel balance of plant (BOP) components with aluminum.
- Reduced storage vessel carbon fiber composite mass by employing a hoop-intensive winding pattern proposed by Yamashita (4) and modeled by Hua et al. (5).
- Adjusted model to:
  - Reduce the in-tank gas temperature assumption from 20°C to 15°C consistent with J2601 and typical -40°C precooling requirements (6).
  - 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, $\Delta P = 10$ bar) compared with the previous assumption of 20 bar at the regulator inlet ($P_{FC} = 5$ bar, $\Delta P = 15$ 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 DOE cost analyses.
  - Reflect updates to carbon fiber price assumptions (i.e., current cost of T700S is ~9% lower than in 2010).

Analysis results were initially presented by ANL and SA at the 2018 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Review Evaluation meeting (7,8). All system capacities are reported as net usable H_2 capacity (5.6 kg) able to be delivered to the fuel cell.

System Assumptions

The storage system includes the interface with the station fueling dispenser (receptacle and communication hardware for refueling), the storage vessel itself, and BOP components. The BOP includes safety devices, regulators, electronic controllers and sensors, all onboard conditioning equipment necessary to store H_2 (e.g. filters), as well as mounting hardware and gas lines to connect the storage system components. Figure 1 shows a schematic of the system diagram used in performance and cost analyses and a summary of system design assumptions is provided in Table 2. The system schematic remains unchanged from 2015.

System Performance

A brief description of the relevant performance analysis methods and findings reported by Hua (5) are summarized below. Finite element analysis based on the ABAQUS software package was used to predict composite mass for several different filament winding strategies and choices of composite materials. The modeled strain-to-failure dependence on internal pressure and total composite mass were calibrated to experimental burst test results for a 35 L test vessel using a conventional winding pattern of alternating hoop and helical layers (9). The validated model geometry was extended to the baseline 147 L system to predict the composite mass, which forms the basis for the 2015 baseline system parameters. Agreement between the sub-scale model and test vessel composite masses were within 1%. Carbon fiber mass was then extrapolated using a regression model for the 147 L pressure vessel, which is estimated to be within 2% of the actual tank mass. Additionally, ANL extended their finite element analysis models to address innovations inspired by Yamashita compared with the 2015 baseline system:

1. Sharp discontinuity at the cylinder/dome interface,
2. Hoop-intensive winding pattern that concentrates hoop windings in the interior layers rather than alternating hoop and helical windings through the entire thickness.

In the 2013 baseline system, prefabricated composite caps (doilies) were used for local dome and cylinder-to-dome interface reinforcement. The doily approach to reinforcing the dome and cylinder-to-dome interface was an efficient method of reducing high angle helically wound filaments in the cylinder region, but suffered from concerns about manufacturability in high-rate production environments. Due to these concerns, the doily approach was dropped from the 2015 baseline system. However, the hoop intensive winding pattern achieves a similar result (reduced high angle helical windings) using filament winding methods that are repeatable in high-rate production.

