DOE Hydrogen Program Record	
Record #: 24006	Date: April 28, 2025
Title: Onboard Type IV Compressed Hydrogen Storage System - Cost and Performance Status	
Update to: Record 19008	
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Item

The projected cost, gravimetric capacity, and volumetric capacity of 700 bar Type IV compressed hydrogen storage systems for light-duty automotive applications[1] have been updated to reflect the results of carbon fiber cost reduction efforts initiated in 2021, led by the Hexagon Agility [1] project team, and are as follows:

- System Cost (in 2020$) for a complete 700 bar system holding 5.6 kg of usable hydrogen
  - The system cost ranges from $12.1/kWh to $13.3/kWh (2020$) when manufactured at 100,000 units per year. The median system cost is $12.7 ± 0.6/kWh.
  - The projected cost of a 700 bar Type IV compressed hydrogen system has been reduced by ~25% since 2019, from $16.9/kWh to $12.7/kWh, due primarily to the development of lower-cost carbon fiber and updated storage tank designs using the new lower-cost fiber, while maintaining the 2019 Program Record integrated balance of plant components. This also represents a ~47% reduction in system cost from the 2013 Program Record [2], when reported in 2020$.
  - Carbon fiber composite contribution costs to the storage system were $10.7/kWh for 2019 [2] and $6.97 ± 0.63/kWh for 2023 [1], indicating a ~35% reduction in composite costs with lower fiber price and optimized tank design.
- Gravimetric Energy Density: 1.71 kWh/kg system, demonstrating approximately 16% increase since 2019, due to improvements in pressure vessel design and efficiency in carbon fiber use.
- Volumetric Energy Density: 0.86 kWh/L.

Summary

This record summarizes the 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

[1] While DOE's focus is currently on heavy and medium duty (HMD) transportation applications, this Record updates previous assessments focused on light-duty automotive applications. These advances are also applicable to HMD applications.

Storage System targets [2]. Analyses were performed in support of the Hydrogen Infrastructure Technologies RD&D Program of the DOE Hydrogen and Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy. For reference to the previous record, system costs are reported in 2016$ and 2020$.

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 [2]	Ultimate Target [2]	2013 Status [2]	2015 Status [3]	2019 Status [2]	2023 Status
Gravimetric Capacity	kWh/kg system	1.8	2.2	1.5	1.40	1.48	1.71
Volumetric Capacity	kWh/L system	1.3	1.7	0.8	0.81	0.83	0.86
Cost at 100,000 units/year[a]	2020$/kWh	9	8	23.8	19.4	16.9	12.7
	2016$/kWh	9	8	22.1	18.0	15.7	11.8

[a] An inflation factor of 1.075 relative to 2016$ was applied for 2020$.

Accomplishments and Rationale

Previous analyses by Argonne National Laboratory (ANL) and Strategic Analysis, Inc. (SA) projected system performance using finite element analysis and system costs using the Design for Manufacture and Assembly® (DFMA®) costing methodology for 700 bar Type IV[2] compressed hydrogen storage systems based on state-of-the-art technology designs and tank manufacturing projections. This update uses the balance of plant (BOP) components for the systems found in the 2015 and 2019 DOE Program Records [2] and continues to compare the improvements in materials and design to demonstrate continued cost reductions.

The analysis by ANL and SA was previously presented at the 2018 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting [4,5]. All system capacities are reported as net usable H_2 capacity (5.6 kg) able to be delivered to the fuel cell.

At the DOE Hydrogen Program 2024 Annual Merit Review and Peer Evaluation Meeting, Hexagon Agility presented the results of their carbon fiber cost reduction project performed in collaboration with partners Cytec Engineered Materials (CEM), Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Kenworth Truck [1]. These results met or exceeded the target goals for the first phase of their carbon fiber development project. Significant accomplishments are noted below:

- Finished carbon fiber was produced from oxidized polyacrylonitrile (PAN) fiber, with target oxidation densities, at 2x normal oxidation line speeds and 1.5x normal conversion line speeds.
- The converted fiber yielded a 24k carbon fiber tow with tensile strength > 725 ksi and tensile modulus > 35 Msi.

