Cost analysis of compressed gas storage for medium and heavy duty vehicle applications

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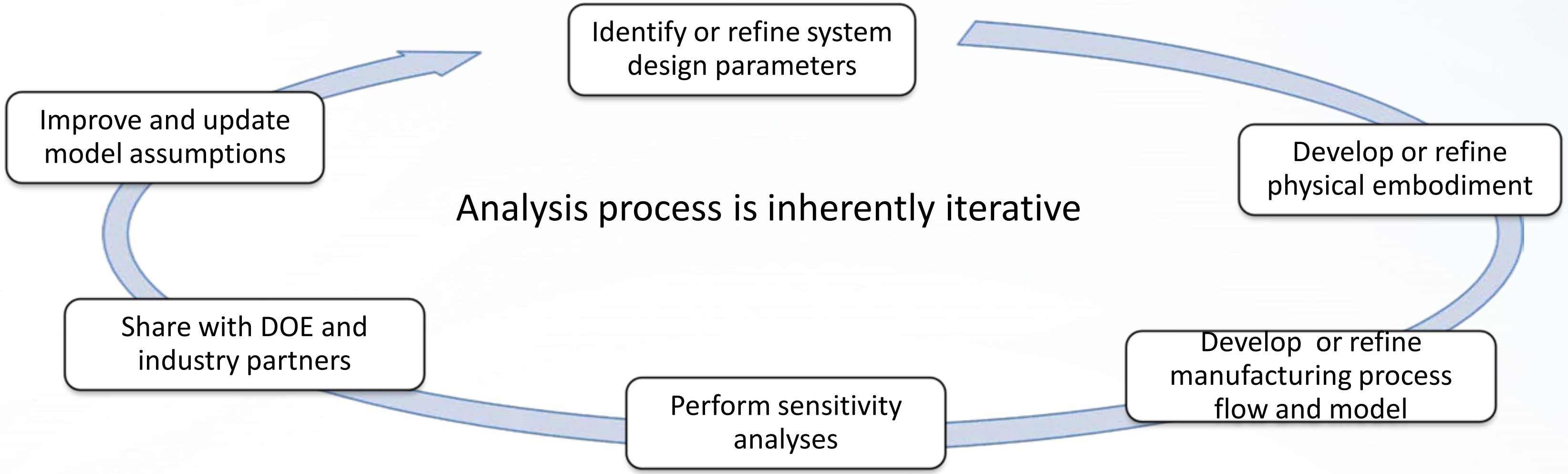
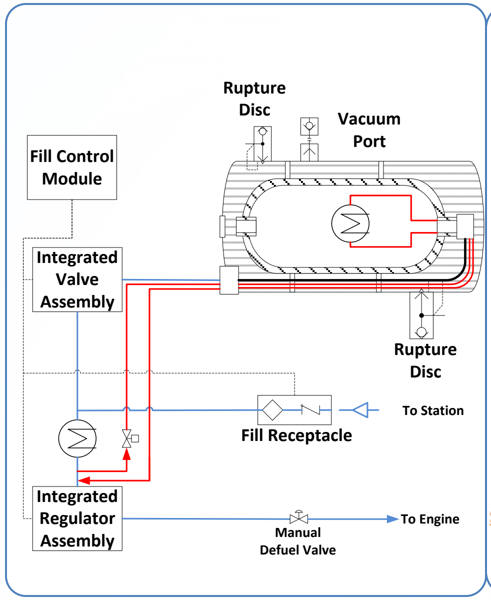
Compressed Gas Storage for Medium and Heavy Duty Transportation Workshop, 21 January 2020