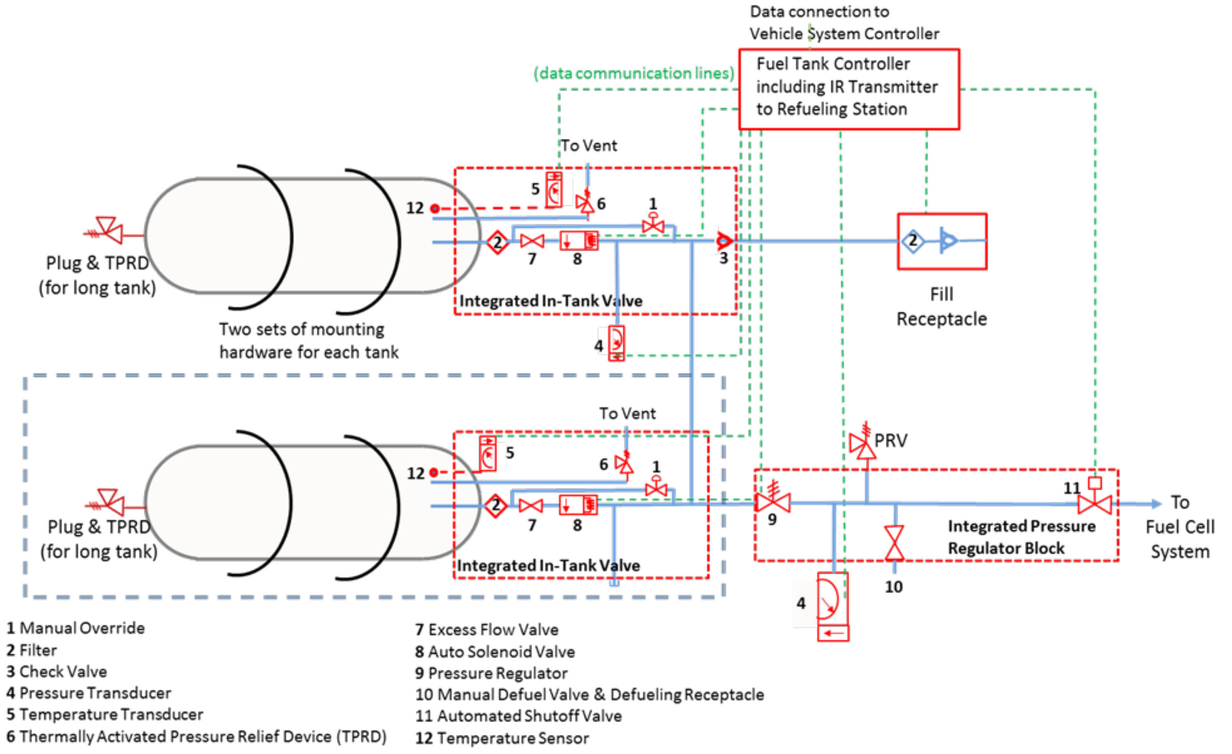


Figure 1: System diagram showing the one- and two-tank configurations used in the cost and performance models. Components in the gray dashed box indicate additional components included in multi-tank systems. For example, two and three tank systems have one or two sets of additional components, respectively.

The storage system analysis is based on Toray T700S carbon fiber material properties for yield and tensile strength. Yamashita reported a higher strength carbon fiber interpreted by Hua to be Toray T720. While higher strength carbon fiber is expected to reduce the total tank mass, there is scant information on the price of T720. Yamashita notes that, “with the cooperation of carbon fiber manufacturers, the properties of general purpose carbon fiber were improved” (4). Estimates based on informal discussions with industry experts suggest T720 can be as much as 40% more expensive than T700S, which, if accurate, would eliminate the savings due to carbon fiber mass reductions. Until T720 or another comparable strength fiber becomes commercially available and reliable high-volume prices become available, it will be difficult to say with confidence what the material cost and performance tradeoffs are between T720 and T700S. Consequently, the baseline will continue to be calibrated to T700S price and properties.

Table 2: System design assumptions

Parameter	Units	Value	Notes
Tank type		IV	Type IV tanks utilize polymer liners
Tank interior diameter	cm	39.6	
Tank interior length	cm	118.9	
Usable H_2	kg	5.6	
Total H_2 stored mass	kg	5.8	
Nominal working pressure	bar	700	
Minimum empty pressure	bar	15	
Hydrogen temperature	°C	15	
Liner material		HDPE	HDPE = High density polyethylene
Liner thickness	cm	0.5	
Carbon fiber precursor		PAN-MA	Low-cost, high-volume precursor (10)
Carbon fiber		ORNL fiber	Fiber developed with DOE support (10)
CF tensile strength	MPa	4900.0	Based on Toray T700S performance (11)
Fiber density	g/cc	1.8	
Resin		Vinyl Ester	Low-cost alternative resin (12)
Resin density	g/cc	1.138	
Fiber volume fraction		64.7%	For vinyl ester.
Translation efficiency		72% hoop / 85% helical	ANL model assumptions (5)
Composite strength	MPa	2295	ANL model calculation (5)
Design safety factor		2.25	
Manufacturing COV		3.3%	COV = coefficient of variation
Fiber COV		3.3%	
Manufacturing overdesign		14%	$3\sigma = 3\sqrt{COV_{Manufacturing}^2 + COV_{Fiber}^2}$
Effective safety factor		2.57	Includes 3σ manufacturing overdesign