[2] Type IV refers to pressure vessels with a polymer liner wrapped completely with a composite of fiber and resin.

- CEM projected carbon fiber price ranges between \$15/kg and \$20/kg and results in a median estimated tank composite cost of \$6.97 $\pm$ 0.63/kWh.[3]
- Performance (burst pressure) of carbon fiber tested on two subscale pressure vessels was on par with baseline carbon fiber performance.
- Projected system cost: \$12.7 $\pm$ 0.58/kWh.
- Gravimetric and volumetric capacity: 1.71 kWh/kg and 0.86 kWh/L.

System Assumptions

This program record focuses on carbon fiber performance and cost reductions and maintains the identical storage system design and BOP components as described in the 2019 Program Record [2]. Key system design assumptions for this single tank system are described in Tables 2 and 3. The system components include the interface with the station fueling dispenser (receptacle and communication hardware for refueling), the storage tank 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 for a single system. As with the 2019 Program Record, the current analysis is based on a single tank system with 5.6 kg usable H_2 capacity and all the system components required for a single tank. Maintenance of most assumptions between the 2019 Record and this record allows for direct assessment of the performance and cost impact of the improved tank design and fiber performance shown in Table 3.

System Performance

The Hexagon Agility-led carbon fiber development project designed the storage vessel cylinder using assumptions and methods consistent with current Hexagon production designs. The design assumes a Type IV vessel consisting of a polymer liner with aluminum end bosses. The internal diameter of the pressure vessel is fixed, and the length is adjusted to accommodate the wet volume of 144.2 L. The design uses the nominal fiber properties provided by CEM. The fiber is combined with a general-purpose epoxy to form the composite. Composite properties are calculated using the fiber and resin properties and a Hexagon in-house micromechanics model. The composite structure is designed with interspersed hoop and helical winding patterns. Composite translation efficiency and manufacturing variation are accounted for in the design, based on historical performance data, and are proprietary to the manufacturers of pressure vessels. Typical proprietary information includes translation efficiency, composite strength, fiber and manufacturing coefficients of variance, which all combine to an overall effective safety factor. The design assumes that polyurethane foam caps are bonded to the exterior of the composite domes for drop/impact protection. For validation, the design was converted to a finite element model using in-house software tools and solved using Ansys engineering simulation software. This process was repeated to optimize the layer sequencing and fiber placement in the domes.

[3] Proprietary exact price of carbon fiber reported directly to DOE.

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 volume	L	144.2	NIST REFPROP [6]
Usable H_2	kg	5.6	Assumed the same net unusable H_2 as the previous study [2]
Total H_2 stored mass	kg	5.8	Tank design set based on this mass
Nominal working pressure	bar	700	
Minimum empty pressure	bar	15	
Hydrogen temperature	°C	15	
Minimum design safety factor		2.25	CSA HGV2 Standard [7]

Table 3: Comparison of carbon fiber composite properties between 2019 and 2023

Parameter	Units	Value		Notes
		2019	**2023**	
Liner material		HDPE	PA	HDPE: High-density polyethylene; PA: Polyamide
Liner thickness	cm	0.5	0.38	
Carbon fiber precursor		PAN-MA	PAN	PAN: Polyacrylonitrile; PAN-MA: Low-cost, high-volume precursor [2]
Carbon fiber source		ORNL	CEM	Fibers developed with DOE support [1,2]
CF tensile strength	MPa	4,900[a]	5,123[b]	[a] Based on Toray T700S performance [8] [b] Based on CEM fiber performance [1]
Fiber density	g/cc	1.8	1.8	
Resin		Vinyl Ester	Epoxy	General purpose epoxy - 2013 Program Record [9]
Resin density	g/cc	1.138	1.25	
Fiber volume fraction	%	64.7	51	
Fiber mass fraction	%	74	60	

System Cost

The system cost analysis focused primarily on the carbon fiber performance and cost. The prior 2019 Program Record [2] analyzed the manufacturing cost of 700 bar compressed hydrogen storage using the DFMA® cost methodology to project high volume manufacturing costs. This updated system cost analysis uses the 2019 Program Record component costs and projects the system cost with the new pressure vessel design, new carbon fiber performance, and high-volume carbon fiber production costs. Figure 1 compares the tank composite mass based on pressure vessel design and carbon fiber performance changes. These masses are used to help develop the cost comparison of fiber performance and the cost effects by mass.

