2019 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: ~50% (in year 3 of 5)

Barriers

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

Budget

- Total Project Budget: $1,500,000
  - Total DOE Funds Spent: ~$538,000 (through February 2019 , including subs)

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.

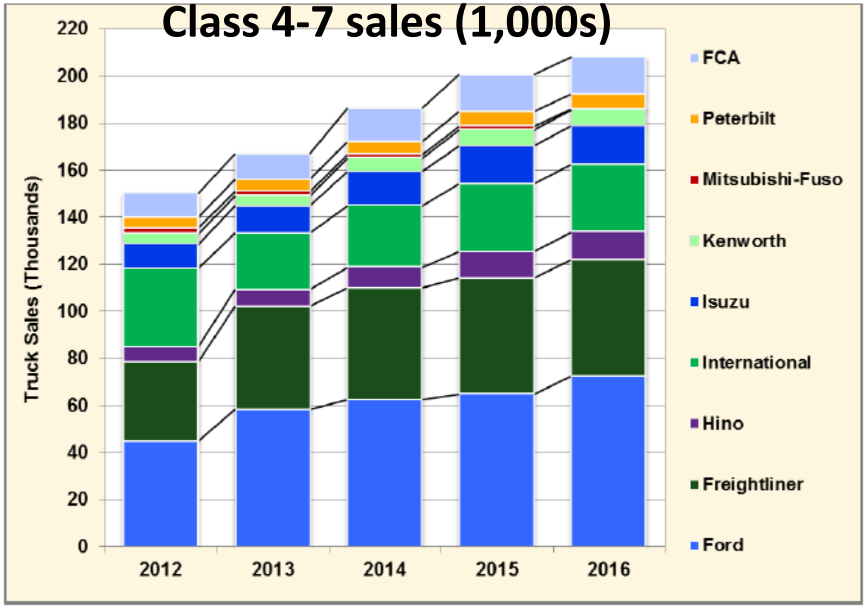
- **Results and Impact**
  - DFMA® analysis can be used to predict costs based on both mature and nascent components and manufacturing processes depending on what manufacturing processes and materials are hypothesized.
  - Identify the cost impact of material and manufacturing advances and to identify 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/Activities in Past Year

- **H_2 storage for Fuel Cell Electric Trucks**
  - scoping analysis for medium and heavy duty trucks (MDV/HDV) to determine size of onboard storage required, size of markets, and packaging options for multiple vehicle vocations
  - preliminary composite thickness estimates using Tankinator model (HSECoE)
- **Carbon fiber price update**
  - revised carbon fiber prices based on industry feedback
  - revisited additional reductions at high volume (>100k LDV per year) assuming process efficiencies can be realized from plant scale-up.
- **Baseline system cost update for 700 bar Type 4 LDV COPV system**
  - updated inflation factors to index system cost to $2016 (previously $2007)
  - updated carbon fiber price assumptions
  - revised low-volume BOP component costs
  - reported system cost in new DOE Program Record

Accomplishments & Progress
MDV/HDV Scoping Analysis

Class 4-7 sales (1,000s)

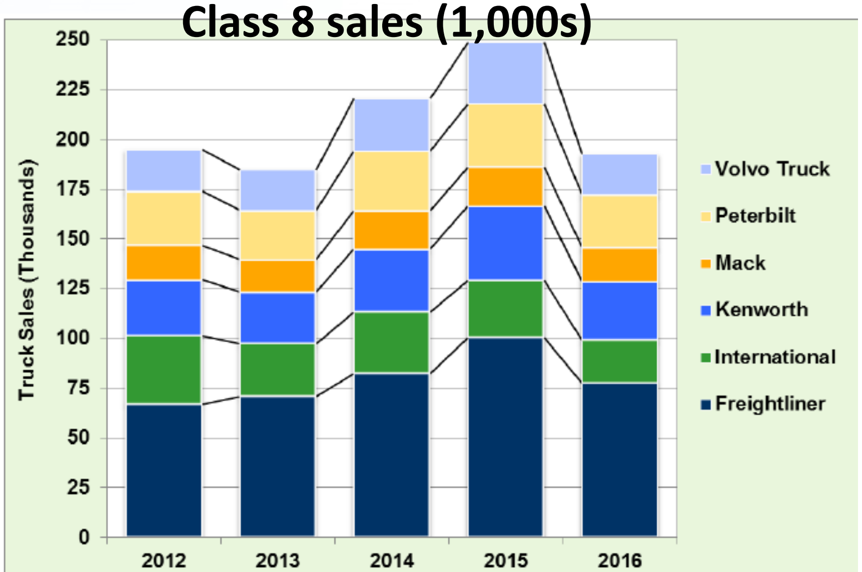


Combined US MDV/HDV manufacture ~400k

Compared to:

- **~12M Light-Duty Vehicle made in US in 2015**
  - (~90M LDV produced worldwide)
- **~4k Transit buses made in US in 2015**
  - (~75k Transit Buses produced worldwide)

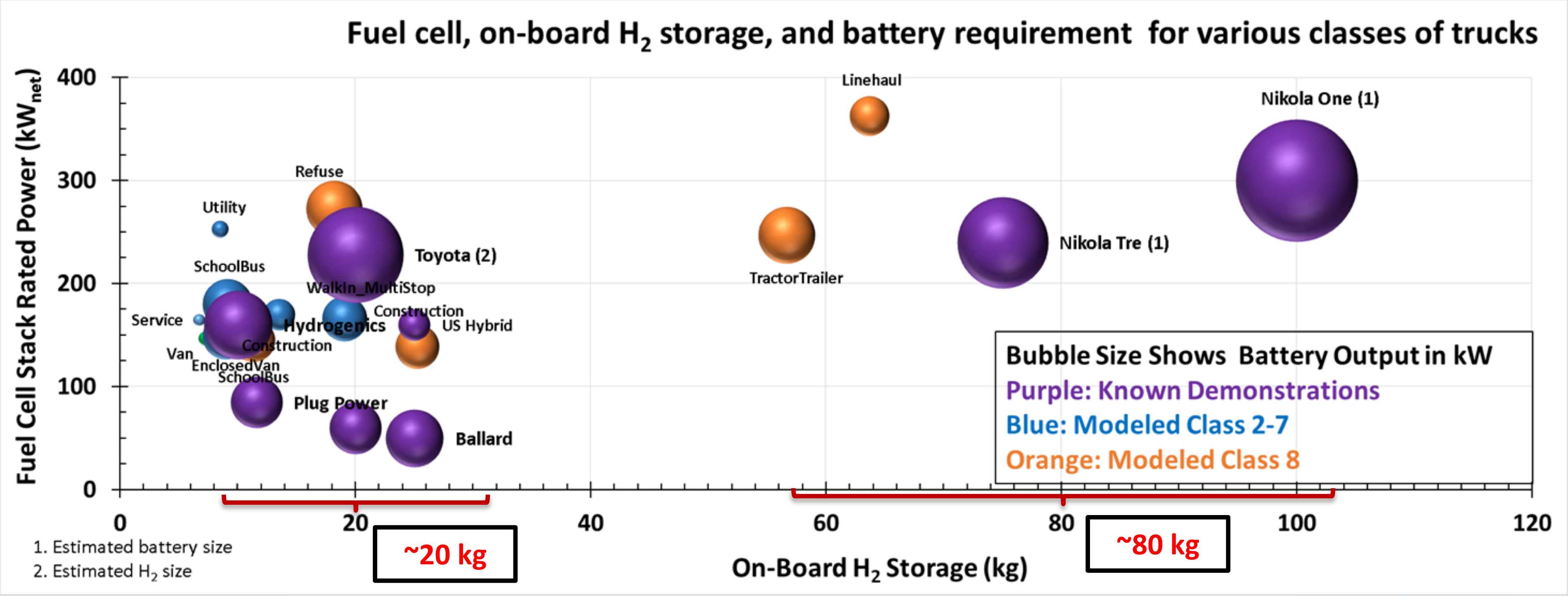
Class 8 sales (1,000s)