Other changes to the model assumptions include reducing the minimum empty pressure and reducing the temperature at which the gas density is calculated. Hua notes that the empty pressure depends on the design of the pressure regulator, which is required to deliver 5 bar to the fuel cell per DOE targets. Analysis of one and two stage regulators suggests two stage regulators can be as much as 50% higher cost, which may not be justified to maintain full flow at near-empty tank conditions (8). Based on recent improvements in regulator performance, the minimum tank empty pressure assumption was reduced from 20 bar to 15 bar for a single stage regulator (4,13,14). This was deemed consistent with current regulator designs based on discussions with automotive industry experts. The gas temperature was reduced from 20°C to 15°C based on guidance in J2601 fueling protocols, increasing the gas density (6). Changes in the gas temperature and empty pressure assumption led to an overall smaller and less expensive tank.

Table 3: Composite mass breakdown for 147 L 700 bar Type IV tanks

	Doilies	Weight (kg)			
		Hoop	Helical	Doilies	Total
2013 Baseline (2)	Yes	40.2	48.0	2.8	91.0
2015 Baseline (3)	No	30.3	66.7	N/A	97.0
2019 Baseline: Hoop-intensive winding	No	32.6	58.2	N/A	90.3

System Cost

SA analyzed the manufacturing cost of 700 bar compressed hydrogen storage using DFMA cost methodology to project the high-volume manufacturing cost. DFMA is a process-based cost analysis methodology which projects material and manufacturing costs of the complete system by summing the costs of each manufacturing step. The cost analysis results reported are the costs to manufacture storage systems, not the price. The system cost results do not include mark-up for profit, one-time costs such as non-recurring engineering costs, and general expenses; however, some components (e.g. valves, gas lines, etc.) are purchased by the system fabricator and include vendor markup.

Figure 2 summarizes the changes to the system cost since the 2015 record for system cost 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 (PPIFG) (15). 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 OEMs, 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 (10) and a high-volume oxidation plant (16). 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 to Strategic Analysis by tank manufacturers and OEMs. In 2019, the cost of T700S is ~9% lower than in 2010 at all purchase quantities. Figure 2 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 3 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 towards reducing 700 bar compressed hydrogen storage. Cost breakdowns for varying production rates considered are shown in Figure 4.