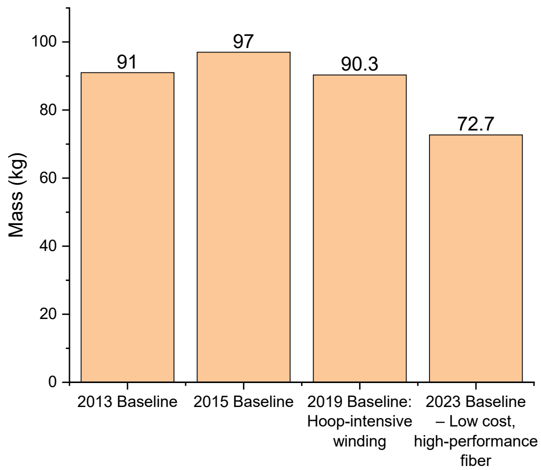

Figure 1: Composite mass breakdown for 144.2 L 700 bar Type IV tanks.

The primary outcome of the analysis is an improvement in gravimetric and volumetric capacity due to improved pressure vessel design and carbon fiber use efficiency. The decrease in composite mass equates to reduced overall composite thickness, thereby lowering overall tank volume. Gravimetric capacity increased by 15% over the previous program record to 1.71 kWh/kg, while the volumetric capacity increased to 0.86 kWh/L. This combination of vessel design and lower-cost high-performance fibers reduces overall material use and system costs.

Figure 2 summarizes the changes to the storage system costs since the 2013 Program Record at an annual production rate of 100,000 units. Basis years of both 2016$ (used in the 2019 Program Record) and 2020$ are used to provide a consistent basis for comparison. Material prices were adjusted where appropriate using the Producer Price Index: All Commodities [10]. The inflation factor between 2016 and 2020 is ~7.5%, and all inputs (carbon fiber composite, material, purchased components, labor, electricity, and equipment) were initially calculated in 2016$. Finally, with the newly developed carbon fiber and their fiber prices in 2016$, the system cost using the Hexagon project's carbon fiber ranges from $11.3 to $12.4/kWh, with a median cost of $11.8/kWh. With the inflation factor applied, this translates to a range of $12.1/kWh to $13.3/kWh and a median of $12.7/kWh in 2020$. This comparison highlights the steady progress made towards reducing the cost of 700 bar compressed hydrogen storage.

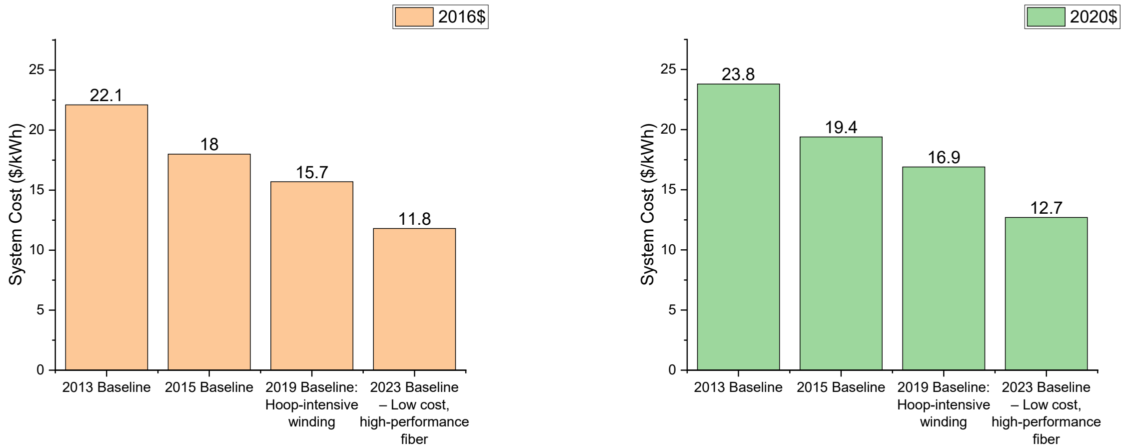

Figure 2: Summary of changes to the high-volume manufacturing (100,000 units/year) system cost from 2013 to the present update. References [2] and [9]. ***Left:*** **System cost in 2016$.** ***Right:*** **System cost in 2020$.**

Figure 3 compares the breakdown of storage system costs between the 2019 Program Record [2] and this current record for an annual production rate of 100,000 units. The impact of the carbon fiber cost on the overall cost of the pressure vessel is reduced by nearly 20%.