- **Only ~3% of MDV/HDV are imported into US**
- **Class 4-7 truck sales up 38% since 2012**
  - ~200k truck sales in 2016
- **Class 8 truck sales stagnant/declining**
  - Reflects shift away from long-haul toward regional-haul
  - Will driver-less trucks reverse this trend?
- **~400k combined truck sales in 2016**

Source: 2016 Vehicle Technologies Market Report, Oak Ridge National Laboratory, http://cta.ornl.gov/vtmarketreport/index.shtml

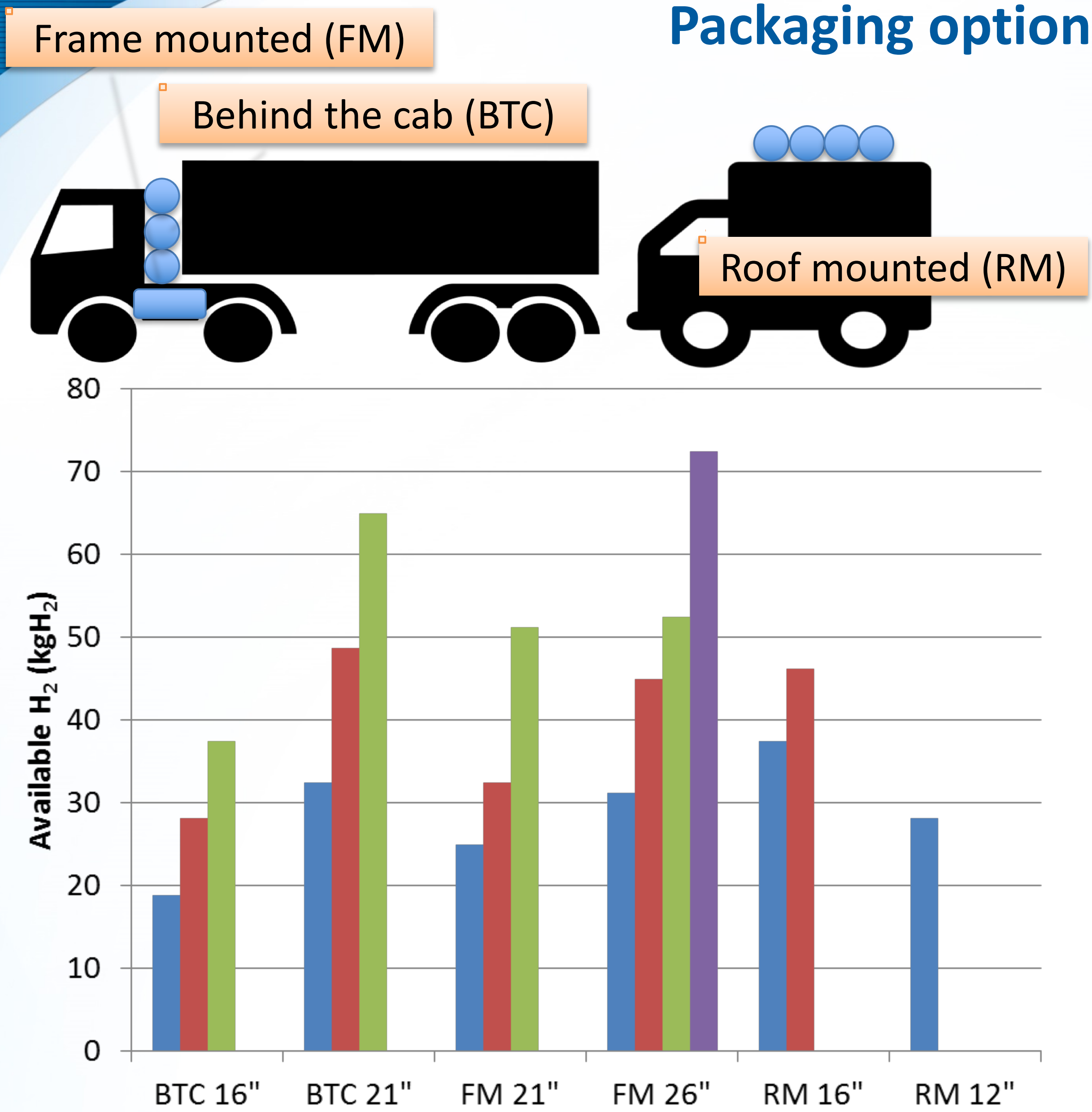
Accomplishments & Progress
On-board H_2 storage



- ANL* conducted drive cycle analyses of several MDV and HDV vocations to determine optimal fuel cell, battery, & on-board H_2 requirements for a **fuel cell dominant architecture**
- 20 kg and 80 kg are representative H_2 storage systems for MDV and HDV, respectively
- There is quite a large range, however:
  - 10-30 kg H_2 (MDV)
  - 60-100 kg H_2 (HDV)

* Vijayagopal (2016 AMR)

