2020 DOE Hydrogen and Fuel Cells Program Review

Hydrogen Storage Cost Analysis (ST100)

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Overview

Timeline

Project Start Date: 9/30/16
Project End Date: 9/29/21
% complete: ~70% (in year 4 of 5)

Budget

Total Project Budget: $999,946
Total DOE Funds Spent: ~$615,000
(through March 2020 , excluding Labs)

Barriers

A: System Weight and Volume
B: System Cost
K: System Life-Cycle Assessment

Partners

Pacific Northwest National Laboratory (PNNL)
Argonne National Lab (ANL)

Relevance

- **Objective**
  - Conduct rigorous, independent, and transparent, bottoms-up techno-economic analysis of H_2 storage systems.
- **DFMA® Methodology**
  - Process-based, bottoms-up cost analysis methodology which projects material and manufacturing cost of the complete system by modeling specific manufacturing steps.
  - Predicts the actual cost of components or systems based on a hypothesized design and set of manufacturing & assembly steps
  - Determines the lowest cost design and manufacturing processes through repeated application of the DFMA® methodology on multiple design/manufacturing potential pathways.
- **Results and Impact**
  - DFMA® analysis can be used to predict costs based on both mature and nascent components and manufacturing processes depending on what manufacturing processes and materials are hypothesized.
  - Identify the cost impact of material and manufacturing advances and to identify areas of R&D interest.
  - Provide insight into which components are critical to reducing the costs of onboard H_2 storage and to meeting DOE cost targets

Approach: DFMA® methodology used to track annual cost impact of technology advances

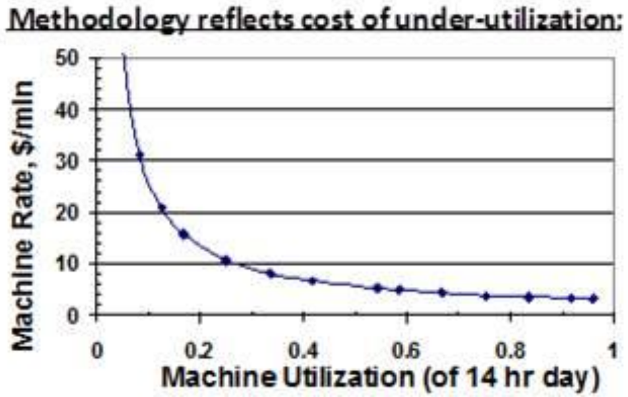
What is DFMA®?

- DFMA® = Design for Manufacture & Assembly = Process-based cost estimation methodology
  - Registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Company (Ford) design/costing method for the past 20+ years
- SA practices are a blend of:
  - “Textbook” DFMA®, industry standards and practices, DFMA® software, innovation, and practicality

Estimated Cost = (Material Cost + Processing Cost + Assembly Cost) x Markup Factor

Manufacturing Cost Factors:

1. Material Costs
2. Manufacturing Method
3. Machine Rate
4. Tooling Amortization



Methodology Reflects Cost of Under-utilization:

Capital Cost
Installation
} **Initial Expenses** → **Used to calculate annual capital recovery factor based on:**

- Equipment Life
- Interest Rate
- Corporate Tax Rate

Maintenance/Spare Parts Utilities
Miscellaneous
} **Operating Expenses**

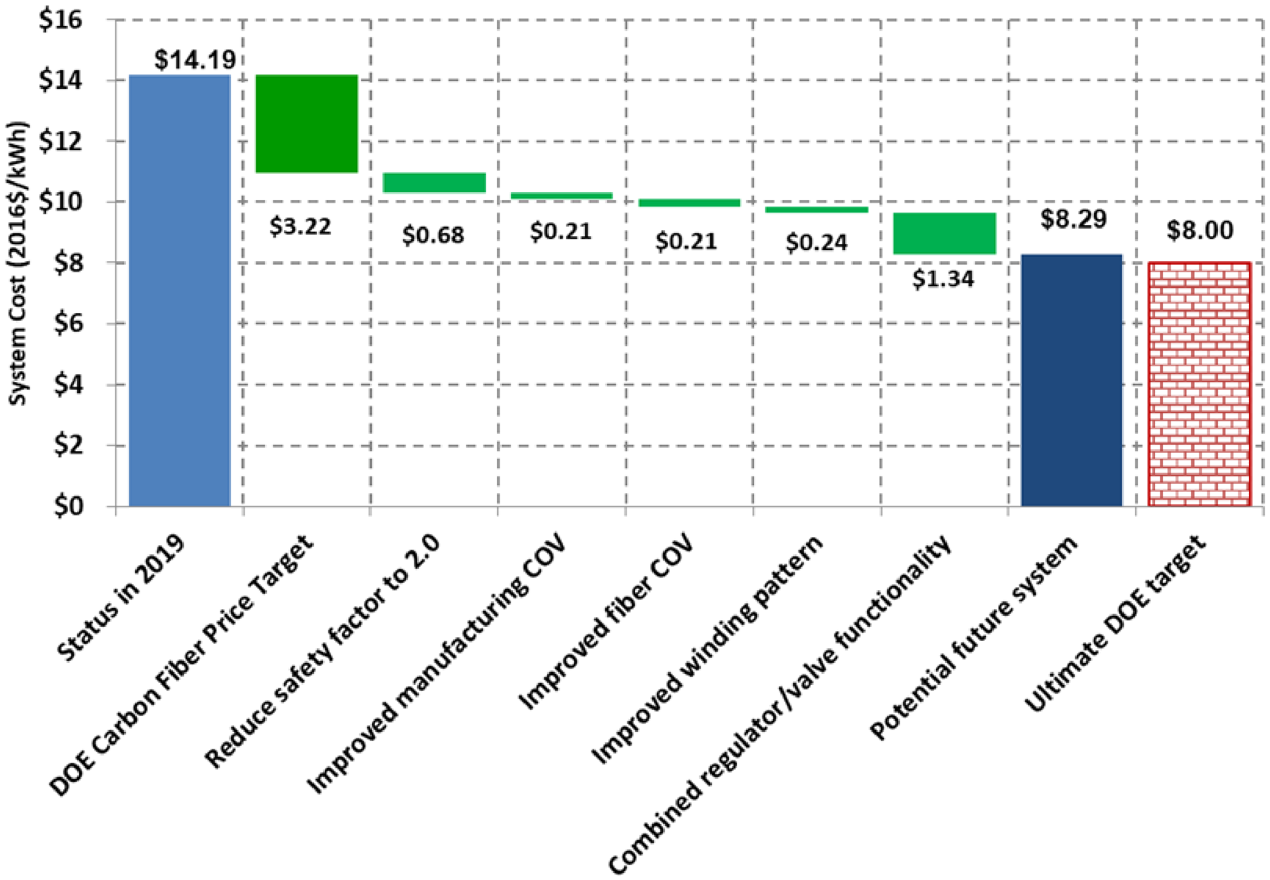
$$\frac{\textbf{Annual Capital Repayment} + \textbf{Annual Operating Payments}}{\textbf{Annual Minutes of Equipment Operation}} = \textbf{Machine Rate (\$/min)}$$