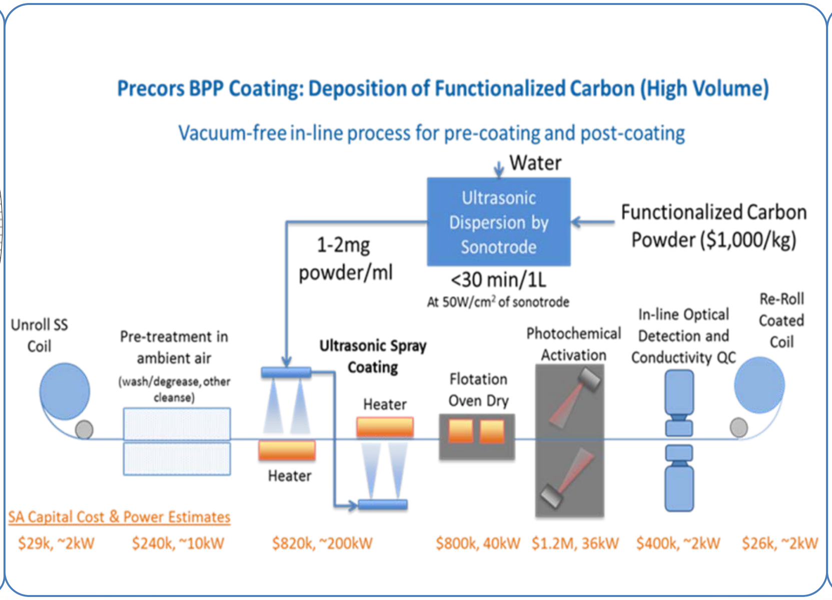
Overview of Our Approach to Cost Analysis



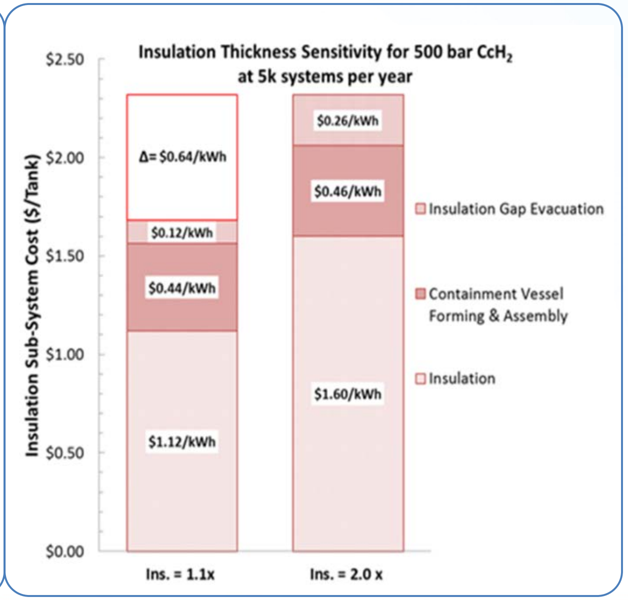
Embodiment



Process flow



Sensitivity analysis



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

What is DFMA® ?

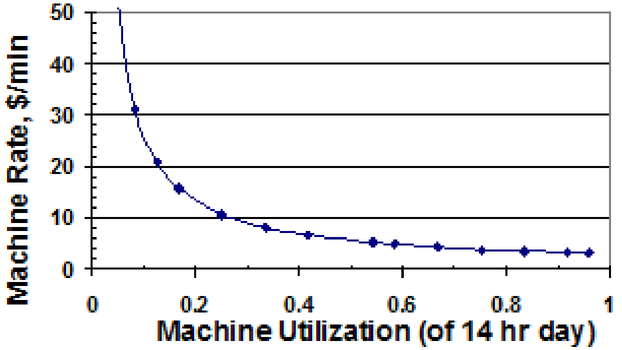
- DFMA® = Design for Manufacture & Assembly = Process-based cost estimation methodology
  - Registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Company (Ford) design/costing method for the past 20+ years
- SA practices are a blend of: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



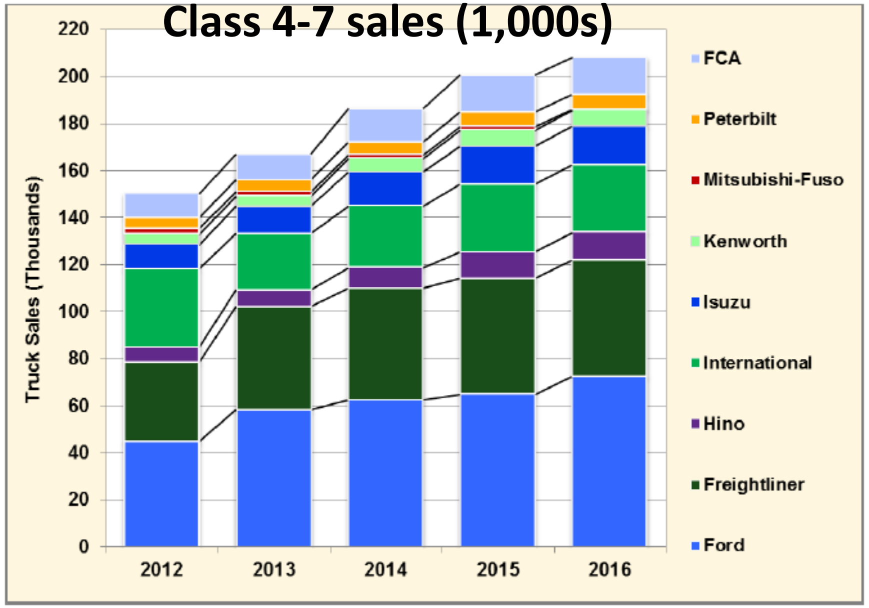
Methodology Reflects Cost of Under-utilization:

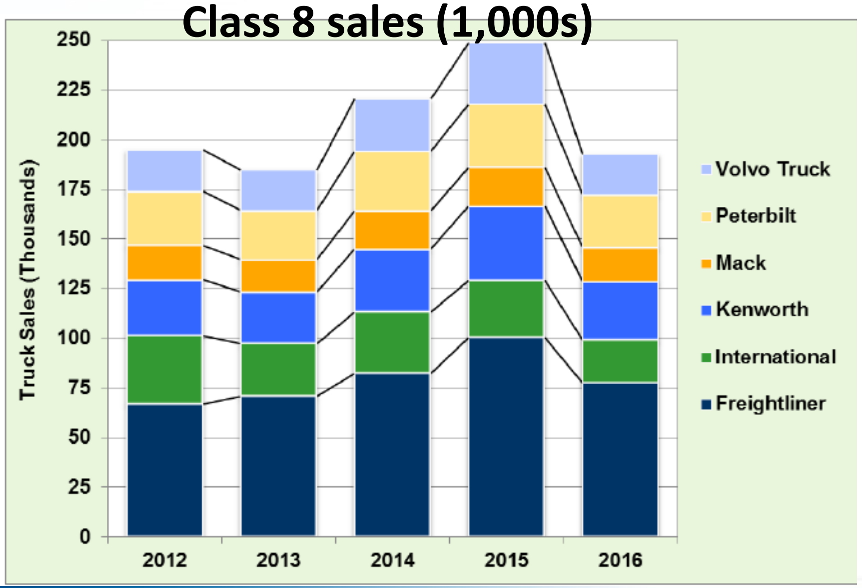
Capital Cost
Installation
} **Initial Expenses** → **Used to calculate annual capital recovery factor based on:**
- Equipment Life
- Interest Rate
- Corporate Tax Rate

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

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

U.S. Market Size of Medium and Heavy-Duty Vehicles





Combined US MDV/HDV manufacture ~400k

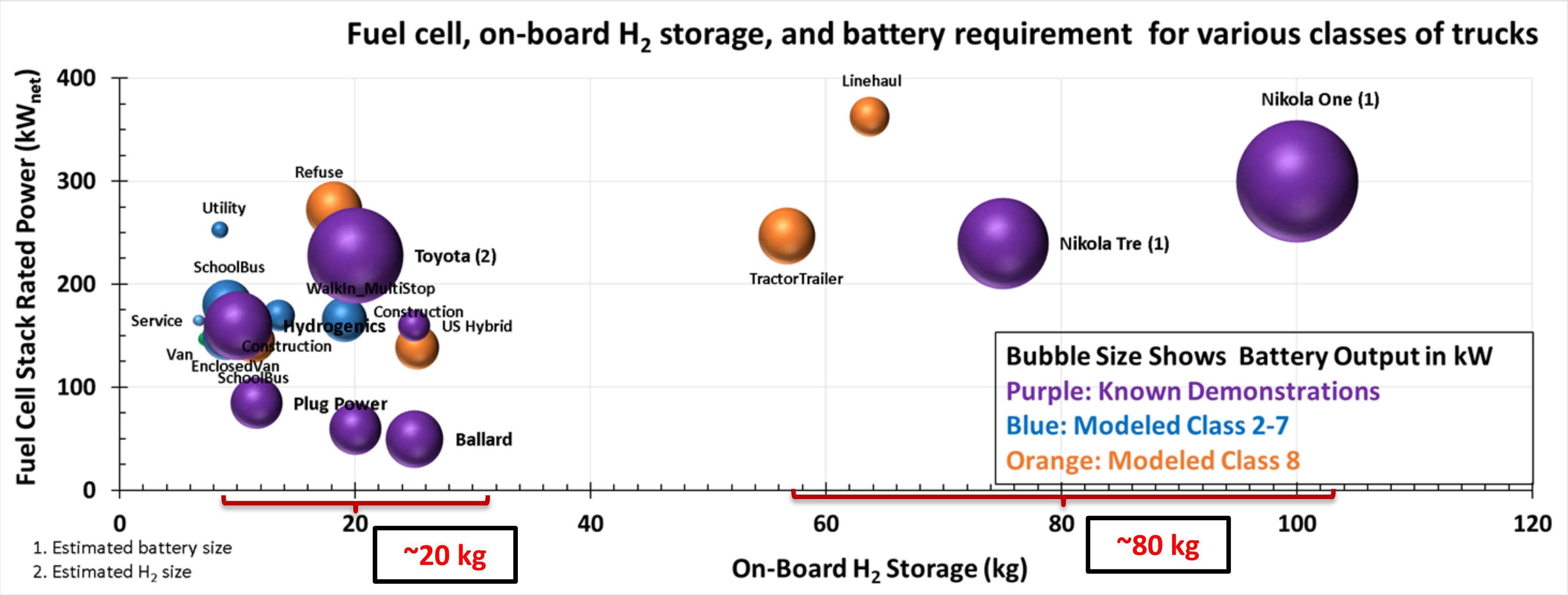
Compared to:

- **~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)

- **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

Projected On-board H_2 Storage Requirements

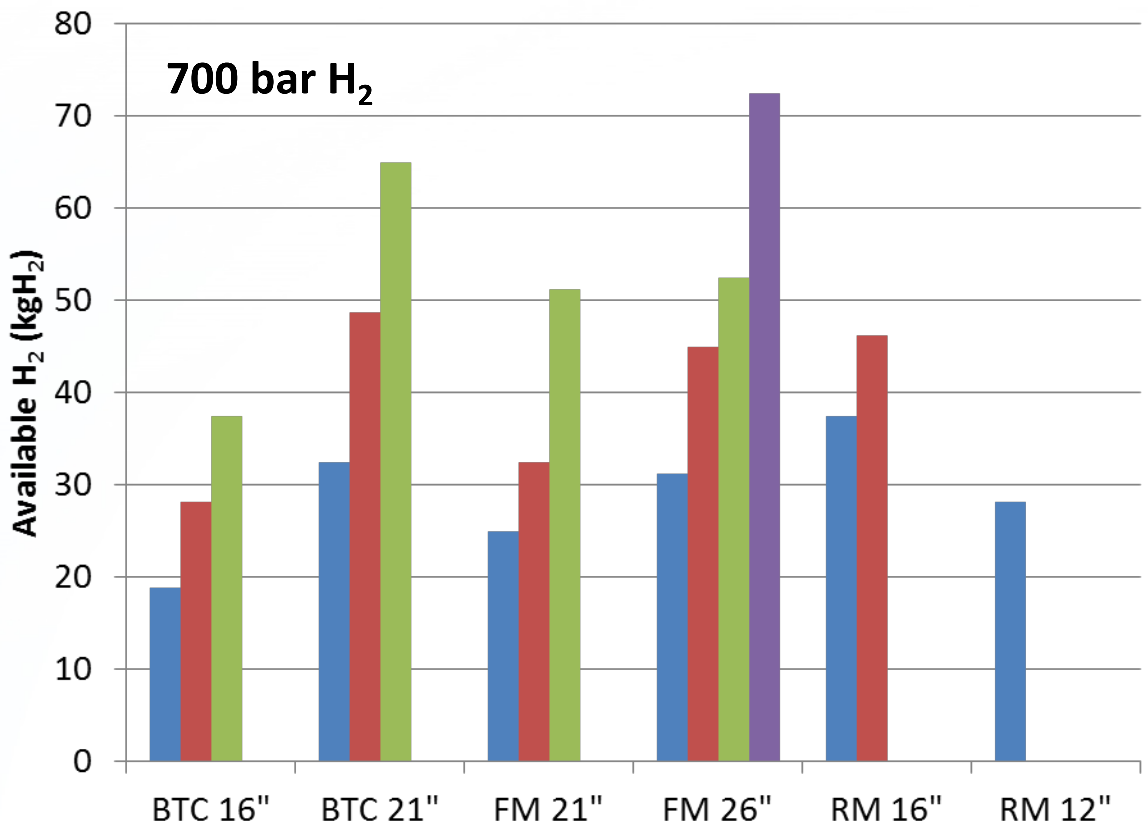


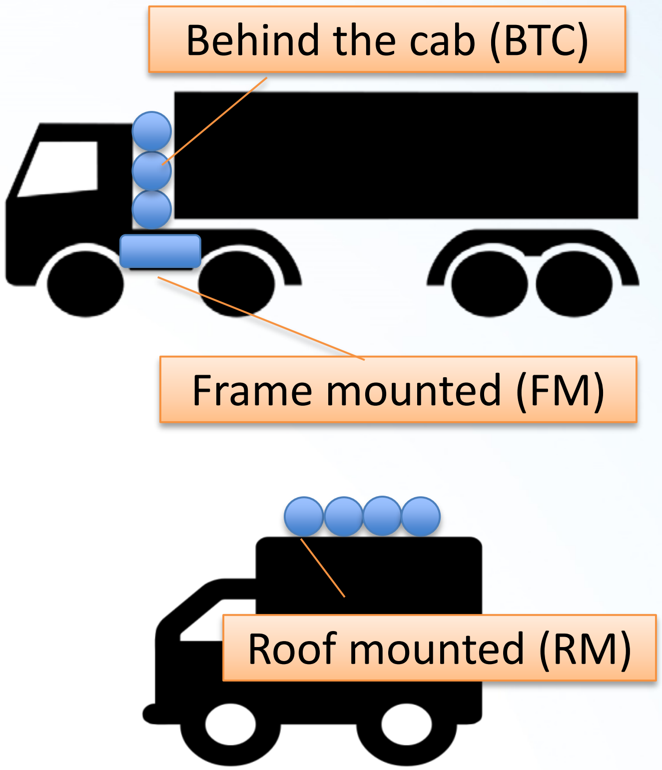
- ANL* conducted drive cycle analyses of several MDV and HDV vocations to determine optimal fuel cell, battery, & on-board H_2 requirements for a **fuel cell dominant architecture**
- 20 kg and 80 kg are representative H_2 storage systems for MDV and HDV, respectively
- However, the range is large:
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

* Vijayagopal (2016 AMR)