Accomplishments & Progress
Packaging options



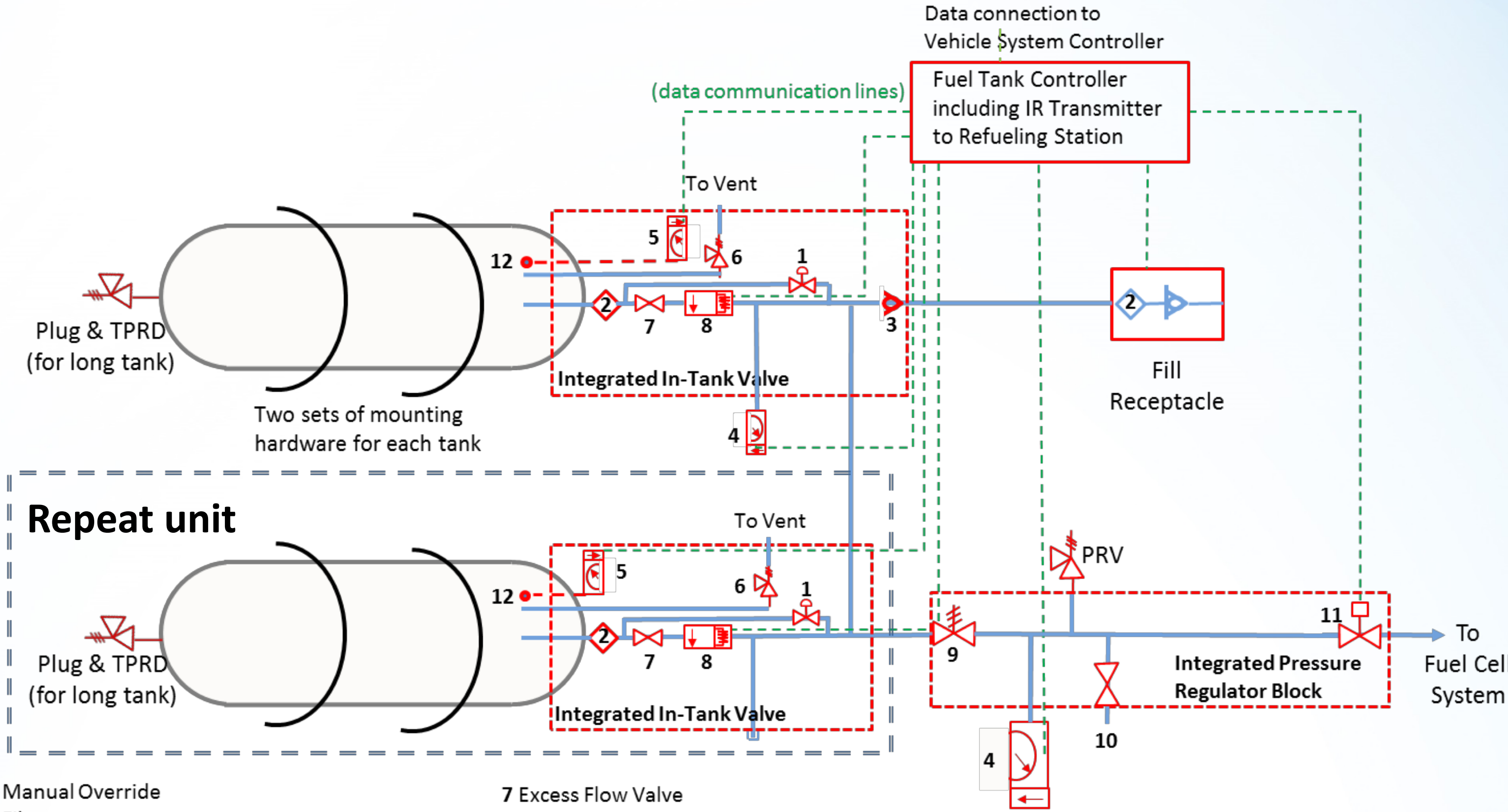
- Available H_2 storage capacity calculations built on envelope method described by Gangloff[1]
- Commercially available CNG systems[2] were used as representative available envelope dimensions
- Available H_2 stored mass shown as colored bars in the figure depends on
  - Number of tanks (2-4) for BTC configuration
  - External tank length (60”-180”) dimensions for FM
  - External tank length (80”-96”) for RM configuration
- X-axis shows external radius

1. Gangloff, Kast, Morrison, and Marcinkoski https://doi.org/10.1115/1.4036508.
2. http://www.a1autoelectric.com/

Accomplishments & Progress
System Parameters

Parameter	LDV	MDV	HDV
H_2 mass	5.6 kg	20 kg	80 kg
Pressure	700 bar	700 bar	700 bar
Number of tanks (options listed)	1-2	2-4 (roof mounted) 4-6 (behind the cab)	2 (frame mounted)
Liner	HDPE	HDPE	HDPE
Liner thickness	0.5 cm	0.5 cm	0.5 cm
Inlet diameter	35 mm	35 mm	35 mm
Composite mass (ANL investigating geometry effects)	91 kg	~350 kg	~1100 kg
Carbon fiber	PAN-MA based CF	PAN-MA based CF	PAN-MA based CF
Resin	Vinyl ester	Vinyl ester	Vinyl ester
Fiber volume fraction	0.65	0.65	0.65
Valve	Integrated in-tank	Integrated in-tank	Integrated in-tank
Stack size (net power)	80 kW	160 kW	300 kW
Peak flow (60% stack efficiency)	1.1 g/s	2.2 g/s	4.1 g/s
Regulator	Integrated	Integrated	Integrated
High pressure gas lines	¼”-16 gauge 316L	¼”-16 gauge 316L	¼”-16 gauge 316L
Low pressure gas lines	¼”-22 gauge 316L	¼”-22 gauge 316L	¼”-22 gauge 316L
Tank aspect ratio (internal)	1.7-3	3.8-5	5
Mounting hardware		Specific to tank placement	

Proposed truck system diagram looks like multi-tank LDV system



1 Manual Override
2 Filter
3 Check Valve
4 Pressure Transducer
5 Temperature Transducer
6 Thermally Activated Pressure Relief Device (TPRD)

7 Excess Flow Valve
8 Auto Solenoid Valve
9 Pressure Regulator
10 Manual Defuel Valve & Defueling Receptacle
11 Automated Shutoff Valve
12 Temperature Sensor

Carbon fiber price updates

- Updated price quotes from industry expert(s) suggests T700 prices are **~15% lower (in 2018)** than previous SA assumptions due partly to competition from new market entrant
- Prices predicted to **increase again by ~8% in 2019**
- From CEMI study of global **carbon fiber composite trends** over the period from 2012 to 2020:
  - CF demand projected to be **92,000 tonnes for all applications** in 2018
  - **2018 CF demand** from pressure vessel industry projected to be 7,000 tonnes
  - Compare with 700 bar Type 4 H_2 demand of ~7,000 tonnes/year and 34,000 tonnes/year at annual production of 100k and 500k vehicles, respectively
  - Installed capacity projected to approximately double from 2012 to 2020
  - Plant utilization projected to increase to ~100%
  - Plant efficiency projected to increase by 20% from 60% to 72%