Activities in the Past Year

Topic	Description	Notes
Light-duty vehicle analysis	• Completed an update to the 700 bar Type 4 light-duty on-board storage analysis • Investigated strategies to achieve DOE cost targets for 700 bar Type 4 on-board storage	• Reported in DOE Program Record 19008. Results were presented at 2019 AMR. • Sensitivity results presented this year.
H_2 storage for medium and heavy-duty vehicle applications	Analysis of storage systems for multiple vocations: • 700 bar Type 4 compressed gas • 350 bar Type 3 compressed gas • 500 bar cryo-compressed	Analysis completed
Refueling station bulk and cascade storage	• Focus of analysis is on storage, not a full station analysis • Gaseous and liquid storage systems will be analyzed • Bulk storage system cost analysis sized for 1,000 kg/day • Coordinated with ANL's performance analysis	Completed system definition and bill of materials for current Milestone 9. Preliminary models of Type 2 cascade storage and Type 4 tube trailer delivery were completed and results included in this report

Accomplishment & Progress: Analyzed 700 bar LDV System Cost Reduction Strategies & Identified Path to Near Ultimate DOE $/kWh target

Sensitivity analysis showing potential cost reduction strategies for 700 bar Type 4 storage system at 500k/year

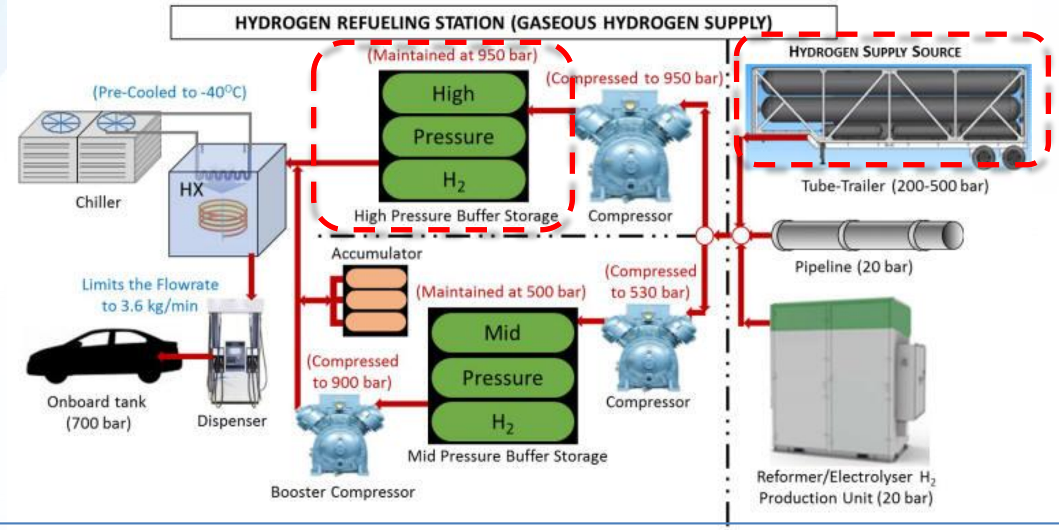


Category	Baseline	Target	Basis
Carbon fiber cost target	$21.48/kg	$12.60/kg	2017 FCTO Funding Opportunity
Safety factor	2.25	2.0	GTR discussions
Manufacturing Coefficient of variation (COV)	3%	1%	Hypothetical based on industry discussions
Fiber COV	3%	1%	Hypothetical based on industry discussions
Improved winding pattern	90.3 kg	85.8 kg	Based on an assumed reduction of 5% due to winding pattern improvements similar to the hoop intensive approach
Combined valve/regulator	With regulator	No regulator	Assumed all regulator function can be integrated into solenoid valve without increasing the valve price

- Aggressive carbon fiber price reductions are key to meeting cost targets. Meeting 2017 FOA targets would cut 23% of system cost from current baseline.
- Additional savings can be achieved by reducing the carbon fiber mass. As examined here, 12% can be achieved by reducing the safety factor, COV improvements, and advanced winding patterns.
- BOP cost reductions through, possibly, simplification are needed to squeeze the last bit of savings.

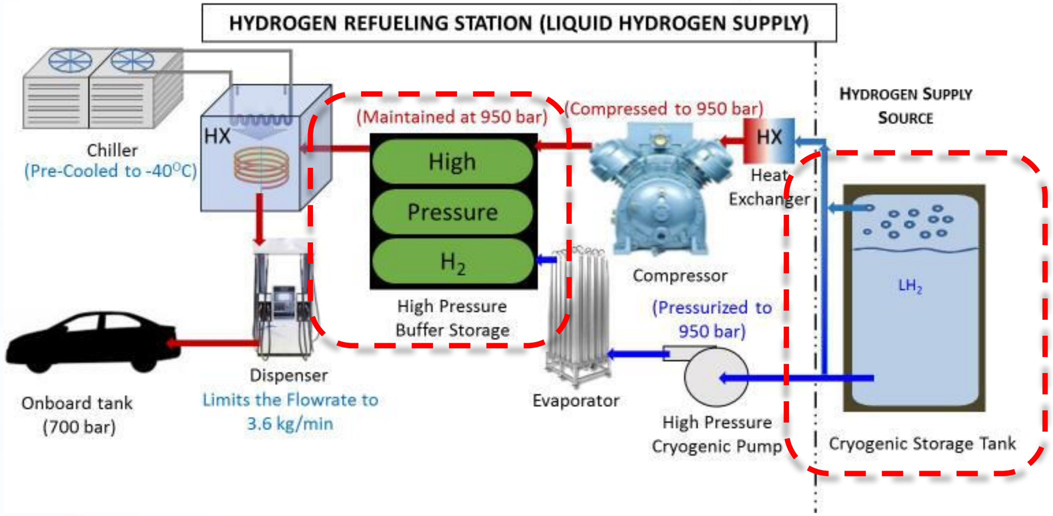
Refueling Station Storage Scoping Analysis Overview

Objective: provide bottom-up cost analysis of onsite **storage** at the H_2 refueling station for both liquid and gaseous bulk storage.



Progress on stations with gaseous supply reported in this briefing

- Gaseous supply onsite storage includes
  - Bulk storage from tube trailer delivery
  - Cascade storage sub-system
- Compressors, dispensers, etc. are excluded from analysis



Analysis of stations with liquid supply not ready to be reported

- Liquid supply onsite storage includes
  - Bulk storage in cryogenic Dewer
  - Cascade storage sub-system
- Pumps, compressors, dispensers excluded from analysis

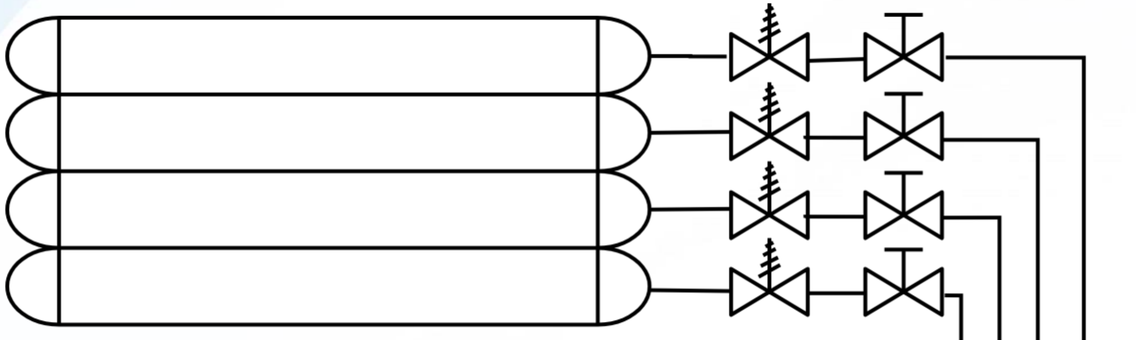
Images taken from https://hdsam.es.anl.gov/