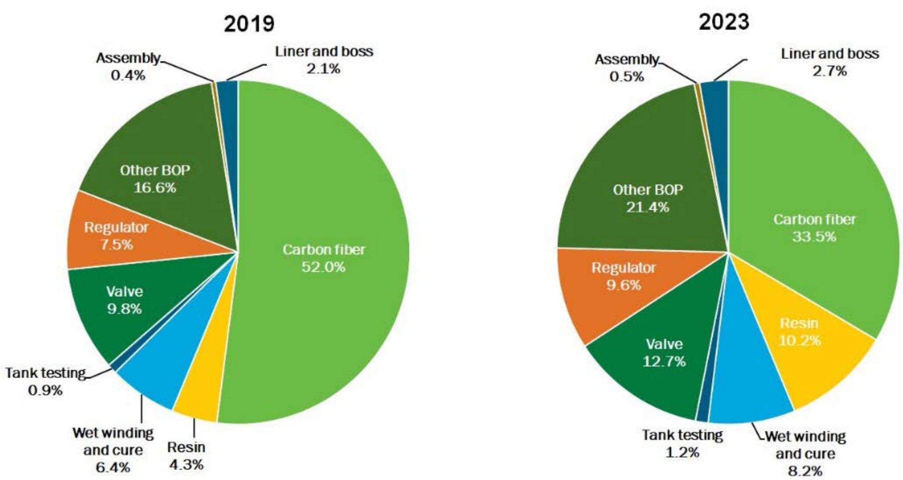

Figure 3: Storage system cost breakdown by percentage of the total cost (annual production rate of 100,000 units). ***Left:*** **2019 Program Record [2].** ***Right:*** **2023, present update.**

Supplemental Information

Additional details are provided in this supplemental section.

Supplemental Table 1: Assumptions used in cost model (in 2016$)

Item	Unit	Value
Labor rate	$/yr	59,000
Electric Utility price	$/kWh	0.0676
Natural Gas price	$/MBTU	2.49
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 Cost	% of capital cost	40
Maintenance and spare parts	% of capital cost/year	10
Miscellaneous expenses	% of capital cost/year	5
Default machine lifetime	years	20

Supplemental Table 2: Single-tank storage system cost breakdown at a production rate of 100,000 units/year. Costs are reported in 2016$.

		2019	2023	
Carbon fiber	***$/kg***	***22***	***Minimum: 15***	***Maximum: 20***
Tank boss	$/tank	28	28	28
Liner blow mold	$/tank	24	24	24
Liner anneal	$/tank	10	10	10
Composite (Fiber + Resin)	$/tank	1,650	825	1028
Wet winding	$/tank	170	170	170
Beta cure	$/tank	6	6	6
Full cure	$/tank	11	11	11
Hydro test	$/tank	9	9	9
He fill & leak test	$/tank	18	18	18
Integrated in-tank valve	$/system	219	219	219
Integrated regulator	$/system	288	288	288
Other BOP[1]	$/system	486	486	486
Assembly	$/system	11	11	11
Total	**$/system**	**2,931**	**2,105**	**2,308**
Total	**$/kWh**	**15.7**	**11.3**	**12.4**

1) other BOP includes safety devices, 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.

Supplemental Table 3: Component mass and volume breakdown

Component	Mass (kg)	Volume (L)
Stored H_2 (total/usable)	5.8/5.6	144.2
Composite (Fiber + Resin)	72.7	48
Tank boss	0.9	2.43
Polyamide (PA) liner	8.0	8.4
BOP	22	12.7
Total	109	215.7
Capacities (based on usable H_2)	1.71 kWh/kg	0.86 kWh/L

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