Packaging Options

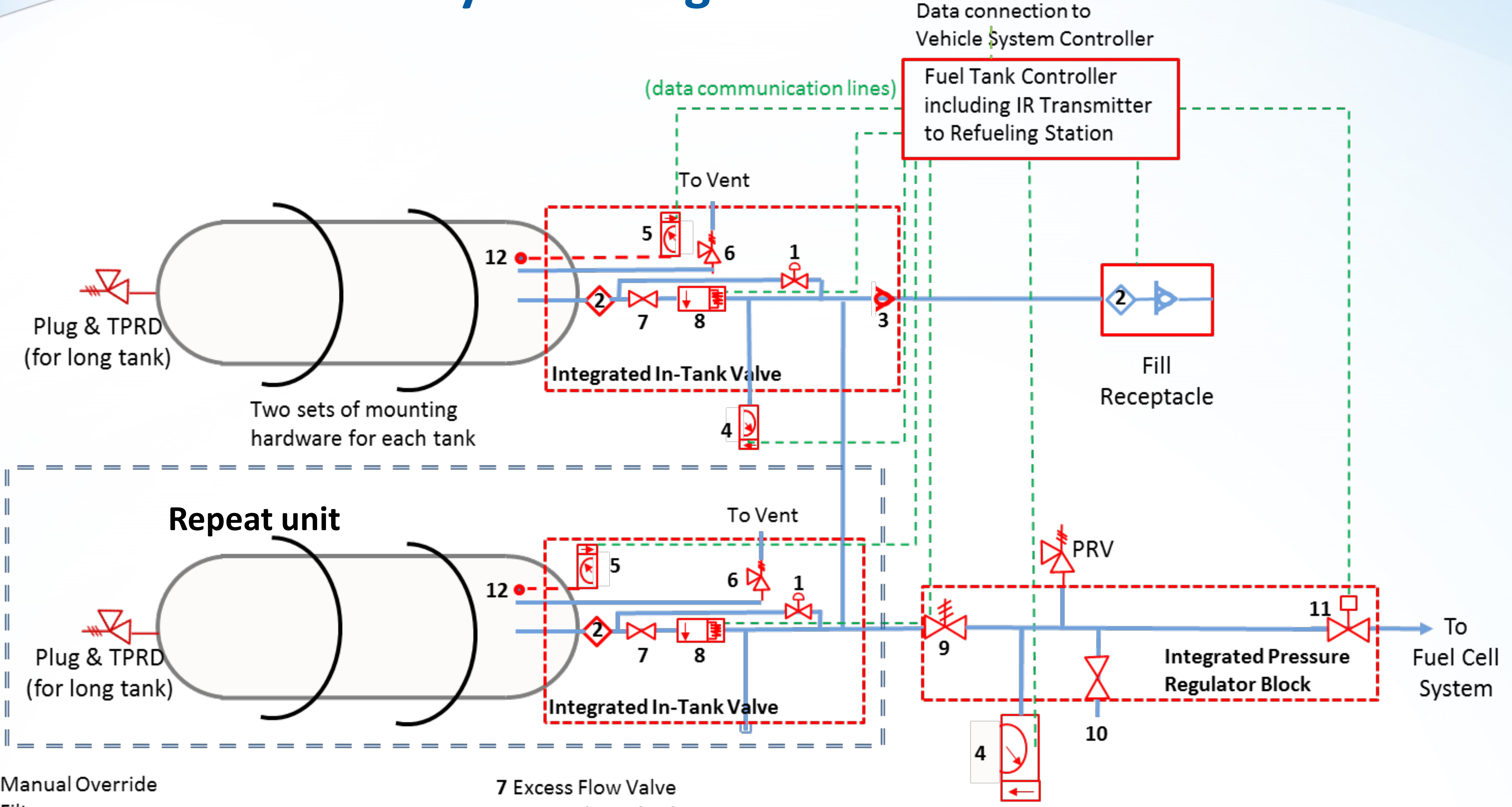
- H_2 storage capacity estimated from envelope[1]
- Based on commercially available CNG packages[2]
- Available H_2 stored mass shows several available configurations, including multiple tanks and different tank sizes.