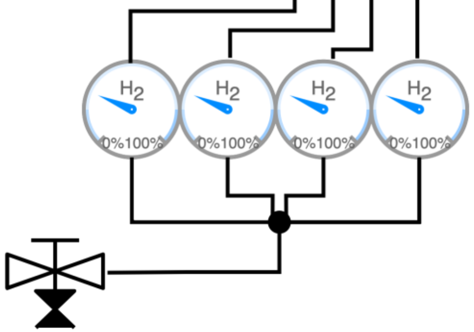
Accomplishments & Progress: Refueling Station System Parameters

Parameter	GH2	LH2	Notes/Design Basis
Bulk Storage Method Assumption	Tube Trailer	Dewer	HRSAM
Station Max Daily Dispensing Capacity (kgH_2/day)	1,000	1,000	HRSAM
Number of refueling modules	4	4	ANL/Linde design
Module Dispensing Capacity (kgH_2/day/module)	250	250	ANL assumption based on Linde design
Target Vehicle Pressure (bar)	700	700	Max dispensed pressure is higher 875 bar
No. of Tanks per Module in Cascade Storage Bank	5	5	ANL optimization parameter
Cascade Vessel Type	Type 2	Type 2	Based on Linde and FIBA Tech design
Cascade Storage Pressure (bar)	300-950	300-950	ANL optimization parameter
Tube Trailer Vessel Type	Type 4	Type 4	Hexagon Titan XL
Tube Trailer Capacity (kgH_2)	885	NA	Hexagon Titan XL
Tube Trailer Pressure (bar)	250	NA	Hexagon Titan XL
Cascade and Tube Trailer Storage Composite	T700S/ Vinyl Ester	T700S/ Vinyl Ester	Adams (2019)
Carbon fiber volume fraction	65%	65%	Gotthold (2015 AMR)

Accomplishments & Progress: Tube Trailer Storage System Designs

SA Interpretation of Hexagon TitanXL design

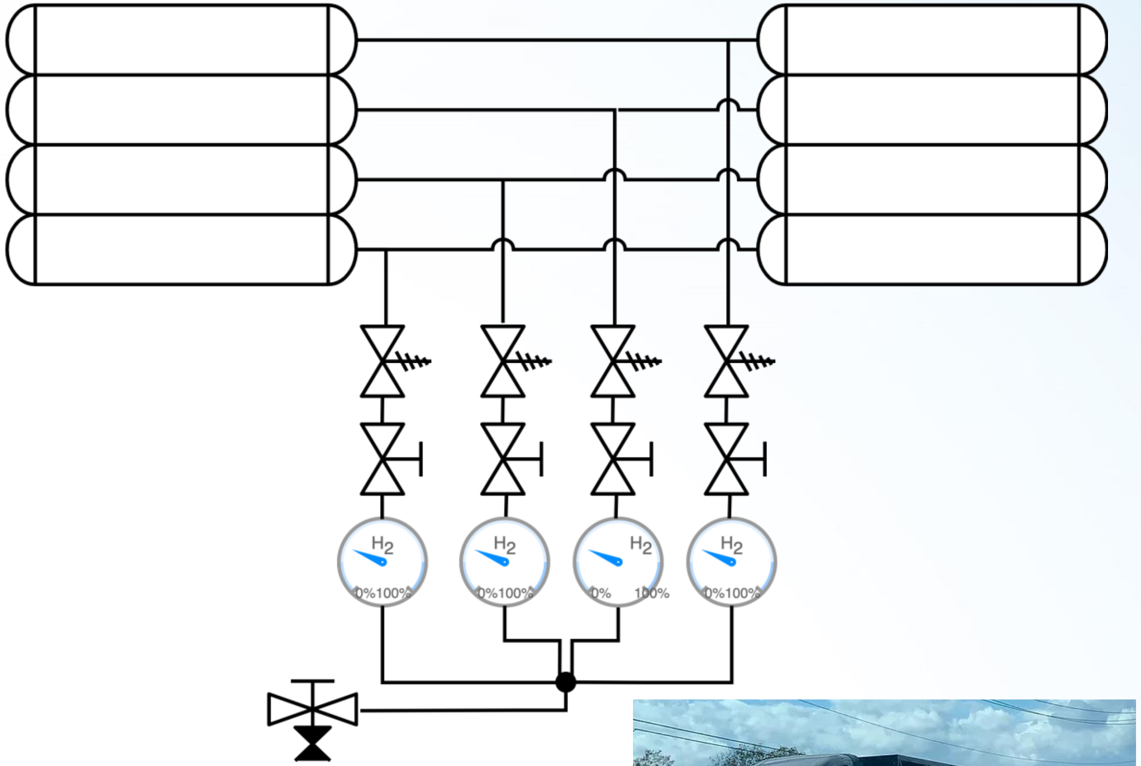




https://www.energy.gov/eere/fuelcells/gaseous-hydrogen-delivery

880 kgH_2 capacity
4-40’ Type 4 tanks per trailer plus smaller all-carbon tanks
Modeled as 4-220kg tanks

SA Interpretation of CATEC CT-590H design



1,000 kgH_2 capacity
8-25’ Type 4 tanks per trailer

https://www.catecgases.com/

Accomplishments & Progress: Tube Trailer Storage Design Parameters

- Tube trailer design parameters are based loosely on the **Hexagon TitanXL**
- Analysis of CATEC CT-590H is in progress
- Tube external dimensions are the controlling parameter
- Composite mass is estimated based on the performance factor derived from the 2019 Program Record
- TitanXL reported loaded vehicle mass is 20,165 kg and is in good agreement with our estimated 20,460 kg

Parameter	Unit	Value	Note
Total On-Board H_2	kgH_2	880	Based on TitanXL
Tubes Per Trailer		4	
Liner		HDPE	
Composite Mass	kg/tank	2,758	SA estimate using 2019 Program Record assumptions
Tube Length	m	12.2	Based on TitanXL
Tube I.D.	m	1.1	Estimated
Vessel Weight	kg	2,995	Estimated (Liner + Comp. +boss)
Estimated Trailer Weight (empty)	kg	7,600	Est. based 5,600 kg trail plus 2,000 kg support structure
Estimated Total Loaded Weight of Tube Trailer	kg	20,460	4 tubes + trailer+H_2