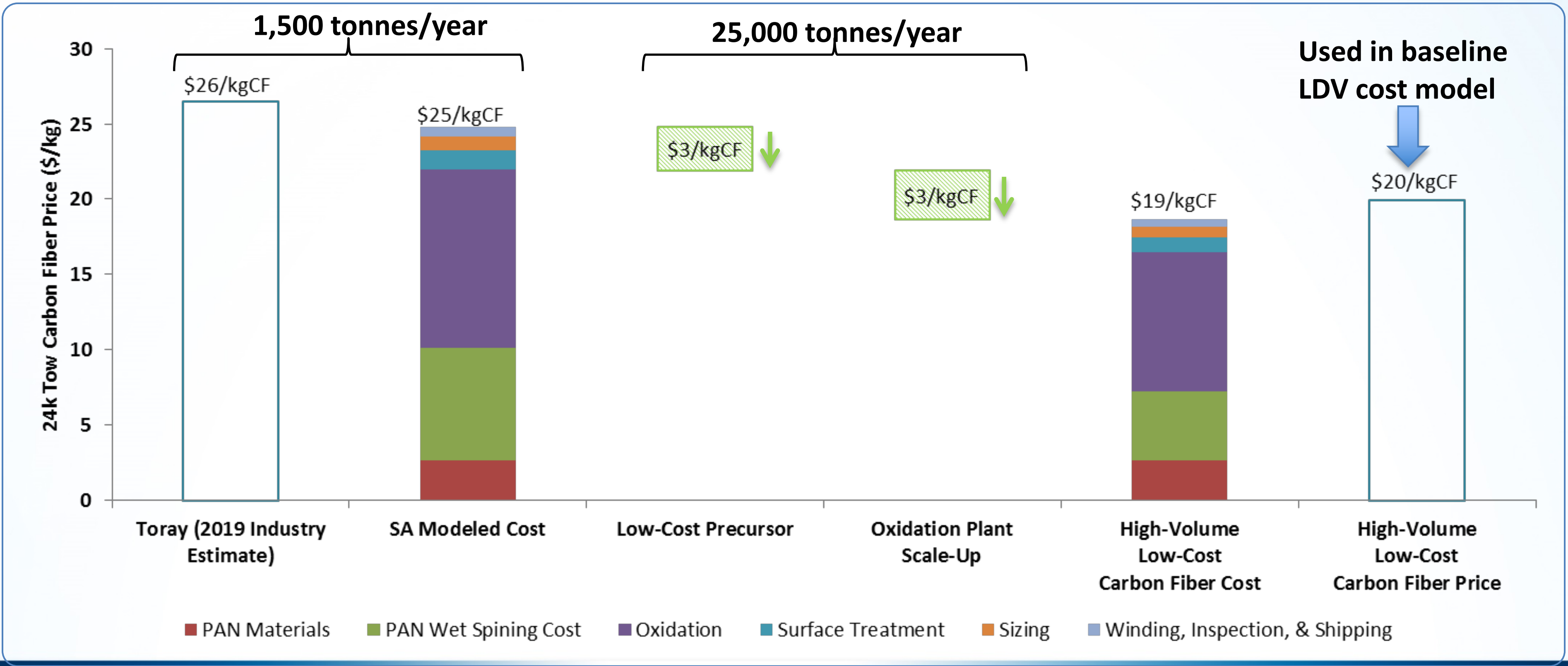
Modeled Annual Tank Production	Modeled Annual CF Demand (tonnes)	T-700 Price in 2007-2015 ($/kg)	T-700 Price in 2018 ($/kg)	T700 price in 2019 ($/kg)
30,000	2,100	$33	$28	$30
50,000	3,500	$33	$28	$30
80,000	5,600	$31	$26	$29
100,000	7,000	$29	$25	$27
500,000	34,000	$29	$24	$26

Das et al. "Global Carbon Fiber Composites Supply Chain Competitiveness Analysis." 2016. http://www.osti.gov/scitech/biblio/1260138-global-carbon-fiber-composites-supply-chain-competitiveness-analysis.

Accomplishments & Progress: Carbon fiber price updates

Precursor and oxidation plant scale-up may lead to carbon fiber cost reductions

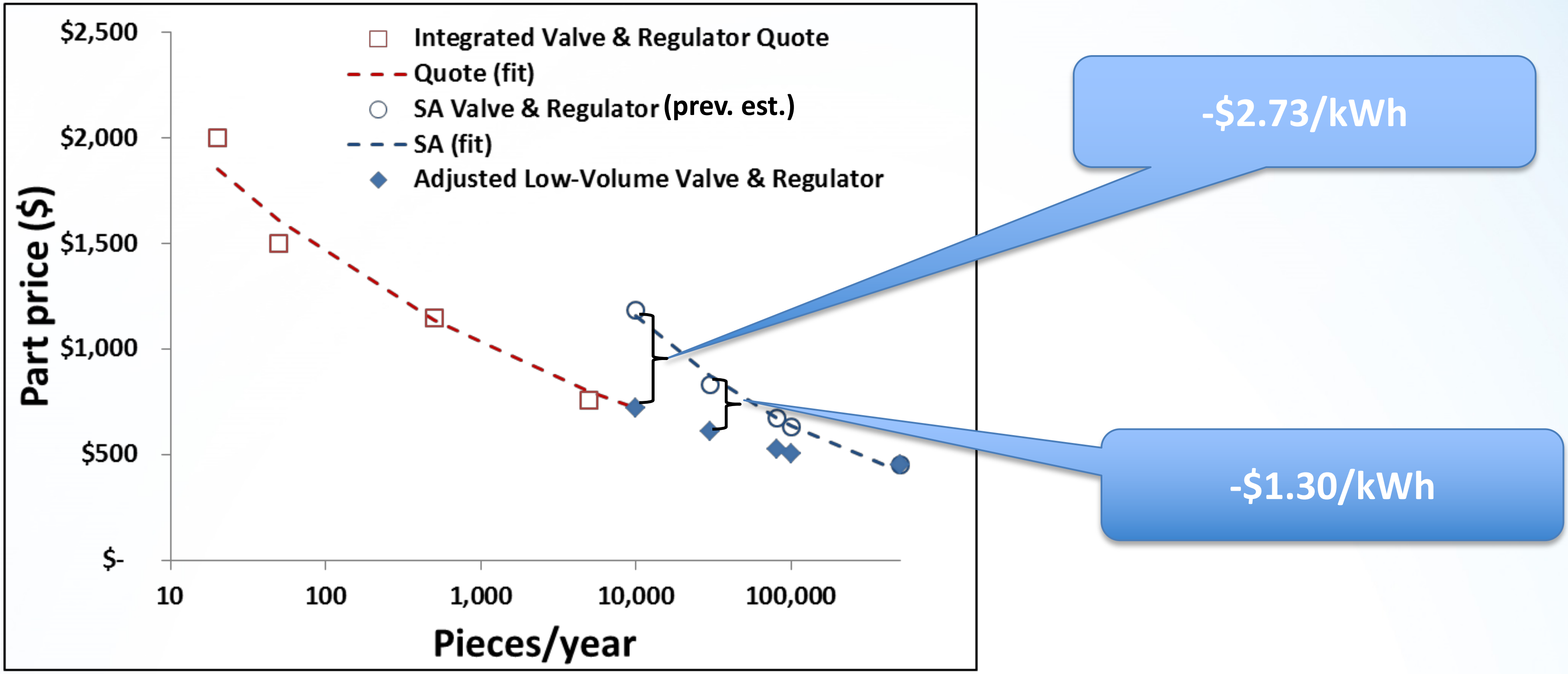
- Three carbon fiber models (SA, Das, Kline) suggest 24k tow 700 ksi CF cost is ~$24-25/kg
- Industry estimate of T700 is $26/kg so either very small margins or models overestimate costs
- T700 price is compared with costs modeled for a 1,500 tonnes/year plant
- Low-cost precursor cost based on Das capital and operating cost reductions
- Oxidation plant scale-up costs based on assumed capital and operating cost reductions reported by Das and Kline
- High-volume CF price is the T700 price scaled by modeled high and low volume costs 26(19/25)=20