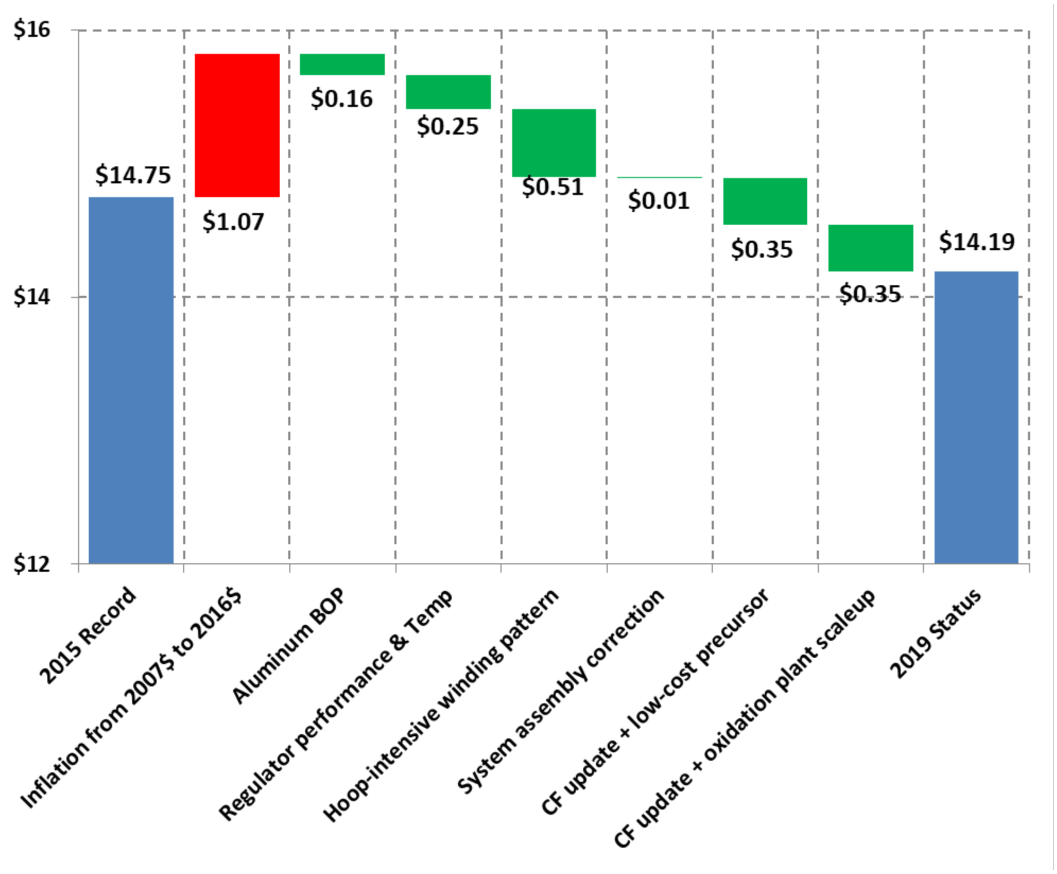


Figure 2: Summary of changes to the high-volume manufacturing (500,000 units/year) system cost from 2015 to the present update.

Uncertainty Analysis

Uncertainty analysis was conducted using a Monte Carlo sampling algorithm. The uncertainty analysis parameters can be found in the Supplemental Information section. Parameter ranges are similar to those assumed in previous years. The uncertainty analysis generates a random parameter value defined by a triangular probability distribution function (PDF) with limits defined in the parameter table for each parameter. The PDF midpoint is the nominal value for the system cost shown in Table 1. The low and high points are informed by discussions with industry experts where available and an assumption of ±25% otherwise. The system cost at that randomly generated point is recorded, and the resulting costs represent the range of possible system costs for the set of assumed parameters. The uncertainties in the system cost are reported in Table 1 represent the 90% confidence interval. Histograms showing the predicted cost distributions at 100,000 and 500,000 systems per year are shown in Figure 5.

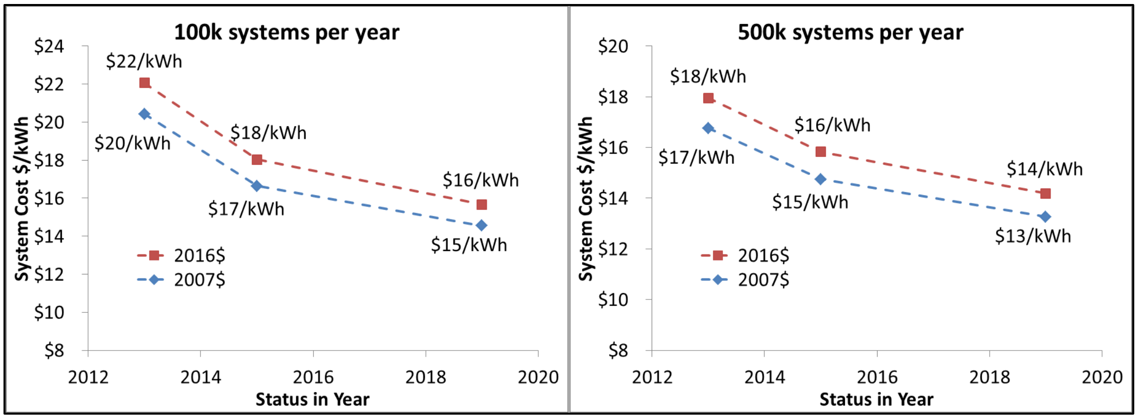


Figure 3: Comparison of storage system cost status in 2007$ and 2016$ as reported in 2013(2), 2015(3), and in 2019. Costs are for annual productions of 100,000 units (left) and 500,000 units (right).