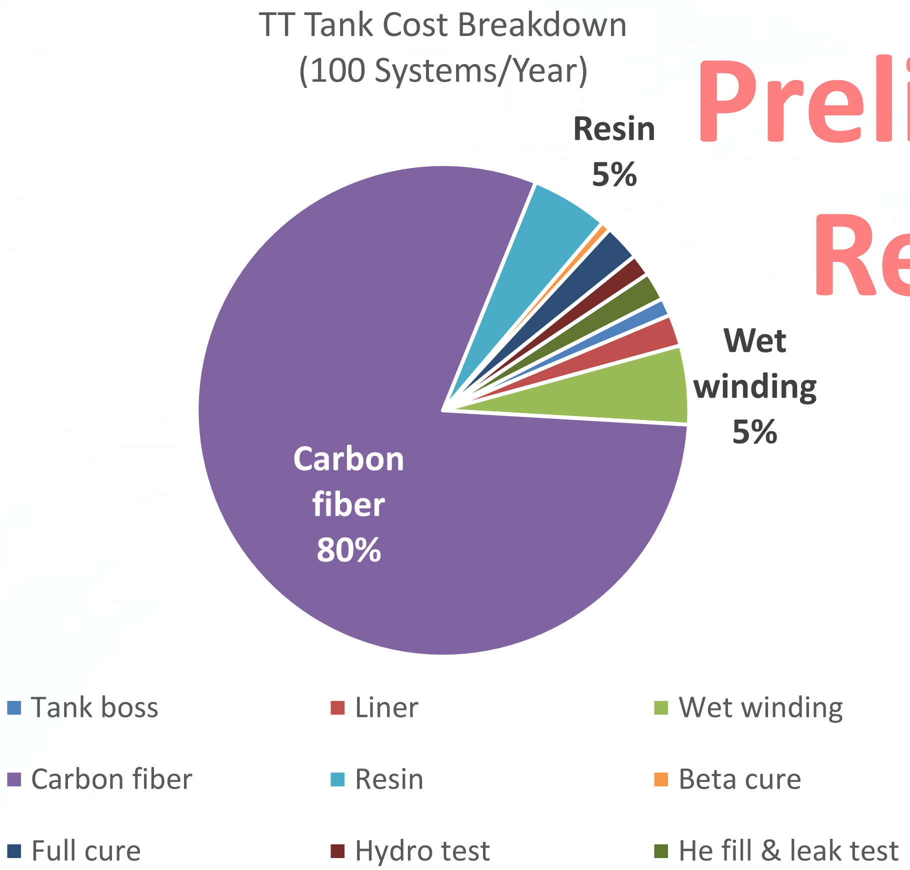
Accomplishments & Progress:
Tube Trailer Storage Bill of Materials & Preliminary Cost Results

Unit	Quantity Per System	Cost per Unit @100 Trailers per Year	Cost per Trailer @100 Trailers per Year
Type 4 220 kgH_2 capacity Pressure Vessel	4	$76,851/vessel	$307,403
40' Trailer	1	$40,000/trailer	$40,000
Steel Containment Structure	1	$50,000/structure	$50,000
Balance of System			
Pressure Relief Device (PRD)	4	$3,000 each	$12,000
Manual Shutoff Valves	9	$270 each	$2,430
Valve Box./Common Manifold	1	$300 each	$300
Block & Bleed Valve	1	$1,250 each	$1,250
Pressure Gauges (analog)	5	$156 each	$780
Tubing	35 ft.	$15/ft	$525
Assembly	1	$8,000	$8,000
Total			$422,688/Complete-Trailer

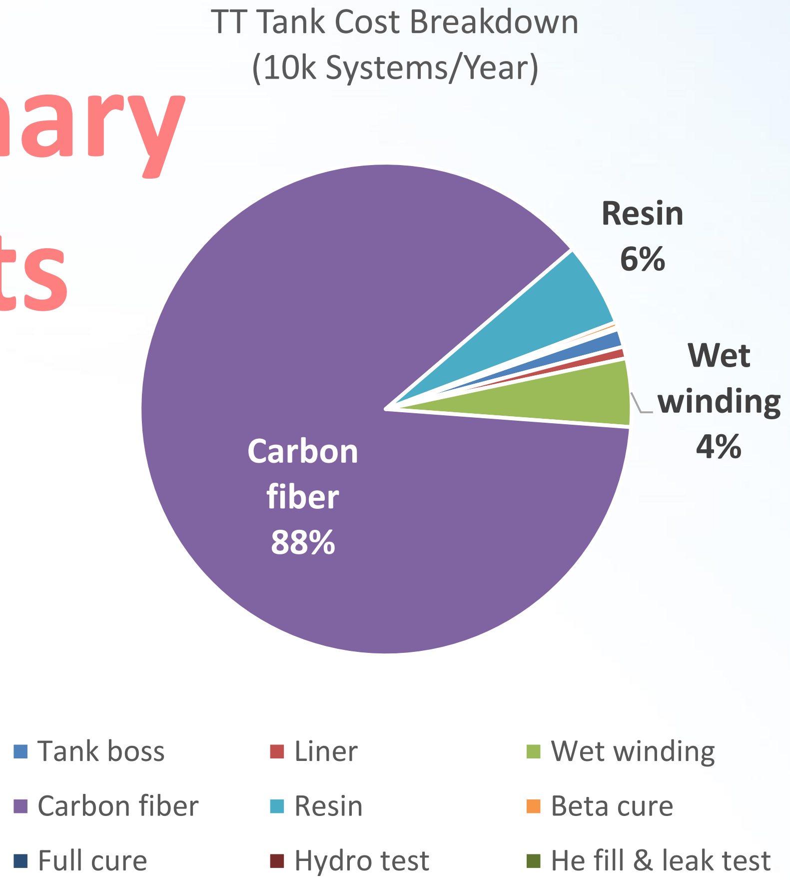
Preliminary Results

These are **Costs**, not **Prices**: they do not include company markup.

Accomplishments & Progress:
Preliminary Tube Trailer Pressure Vessel Cost Breakdowns



Preliminary Results



- Large pressure vessels dominated by carbon fiber cost!
- Note ~2,000 kg carbon fiber per vessel
- We used a performance factor approach based on 140L 700 bar vessels to estimate composite mass, so there is some uncertainty in how well performance factor scales to these volumes
- Tanks appear to be neck supported, so there may be additional materia costs not currently captured in the boss

Accomplishments & Progress:
Cascade Storage Design Parameters

- ANL results (top box) are compared with available FIBA Tech system specifications
- We estimate the average ANL tank gravimetric capacity (wt%H_2 = 1.02 %)
- Compared with average FIBA Tech gravimetric capacity of wt%H_2 = 0.95%
- ANL projections are light compared with FIBA, which may be due to multiple factors.
  - Thinner tank walls
  - Less carbon fiber
  - Higher tensile strength carbon fiber

ANL Optimization Results for Type 2 (Steel/Carbon Fiber) Cascade Storage

- Tank ID: 36 cm/ 14.17"
- Liner thickness: 41.9 mm
- 950 bar (14,000 psi)
- Composite thickness: 25.4 mm
- Tank OD: 42.7 cm/ 16.8"