Das "Global Carbon Fiber Composites Supply Chain Competitiveness Analysis." 2016.
Kline "Cost Assessment of PAN-Based Precursor and Carbon Fiber." Automotive Composites Consortium (2007)

Accomplishments & Progress
Low-Volume Balance of Plant

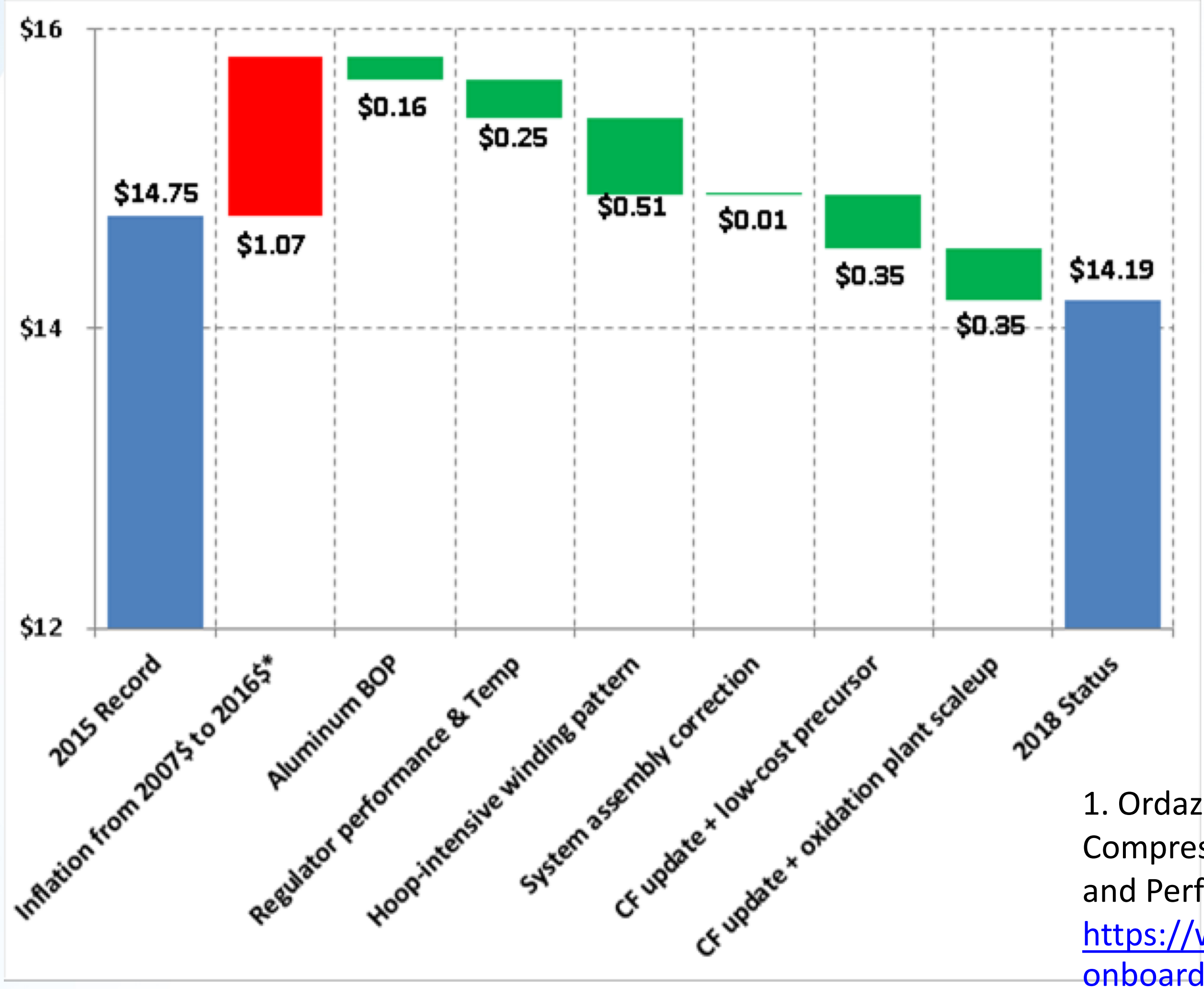
Low-volume Type 4 700 bar system costs revised to reflect available lower-cost BOP



- Currently modeled BOP is optimized for high volume (>100k systems per year)
- Quotes obtained for integrated 700 bar valve and regulator were used to scale DFMA costs modeled at low-volume