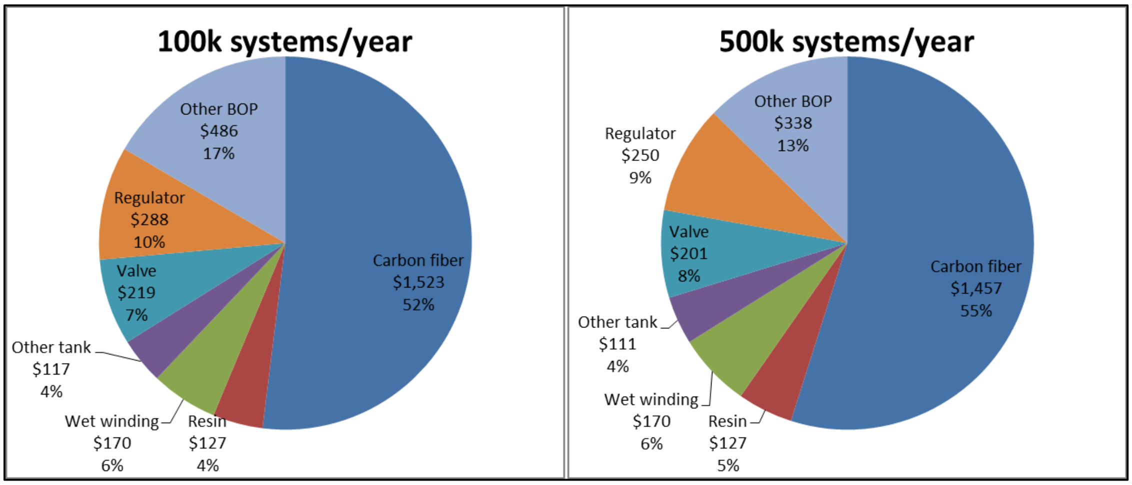


Figure 4: Storage system cost breakdown by percentage of the total cost (annual production of 100,000 units shown on left and 500,000 units shown on right).

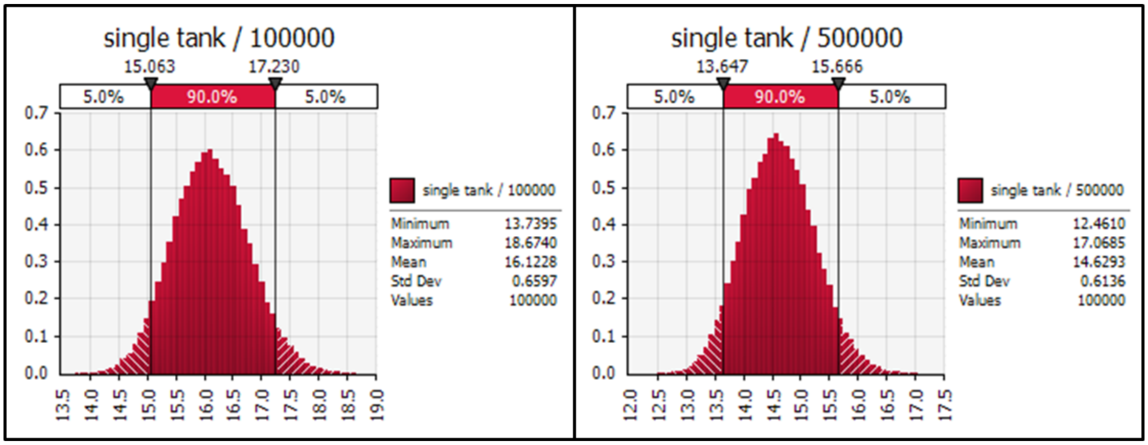


Figure 5: Monte Carlo error analysis histogram results for single-tank configuration system costs in $/kWh are shown at 100,000 and 500,000 systems per year.