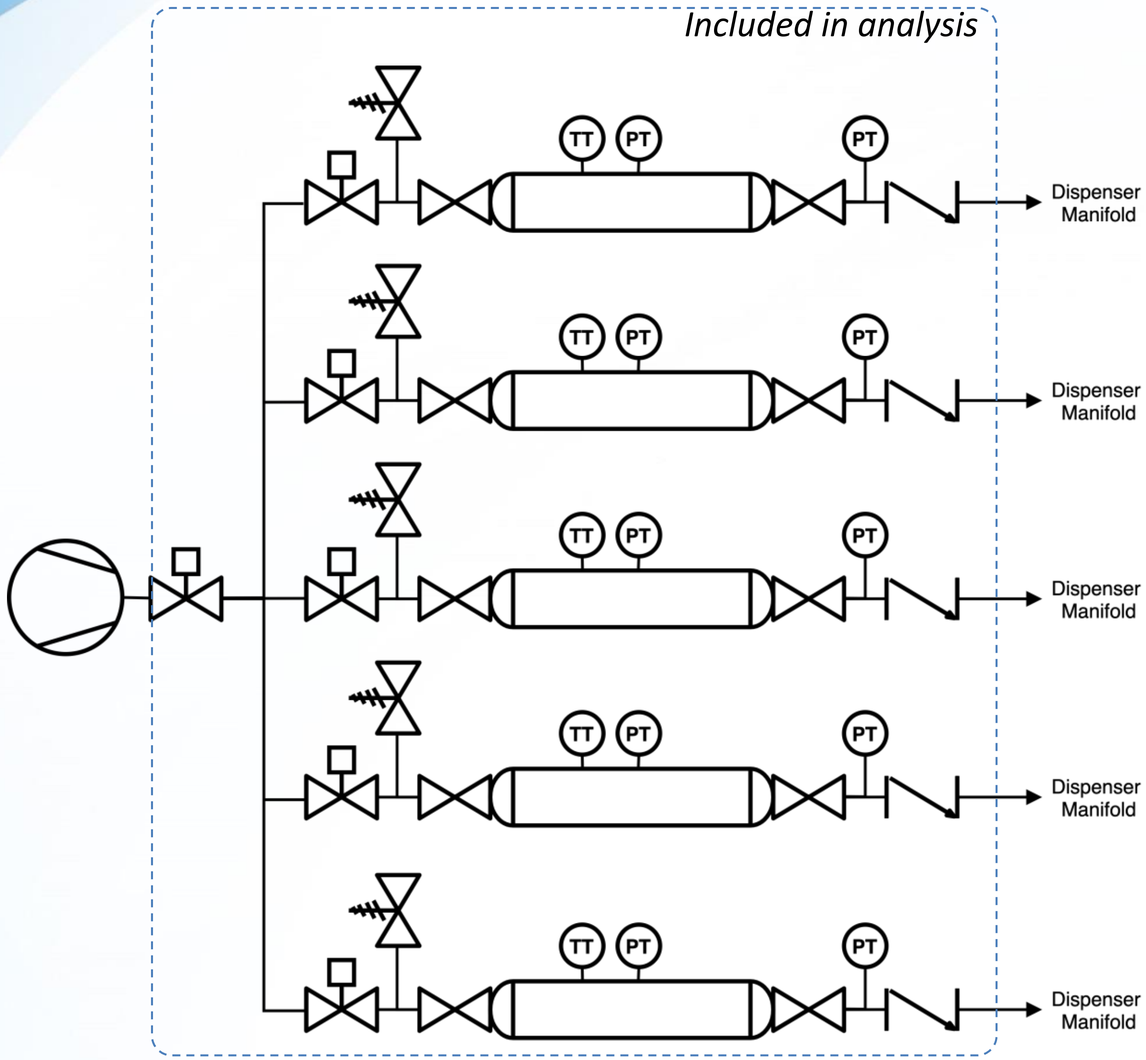
Compressor Capacity	# of Tanks	Tank Volume (L)	L/D	Liner Weight (kg)	Carbon Fiber Weight (kg)	Internal radius (cm)	Internal length (cm)	kgH_2	kgH_2/kgVessel
125%	5	555	14.7	2649	381	18.32	538.60	28.80	0.95%
150%	5	360	9.4	1547	227	18.49	347.58	18.70	1.05%
175%	5	241	6.2	1051	157	18.70	231.87	12.70	1.05%
225%	5	178	4.4	789	121	19.10	168.07	9.30	1.02%

H_2 (kg)	Length (cm)	Volume (L)	Vessel Mass (kg)	kgH_2/kgVessel
34	8800	721	3302	1.03%
16	4400	343	1651	0.97%
10	2900	213	1082	0.92%
7	2100	148	797	0.88%

FIBA Tech

- Tank OD: 16"
- 15,000 psi
- Reasonable agreement on gravimetric capacity

Accomplishments & Progress: Cascade Storage System Diagrams



- Dispenser Module 250 kg/day
- Focus is on storage sub-system
- Compressor
  - Costs are modeled by A. Elgowainy (ANL)
  - Capacity is a parameter in R. Ahluwalia's (ANL) analysis
  - Tank size depends on compressor capacity
- Trade-off is storage and compressor costs vs. performance

Compressor Capacity (100% = 250 kg/day)	Cascade Total Volume (L)	Liner Material
125%	555	SA-372 Grade J
150%	360	SA-372 Grade J
175%	241	SA-372 Grade J
225%	178	SA-372 Grade J

Accomplishments & Progress:
Preliminary Cascade Storage Sub-System Costs

- Preliminary DFMA cost breakdowns for Type 2 cascade sub-system tanks are shown in the pie chart
- The shape of the tank cost breakdown (relative %) do not have a strong dependence on cascade capacity
- Liner is modeled assuming seamless tube materials as inputs with a neck forming operation
- Liner materials dominate the cost of the cascade storage sub-system
- Balance of system (valves, PRDs, etc.) comprise 50% - 20% of cascade sub-system cost depending on size of cascade storage vessels

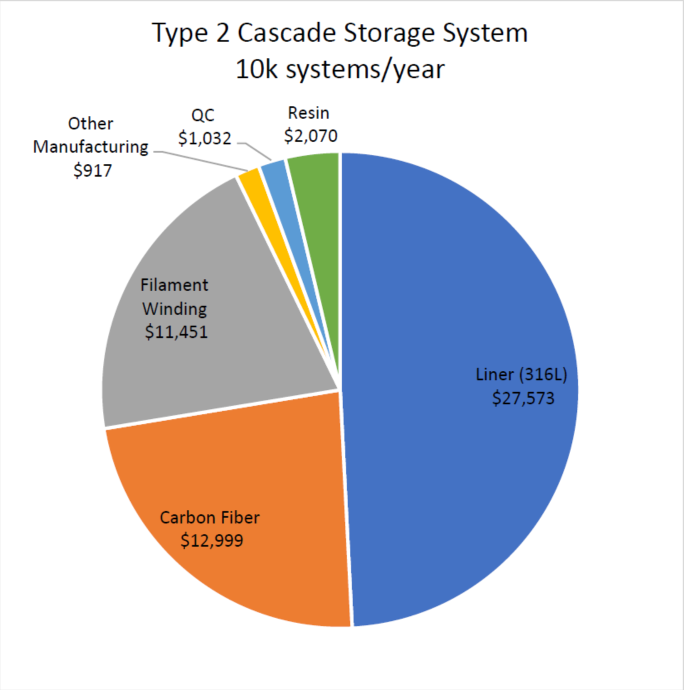
Note that projected costs, not prices, are shown here