Accomplishments & Progress
Updates to the 700 bar LDV cost model

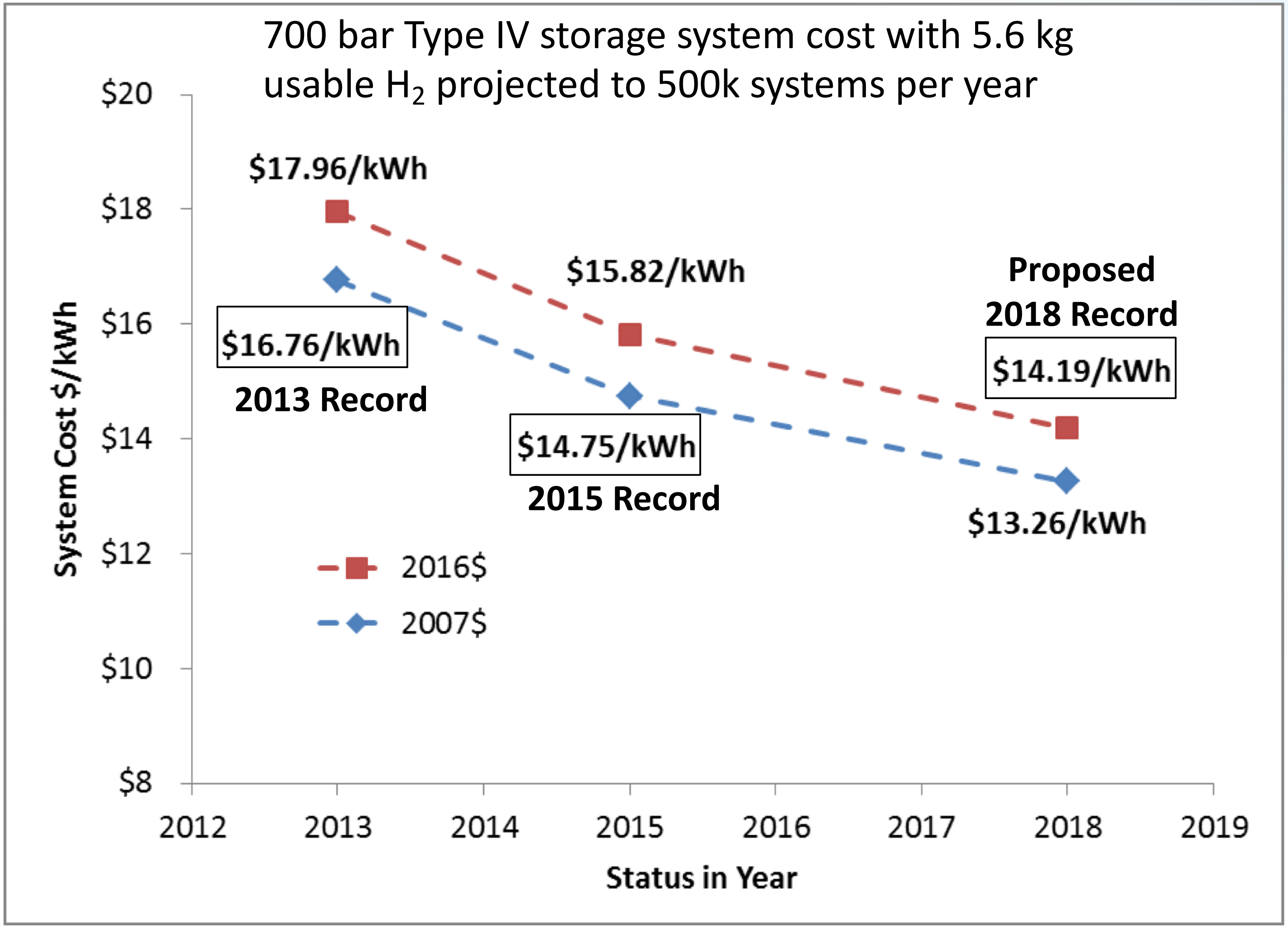
System cost changes (\$/kWh) to 700 bar Type 4 storage system at 500k/year



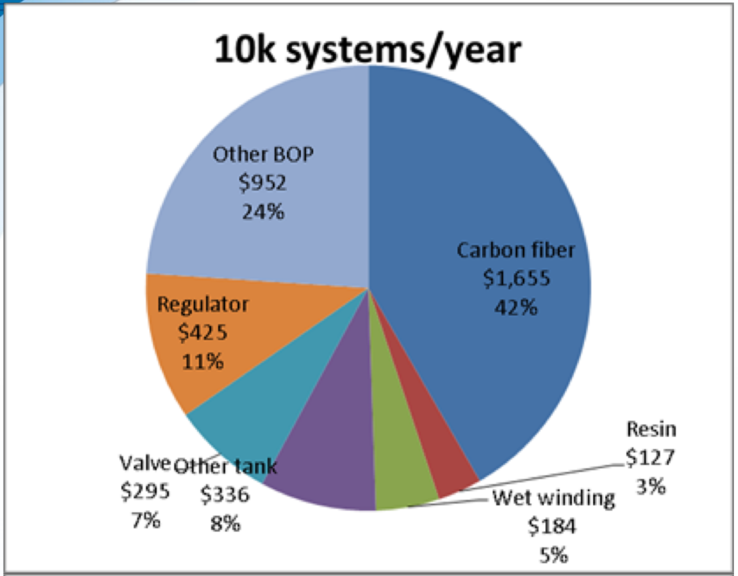
- Prepared report documenting changes to 700 bar Type 4 system (5.6 kg usable H_2) since 2015 DOE Program Record[1]
- Winding pattern, aluminum BOP, and regulator performance discussed previously (2018 AMR)
- Significant new changes this year are the dollar basis (2016\$) and updated carbon fiber

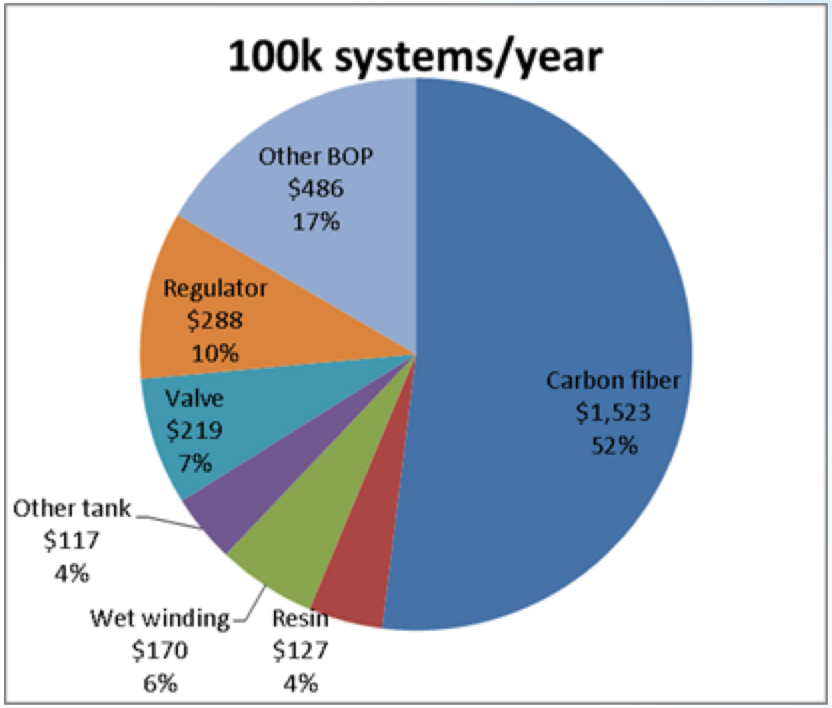
1. Ordaz, Houchins, and Hua. “Onboard Type IV Compressed Hydrogen Storage Systems--Cost and Performance Status 2015.” https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf.