Multi-Tank Configurations

Fuel cell vehicles with compressed hydrogen storage currently on the road employ multi-tank configurations to meet packaging requirements. For instance, the Toyota Mirai has two tanks of different sizes with a combined total onboard hydrogen storage capacity of 5 kg while the Hyundai Nexo has a three-tank configuration. Hua and co-workers (5) analyzed two-tank configurations analogous to the Toyota Mirai. The front tank of the Mirai, which sits beneath the rear passenger seat has an aspect ratio (L/D) of 2.8 while the rear tank, which sits behind the rear passenger seat, has an aspect ratio of 1.7. Hua found that the mass savings from the hoop intensive winding pattern depends on this aspect ratio. While the hoop intensive winding pattern yields a 7% mass reduction for the high aspect ratio tank, there was a modest mass increase of 0.7% for the low aspect ratio tank.

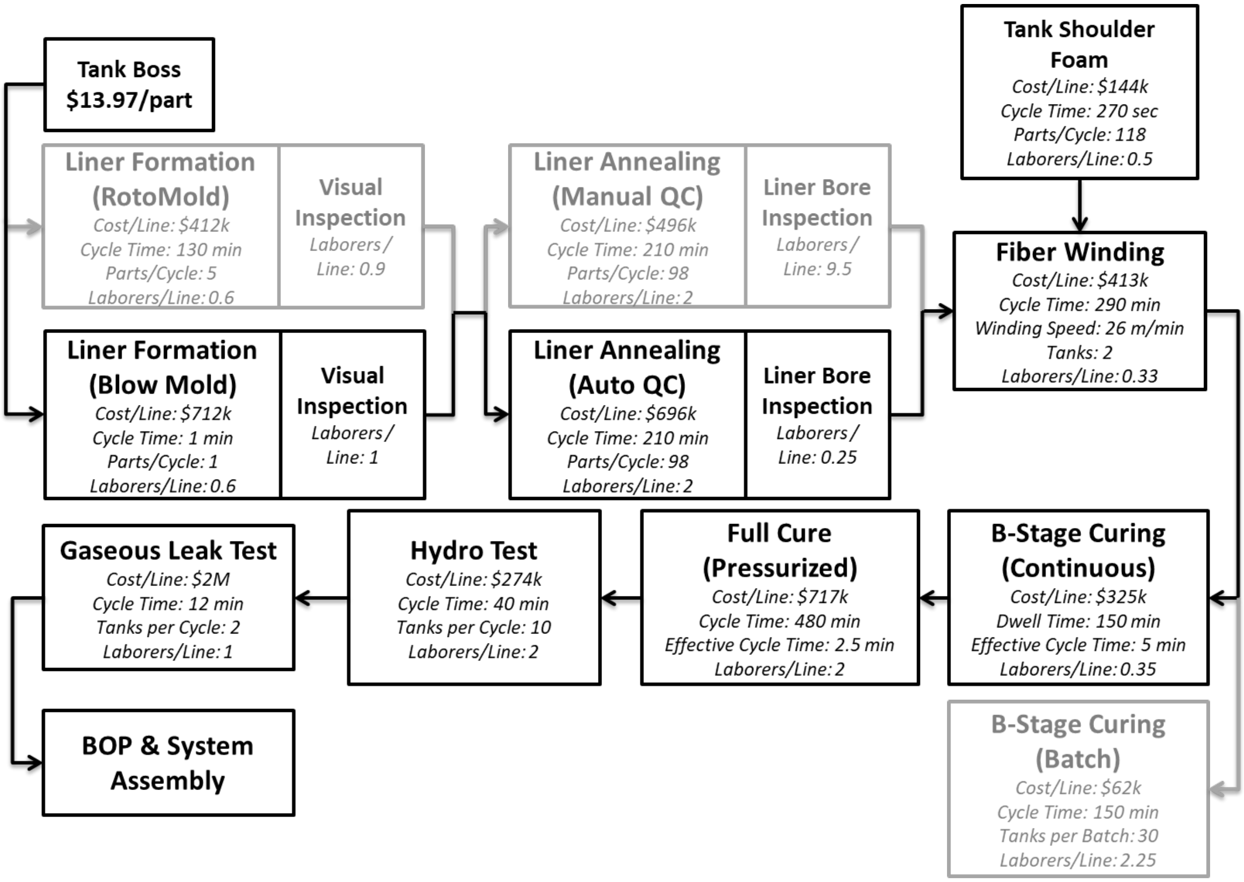
The two-tank configuration system schematic is shown in Figure 1. The main difference in system cost is due to a second set of in-tank valves required for the two-tank configurations. Consequently, two-tank configurations are more expensive than single-tank storage systems. Table 4 shows a comparison of tank configurations. The mixed tank geometry demonstrated by Toyota is assumed for the mixed aspect ratio two-tank configuration, but it is worth noting that packaging considerations are specific to the automaker and some may choose to prioritize lower cost storage over cabin and rear trunk storage.