Cascade Storage Sub-System Capital Costs

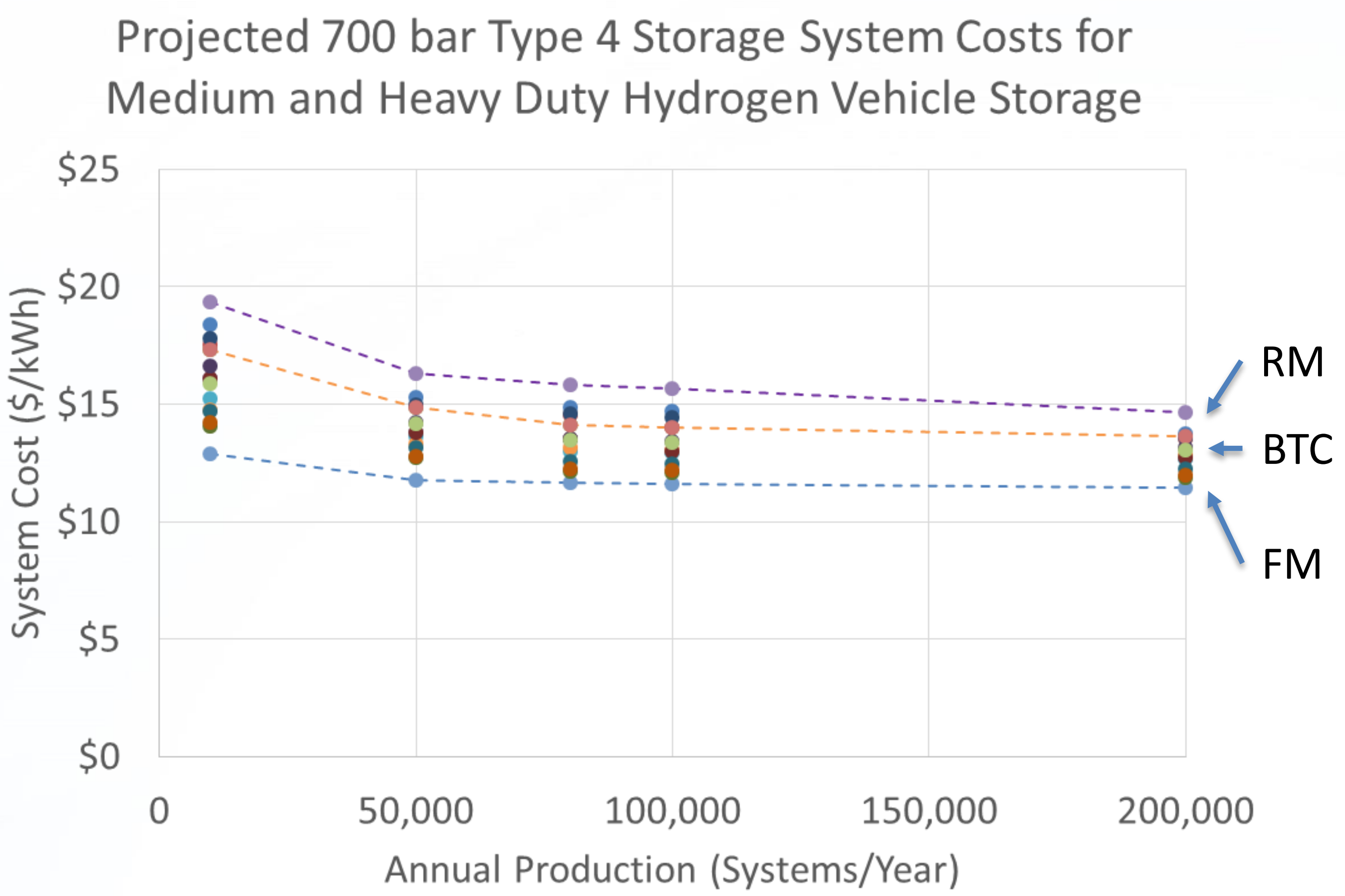
Compressor Capacity	Tanks per Dispenser Module	Tank Cost @ 200 Modules per Year	Tank Cost per Module	BOS*	Cascade Storage Module Cost
225%	5	$ 12,120	$ 60,598	$ 29,692	$ 90,290
175%	5	$ 14,577	$ 72,886	$ 29,692	$ 102,578
150%	5	$ 19,722	$ 98,611	$ 29,692	$ 128,303
125%	5	$ 31,660	$ 158,301	$ 29,692	$ 187,993

Preliminary

*Balance of system (BOS) bill of materials in backup

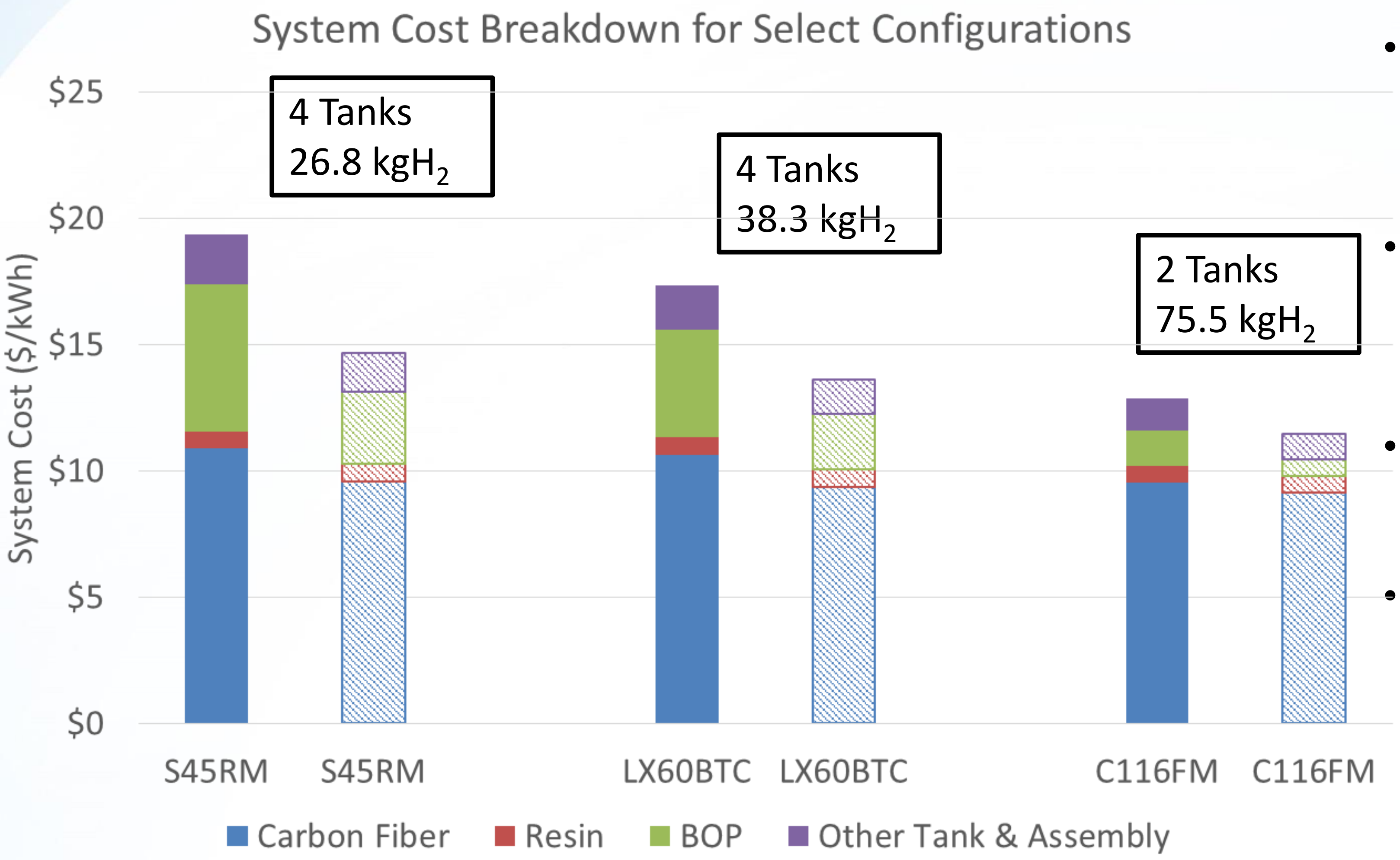


Accomplishments & Progress: Survey of System Cost



- System costs are normalized to total energy content (33.33 kWh/kgH_2)
- Dashed lines shown representative low, mid, high system cost
- Range in system costs is a function of
  - Storage system volume (total kgH_2)
  - Number of repeat parts for multi-tank configurations (dominated by valves)
  - Production rate dependence strongly depends on system size which affects annual carbon fiber purchasing power.
- Largest system studied is lowest cost on a per unit energy basis ($/kWh)