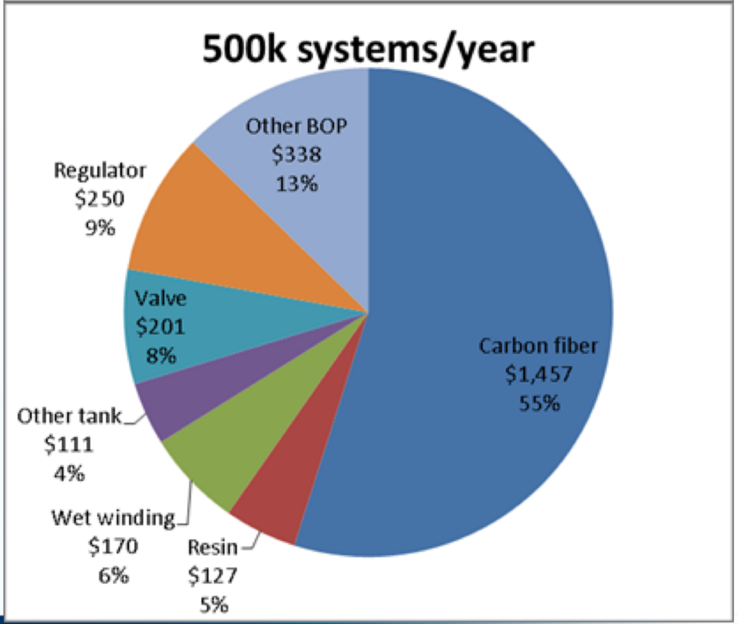
Lower DOE Record system costs projected despite complicating effect of inflation adjustment



Accomplishments & Progress
700 bar Type 4 system cost breakdowns

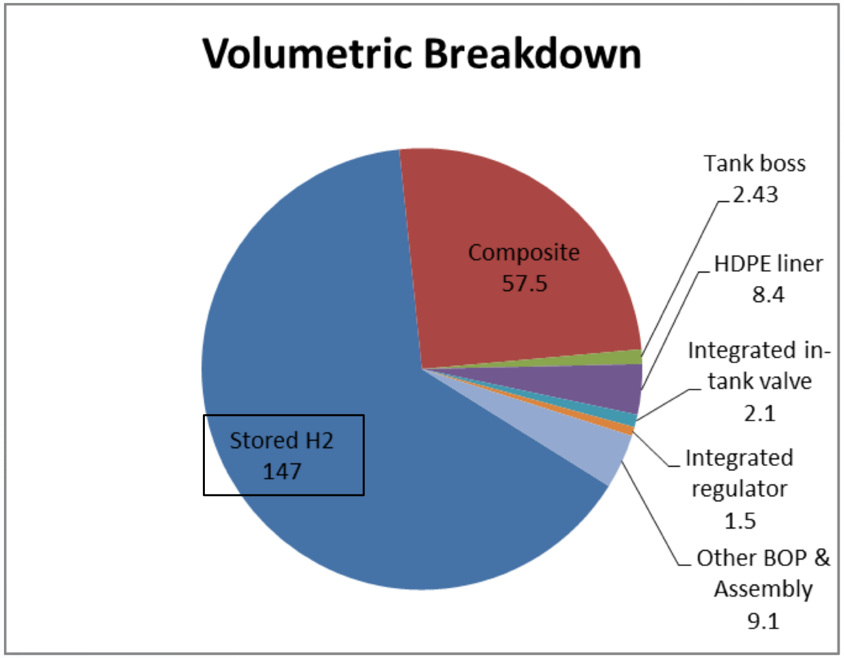


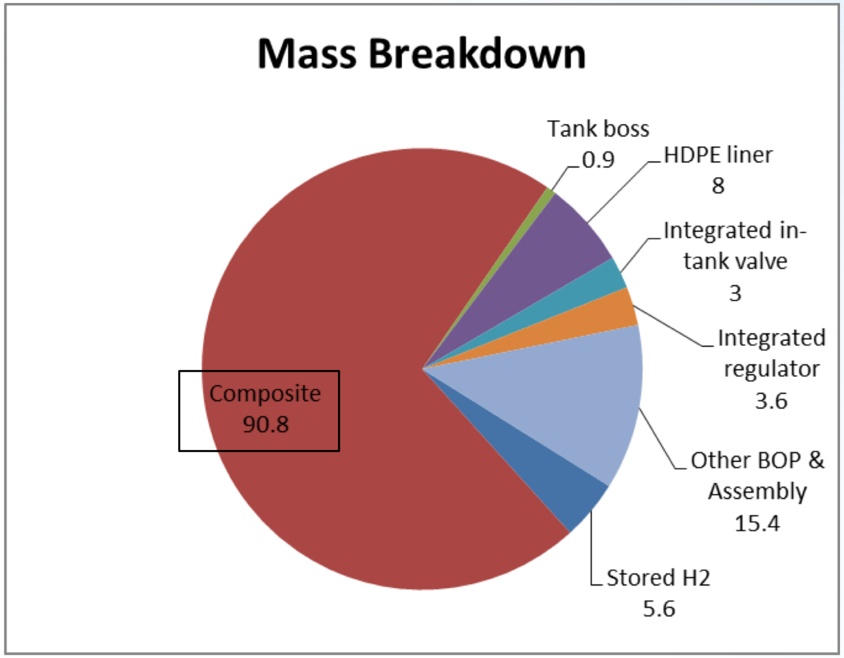




- Carbon fiber continues to represent >50% of the system cost at high volume (100k - 500k/year)
- BOP represents ~40% of the system cost at low volume (10k/year)
- 'Other BOP', which includes mounts, fuel controllers, receptacles, etc., is a large fraction of the total BOP cost low volume

Accomplishments & Progress
700 bar Type 4 system mass and volume breakdowns





- Total system volume is 226 L and volumetric capacity of 0.8 kWh/L
- Total system mass is 126 kg and gravimetric capacity of 1.5 kWh/kg
- Not surprisingly, stored H_2 is the dominate volume fraction and composite is the dominate mass fraction.

2018 Reviewer Comments

System	Value of analysis and recommendations	Actions to address/Response to reviewer
700 bar Type 4	The team should evaluate other BOP components for additional cost reductions.	We're in the process of updating BOP costs, especially at low volume, and have looked at additional component integration.
Metal hydride	Internal heat exchanger design cannot be easily repaired or replaced	There isn't a clear alternative for the reverse engineering system. We considered several designs and ultimately settled on the 'ship-in-a-bottle' as the only manufacturable pathway.
	Liner in a Type IV tank is susceptible to failure. Investigate Type 3.	We agree and have updated the model to address Type 3. The next metal hydride system examined will be Type 3.
CcH2	The cryo-compressed cost estimates should be validated by original equipment manufacturers that have produced these systems, since the cost projections do not seem to align with the current actual costs. The consistency of the cryo-compressed cost analysis should be confirmed for low volume to ensure the initial introduction of these technologies could be implemented without a significant cost penalty.	BMW and Westport were both consulted. We agree that our costs should be validated, but actual costs for cryo-compressed systems reflect their prototype or demonstration status. There is very little data available on comparable automotive-scale systems against which to validate. Thus our cost projections have large uncertainty bars.
General	Reviewers encouraged greater interaction with industrial partners.	We agree and continue to seek input from industry stakeholders.