Table 4: Comparison of tank configurations storing 5.6 kg usable H_2 showing cost impact of mixed vs. identical aspect ratio two-tank configurations

Configuration	Tank 1 composite mass	Tank 2 composite mass	System cost at 100k/per year	System cost at 500k/per year
Single-Tank	90.3 kg (L/D = 3)	--	\$15.7/kWh	\$14.2/kWh
Two-Tank (identical aspect ratio)	45.15 kg (L/D = 2.8)	45.15 kg (L/D = 2.8)	\$20.0/kWh	\$17.9/kWh
Two-Tank (mixed aspect ratio)	45.0 kg (L/D = 2.8)	48.8 kg (L/D = 1.7)	\$18.5/kWh	\$16.4/kWh

Supplemental Information

Additional details are provided in this supplemental section.



Supplemental Figure 1: Manufacturing process flow assumptions. Black text and boxes indicate high volume optimized steps.

Supplemental Table 1: Global cost model assumptions (2016$)

Item	Unit	Value
Labor rate	$/hr	51
Electric Utility price	$/kWh	0.09
Runtime per day	hours/day	14
Workdays per year	days/year	240
Possible annual run time	hours/year	3,360
Corporate income tax rate	%	40
Installation multiplier	% of capital cost	140
Maintenance and spare parts	% of capital cost/year	10
Miscellaneous expenses	% of capital cost/year	7
Default machine lifetime	years	15

Supplemental Table 2: Carbon fiber price inputs (2016$)

Annual tank production (tanks/year)	Annual CF demand (tonnes CF/year)	T700S price ($/kg CF)	PAN-MA CF price ($/kg CF)
30,000	2,100	30	24
50,000	3,500	30	24
80,000	5,600	29	23
100,000	7,000	27	22
500,000	35,000	26	21

Supplemental Table 3: Equipment and material cost assumptions compared in 2007$ and 2016$

	Units	2007$	2016$	Inflation Impact on System Cost, $/kWh
Capital Equipment (Station cost)				
Blow Molding	$/Process Line	$591,940	$711,732	$0.00
Annealing Oven	$/Process Line	$329,435	$396,103	$0.01
Wet Winding	$/Process Line	$343,154	$412,598	$0.15
Beta Curing Oven	$/Process Line	$321,559	$386,633	$0.00
Full Curing Oven	$/Process Line	$639,360	$768,748	$0.01
Hydro Test Station	$/Process Line	$227,545	$273,593	$0.01
Helium Fill & Leak Test Station	$/Process Line	$1,673,747	$2,012,465	$0.02
Injection Molding Shoulder Foam	$/Process Line	$120,000	$144,284	$0.00
Materials & Purchased Components				
Resin	$/kg	$4.35	$4.35	$0.00
HDPE	$/kg	$1.77	$2.12	$0.02
Polyurethane Foam	$/kg	$2.50	$3.01	$0.01
Integrated Regulator	$/unit	$209.90	$249.77	$0.21
Integrated In-Tank Valve	$/unit	$167.58	$201.13	$0.18
Check Valves	$/unit	$11.25	$13.50	$0.01
Fuel System Controller	$/unit	$76.25	$91.68	$0.08
Piping/Fittings for first tank	$/system	$51.06	$61.40	$0.06
Plug and TPRD	$/system	$27.59	$33.17	$0.03
Fill Receptacle (incl. IR Transmitter)	$/unit	$39.68	$47.36	$0.04
Mounting Frame	$/system	$8.97	$10.78	$0.01
Miscellaneous	$/system	$59.23	$70.81	$0.06
Bosses	$/system	$24.35	$29.22	$0.02