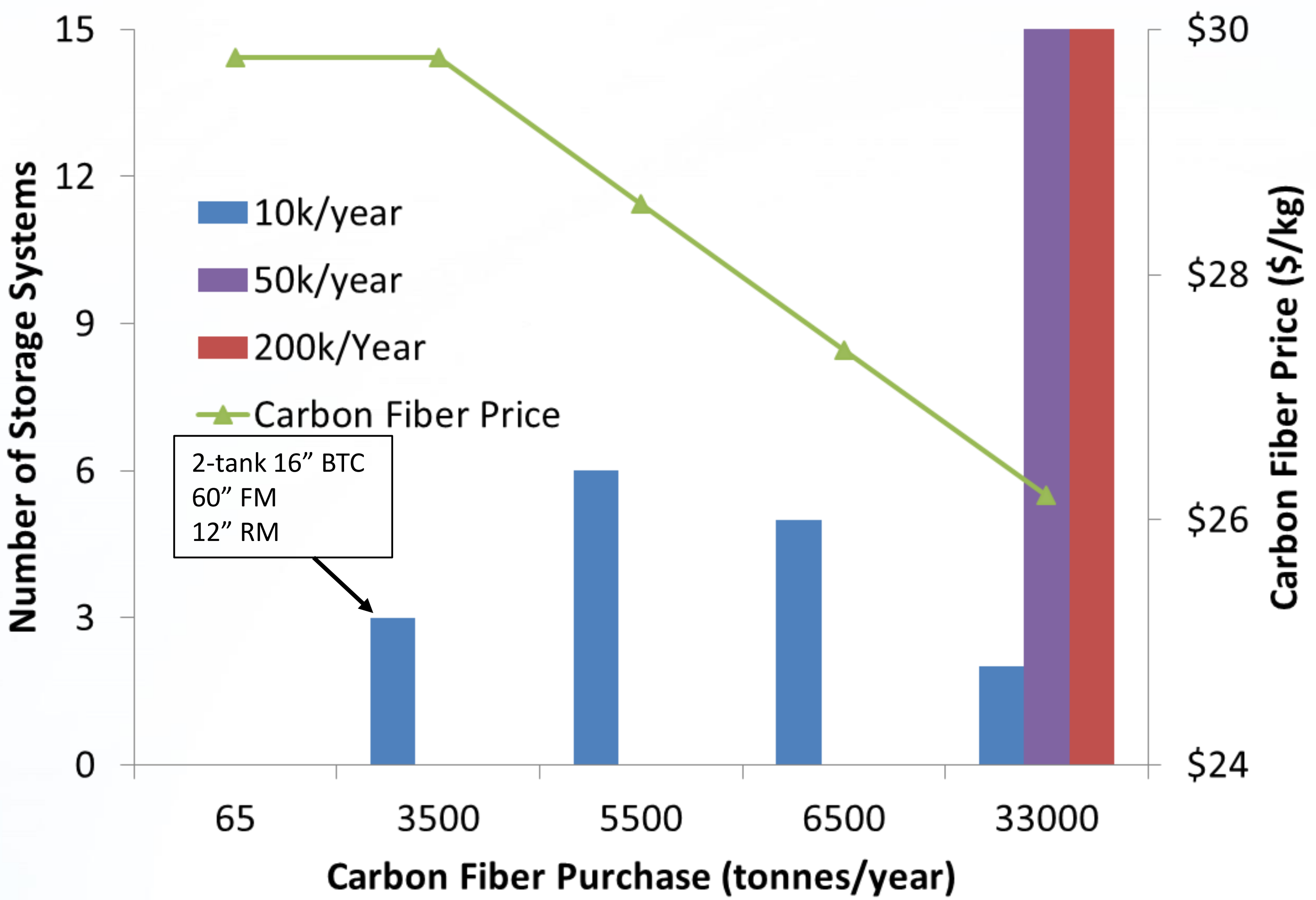
Accomplishments & Progress: System Cost Breakdown Comparisons



- Breakdowns for three configurations: roof-mounted, behind-the-cab, and frame-mounted.
- Category names reflect A1 Autoelectric product dimensions (e.g. S45RM is a roof-mounted system with 45 DGE capacity)
- Carbon fiber mass is modestly sensitive to aspect ratio (length/diameter)
- BOP cost (per kWh) is relatively smaller for larger storage volumes

10k systems/year (solid fill)
200k systems/year (patterned fill)

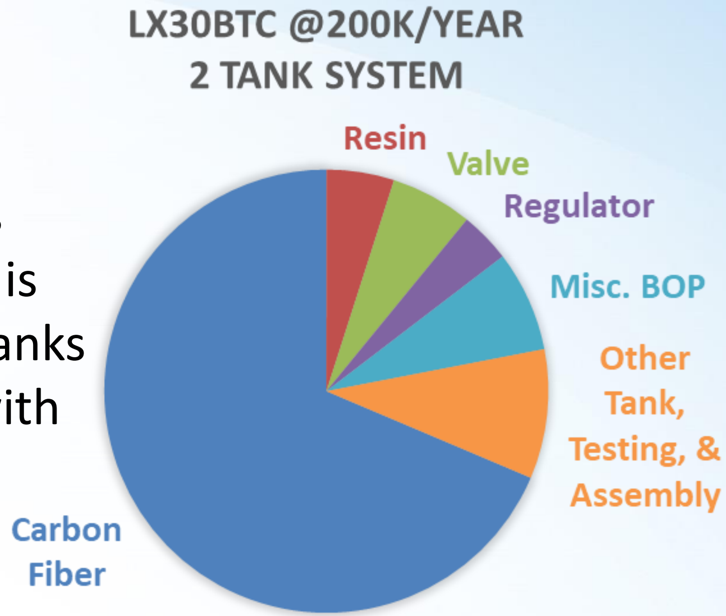
Accomplishments & Progress:
Carbon Fiber Economies of Scale are Reached at Low to Mid-Size Truck Market Penetrations