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

System Diagram



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

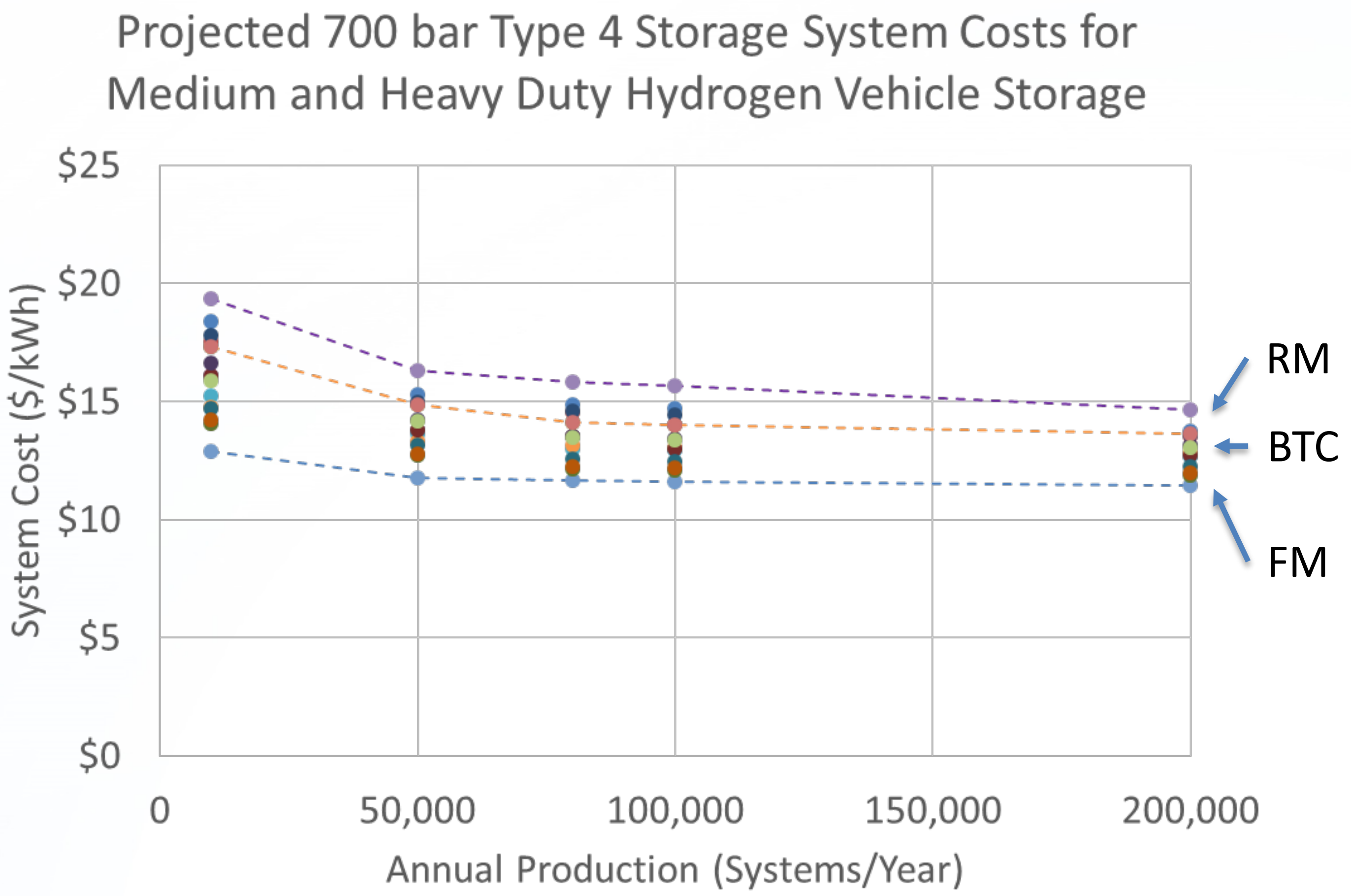
Carbon Fiber Estimates

	Internal Volume (DGE)	Length (inches)	Diameter (inches)	Type	Li/Di	Storage Pressure (bar)	Liner Type	Usable H2 (kg)	ANL: ρ= 1.58 [g/cm3] σu=2550 [Mpa] (VcF=60%) Liner THK, mm	comp THK, mm	liner Weight kg	comp Weight kg	PNNL: ρ= 1.57 [g/cm3] σu=2762.5 [Mpa] (VcF=65%) Liner THK, mm	Comp THK, mm	liner Weight kg	Comp Weight, kg
Behind the Cab																
cH2	30	80	16	4	5	700	HDPE	9.7	5	35.4	13.1	165.6	5	32.7	13.1	152
Behind the Cab																
cH2	52	80	21	4	3.8	700	HDPE	16.3	5	47.3	17.5	280.5	5	43.7	17.5	257.5
Frame Mounted																
cH2	40	60	21	4	2.9	700	HDPE	11.9	5	47.3	13.4	207.9	5	43.7	13.4	190.9
cH2	52	80	21	4	3.8	700	HDPE	16.3	5	47.3	17.5	280.5	5	43.7	17.5	257.5