Supplemental Table 4: Single-tank storage system cost breakdown at multiple annual rates of production. Costs are reported in 2016$

	Units/year	**10,000**	**30,000**	**80,000**	**100,000**	**500,000**
Tank boss	$/tank	$39	$32	$29	$28	$28
Liner blowmold	$/tank	$62	$34	$25	$24	$22
Liner anneal	$/tank	$44	$14	$8	$10	$8
Carbon fiber	$/tank	$1,655	$1,655	$1,589	$1,523	$1,457
Resin	$/tank	$127	$127	$127	$127	$127
Wet winding	$/tank	$184	$172	$171	$170	$170
Beta cure	$/tank	$20	$6	$5	$6	$5
Full cure	$/tank	$77	$15	$8	$11	$9
Hydro test	$/tank	$18	$11	$10	$9	$9
He fill & leak test	$/tank	$63	$25	$21	$18	$18
Integrated in-tank valve	$/system	$295	$262	$223	$219	$201
Integrated regulator	$/system	$425	$347	$302	$288	$250
Other BOP	$/system	$952	$675	$516	$486	$338
Assembly	$/system	$13	$12	$11	$11	$11
Total	**$/system**	**$3,974**	**$3,387**	**$3,045**	**$2,931**	**$2,653**
Total	**$/kWh**	**$21.25**	**$18.11**	**$16.29**	**$15.67**	**$14.19**

Supplemental Table 5: Component mass and volume breakdown

Component	**Mass (kg)**	**Volume (L)**
Stored H_2 (total/usable)	5.8/5.6	147
Composite (Fiber + Resin)	90.3 (67.1 + 23.2)	57.7 (37.3 + 20.4)
Tank boss	0.9	2.43
HDPE liner	8.0	8.4
Integrated in-tank valve	3.0	2.1
Integrated regulator	3.6	1.5
Other BOP	15.4	9.1
Total	126.1	225.6
Capacities (based on usable H_2)	1.48 kWh/kg	0.83 kWh/L

Supplemental Table 6: Parameters used in Monte Carlo analysis

	Unit	Min	Mid	High
Equipment				
Blow Molder	Multiplier	0.75	1	1.25
Annealing Oven	Multiplier	0.75	1	1.25
Wet Winding Station	Multiplier	0.8	1	1.75
Beta Curing Oven	Multiplier	0.75	1	1.25
Full Curing Oven	Multiplier	0.75	1	1.25
Hydro Test Station	Multiplier	0.75	1	1.25
Helium Fill & Leak Test Station	Multiplier	0.75	1	1.25
Injection Molding Shoulder Foam	Multiplier	0.75	1	1.25
Process				
Blow Molding Total Cycle Time Factor	Multiplier	0.5	1	2
B-Stage Dwell Time	hours	2	2.5	3
Full Cure Dwell Time	hours	4	8	12
Average Fiber Laydown Rate	m/min	18	26	31
Materials				
Carbon Fiber Mass	Multiplier	0.9	1	1.1
Liner HDPE Base Price	Multiplier	0.75	1	1.5
Carbon Fiber Base Price	Multiplier	0.9	1	1.1
BOP Cost Factor	Multiplier	0.75	1	1.25
Resin Cost	Multiplier	0.5	1	2
Foam Dome Protection Material Cost	Multiplier	0.5	1	2

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