Collaborations & Coordination

MDV/HDV Trucks	**ANL**—finite element analysis **Multiple fuel cell system integrators**—questionnaire sent to 5 system integrators **PNNL—**system assumptions and preliminary composite thickness estimates **NREL**—Coordinating on system assumptions to feed into a market segmentation analysis
700 bar Type 4 LDV	**ANL**—finite element analysis **PNNL**—BOP component modeling **System manufacturers**—carbon fiber pricing, process assumptions **Component suppliers**—pricing and performance assumptions
Frequently consulted	Mike Veenstra (Ford) and Norm Newhouse (Hexagon ret.)

Summary and Future Work

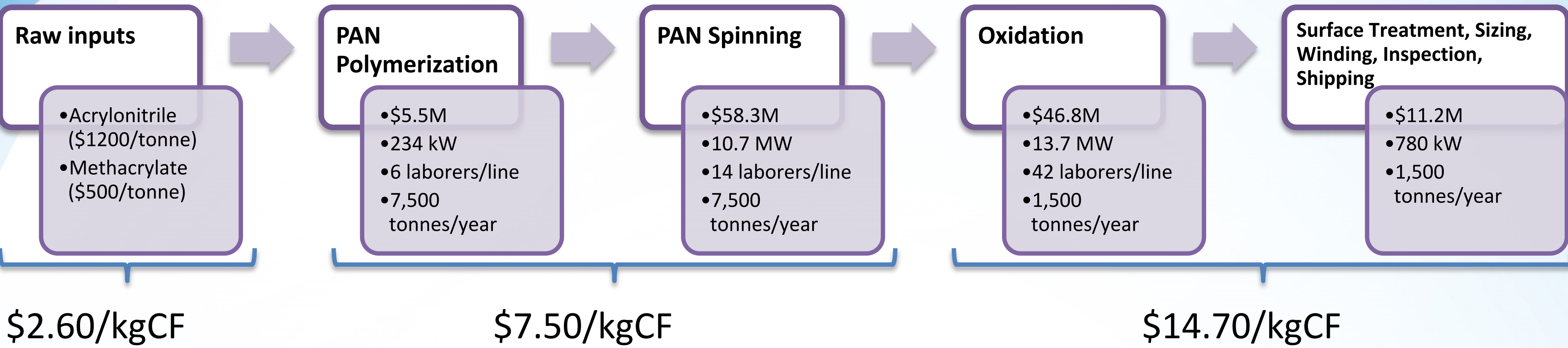
- **MDV/HDV Analysis**
  - **Summary of progress to date**
    - Three configurations (frame mounted, behind the cab, and roof mounted) adequately covers storage requirements for most vocations
    - Coordinating with ANL to address geometric effects and tradeoffs between numbers and sizes of tanks with duplicated BOP
  - **Future work**
    - Complete MDV/HDV analysis to help guide DOE targets
    - Investigate levelized costs (e.g. $/mile) to understand tradeoffs between 350 bar Type 3, 700 bar Type 4, and 500 bar CcH2
- **Baseline system cost update**
  - **Summary of progress to date:** updated system cost, including carbon fiber cost updates, are being finalized in a DOE Program Record
  - **Future work:** finalize and publish program record
- **Station storage analysis (new task)**
  - **Future work:** Analyze 1,000 kg/day station storage in for liquid and gaseous hydrogen to help support H2@Scale.

Thanks!

Backup slides

Accomplishments & Progress
Carbon fiber price updates

Simplified model assumptions



- Modeled CF cost is $24.8/kg compared to $24.30/kg for T700 (industry reported price) and $22.70/kg for Das[1] 24k tow modeled cost suggesting <u>recent T700 prices may not be sustainable</u>
- Model conventional PAN polymerization
  - PAN polymerization capital cost and operating assumptions provided by Sujit Das
  - Oxidation, surface treatments, etc. inputs from equipment supplier
  - Sujit CF competitiveness model assumes low-cost, high-volume precursor leading to a projected 26% precursor cost reduction
- Kline[2] reported that oxidation costs could be reduced by ~25% by increasing from 1,500 tonnes/year to 25,000 tonnes/year.
- Assuming plant efficiency increases by 20% per reported industry expert projections[1], modeled oxidation costs reduce by 22%.

1. Das et al. "Global Carbon Fiber Composites Supply Chain Competitiveness Analysis." 2016.
2. Kline and Company. "Cost Assessment of PAN-Based Precursor and Carbon Fiber." Presentation. Automotive Composites Consortium (2007)

MD/HD FC Truck System Comparison Table

	US Hybrid	Hydrogenics	Loop Energy	Ballard	Plug Power	Toyota	Power Cell
FC System Sizes	80kW (FCe80) (MD) 160kW (HD) – Acquired UTC PEM FC	Celerity 60kW (2 x 30kW) module (MD/HD)	56kWgross (50kWnet)	30kW (MD) 85kW (HD)	20kW (2x10kW)	228kW (HD) (2 Mirai stacks)	300kW (HD)
Truck Application	Drayage	Parcel delivery and refuse	Port/Distrib. Yard and Drayage	Regional/Local Drayage Class 8	Parcel Delivery (FedEx-style truck)	Drayage Class 8	Line-Haul
Demonstrations /Collaborations	Nissan (REX), Jiangsu Dewei Advance Matrls. Co.	Transpower, UPS , CTE (Center for Transportation and the Environment)	Peterbilt, CNGTC	Kenworth, BAE, Total Transportation Services (TTSI), CTE, Dongfeng, Lightning Systems	FedEx, Workhorse Group (DOE project)	Project Portal Semi: Kenworth T680 tractor	Nikola Motors, Fitzgerald Gliders Group, Ryder System, Thompson Caterpillar
FC Dominant/ FC Range Extender (REX)	Both	Both	REX	REX	REX	FC Dominant	REX (FC runs ~50% of time)

MD/HD FC Truck System Comparison Table (continued)

	US Hybrid	Hydrogenics	Loop Energy	Ballard	Plug Power	Toyota	Power Cell
Operating Temp	50C	70C	58-62C	~72C			
Pressure	~1 atm			~1.9 atm (est.)		<=2.5 atm	
H_2 Storage/range	25kg 200 miles	UPS: 10kg 125 miles/day		350 bar, 25kg 110-125 mi/day	350 bar 11.6kg H2 150-270 miles/route	200 miles	100kg 800-1,200 mi/fill
Other Notes	4k FC prod./month (planned), 30kWh battery	140kWh battery UPS: 20+yr lifetime, no external humidification	10yr lifetime	100kWh Battery – Kenworth/BAE 500 orders for Dongfeng (MD) 300 orders for Ford Transit	Battery: 80kWh TM4 Traction Motor 200 kW 2100 N-m	Battery: 12kWh, ~275kW	750kW total pwr Battery: 320kWh, 50k trucks/yr (planned) Range: 100-200 miles pure electr.