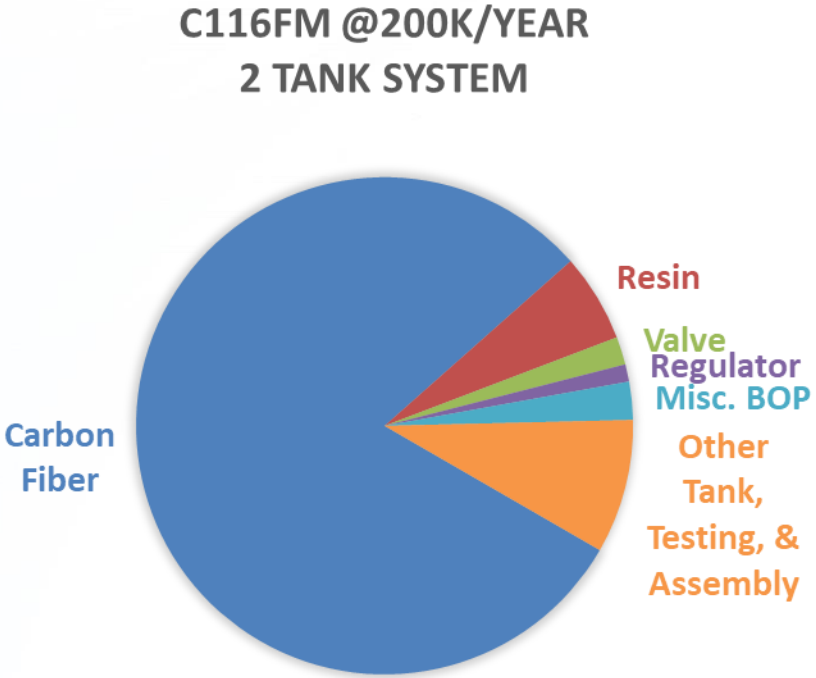


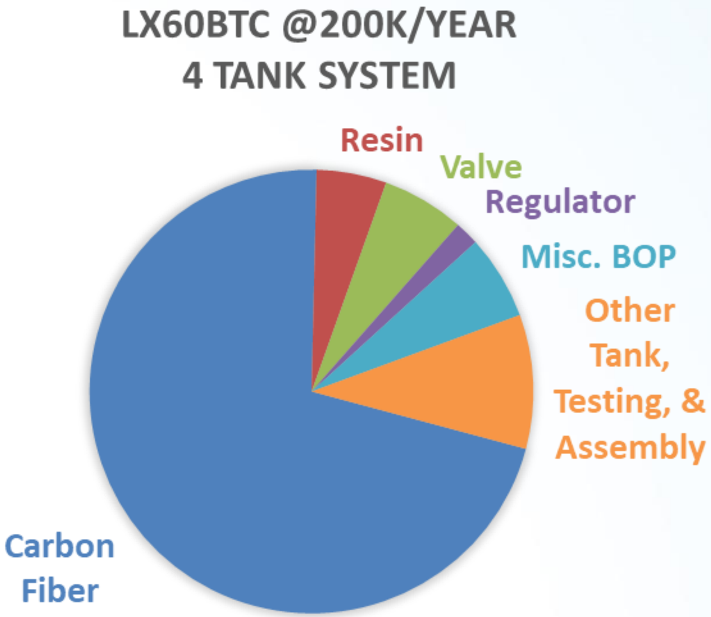
- Figure shows the annual carbon fiber purchased for all storage systems studied (frame, roof, and behind the cab mounted)
- Green trace is the carbon fiber price ($/kg)
- At 10k units per year (blue histogram), a producer of the largest frame mounted tanks would purchase in excess of 33,000 tonnes of carbon fiber and get the lowest price.
- At 50k vehicles per year, all systems sizes we investigated are buying carbon fiber at the lowest price available.

Accomplishments & Progress: Cost Breakdown Trends

- Relative fraction due to the carbon fiber for the frame-mounted (75.5 kgH_2) is much larger than behind-the-cab (20 kgH_2 and 40 kgH_2) storage systems. This is due to tank costs scaling with volume while BOP costs scale with number of tanks
- Also note valve cost fraction (vs. regulator) for 2 vs. 4 tank BTC. Valves scale with number of tanks, while regulators don't.







Miscellaneous BOP is dominated by a 10% (per tank) contingency on BOP

2019 Reviewer Comments

Reviewer Comment	Actions to address/Response to reviewer
In the 2019 AMR, incremental refinements to past analysis focused on compressed hydrogen. The approach would benefit from the inclusion of a cost analysis of other projects within the DOE portfolio.	The analysis presented this year expands the range of systems considered. Per DOE directive, we are focused on high priority storage options around the compressed gas and liquid fuel.
The project team should revisit the models and seek more input from industry.	This comment was specific to the MDV/HDV analysis, but we agree this is broadly true for all the analysis we conduct.
The scope of future work should include novel concepts or the analysis of related concepts in the DOE portfolio to reduce the cost of hydrogen storage systems.	This year we present analysis showing the impacts on cost of LDV storage systems of aggressive targets.
The project team should develop a list of opportunities for DOE and researchers to consider for further reduction in hydrogen tank system costs. The project team could also determine the material cost target by conducting a reverse cost estimation of various material-based systems. In addition, the project team should consider determining the potential cost savings for other project efforts in the DOE portfolio.	Our analysis on system cost of carbon fiber targets suggests additional cost saving approaches are needed to achieve the LDV cost targets. For example, simply halving the carbon fiber cost is not sufficient to reach the ultimate target of $8/kWh. Our analysis suggests additional savings are available from manufacturing improvements and by combining BOP functionality.

Collaborations & Coordination

MDV/HDV	Argonne—finite element analysis PNNL-–system assumptions Informal discussions, system assumptions, and BOP–Iljin, Westport Innovations, Worthington, Nikola
700 bar Type 4 LDV	ANL—finite element analysis
Tube trailers	CATEC Gases—manufacturing assumptions and costs Hexagon (planned)—manufacturing assumptions and costs
Cascade storage	ANL—crack propagation analysis
Helium leak test	PNNL—Updates to design assumptions Nolek—High-rate helium leak tests
Large tank filament winding	McLean-Anderson
Frequently consulted	Mike Veenstra (Ford) and Norm Newhouse (Hexagon ret.)

Conclusions and Next Steps

- **Conclusions**
  - Cascade and tube trailer storage system sizing based on ANL and SA analyses show good agreement with existing product literature from FIBA Tech (cascade tanks) and Hexagon (tube trailers)
  - Results from our analysis of on-site storage costs will provide increased sensitivity in refueling station trade-off analyses, particularly between storage and compressor sizing.
  - Duplicate balance of system components (e.g. PRDs, valves, etc.) do not appear to contribute significant costs to the refueling module, thus approaches to reduce tank volume and cost appear to be justified to reduce cascade sub-system costs.
  - Analysis of 700 bar Type 4 storage options for medium and heavy-duty vehicles was completed in this year
  - Existing CNG packaging options provide proof that roof, frame, and behind-the-cab mounting locations provide adequate fuel storage for most vocations investigated.
  - Retrofitting around existing vehicle designs may be adequate for long haul and other vehicles requiring more than ~70 kgH_2
- **Next steps**
  - Finish tube trailer analysis using CATEC design assumptions and send out for feedback from CATEC and Hexagon
  - Get input from Type 2 manufacturer such as FIBA Tech on cascade storage analysis
  - Complete liquid bulk storage analysis
  - Begin rail and marine applications storage analysis

Backup

Preliminary Cascade Storage Sub-System Costs

Cascade Storage Sub-System Costs

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175%	5	$ 14,577	$ 72,886	$ 29,692	$ 102,578
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125%	5	$ 31,660	$ 158,301	$ 29,692	$ 187,993

Balance of System Component Costs

Balance of System Component	Number/dispenser	Unit cost	Cost/Dispenser
On-tank valve	10	$ 301	$ 3,010
Pressure relief device	5	$ 601	$ 3,005
Automated valve	5	$ 2,860	$ 14,300
Manual valve	1	$ 292	$ 292
Temperature transmitter	5	$ 650	$ 3,250
Pressure transmitter	5	$ 464	$ 2,320
Check valve	5	$ 703	$ 3,515
Total			$ 29,692