cH2	82	120	21	4	5.7	700	HDPE	25.3	5	47.3	25.9	425.6	5	43.7	25.9	390.8
Frame Mounted																
cH2	50	60	26	4	2.3	700	HDPE	17.5	6.2	58.4	20.2	313.9	6.2	54	20.2	288.2
cH2	72	80	26	4	3.1	700	HDPE	24.4	6.2	58.4	26.4	421.2	6.2	54	26.4	386.7
cH2	84	90	26	4	3.5	700	HDPE	27.8	6.2	58.4	29.6	474.9	6.2	54	29.6	436
cH2	116	120	26	4	4.6	700	HDPE	38.1	6.2	58.4	39	635.8	6.2	54	39	583.8
Roof Mounted																
cH2	60	80	16	4	5	700	HDPE	9.7	5	35.4	13.1	165.6	5	32.7	13.1	152
cH2	74	96	16	4	6	700	HDPE	11.7	5	35.4	15.7	199.1	5	32.7	15.7	182.8
cH2	45	97	12	4	8.1	700	HDPE	6.7	4	28.2	9.6	118.2	4	26.1	9.6	108.5

- Close collaboration with Argonne National Lab (Rajesh Ahluwalia and Hee-Seok Roh)
- ANL estimated composite masses for several tank sizes and aspect ratios (L/D)
- Tank dimensions are based on A1 Alternative Fuel Systems product sheets*

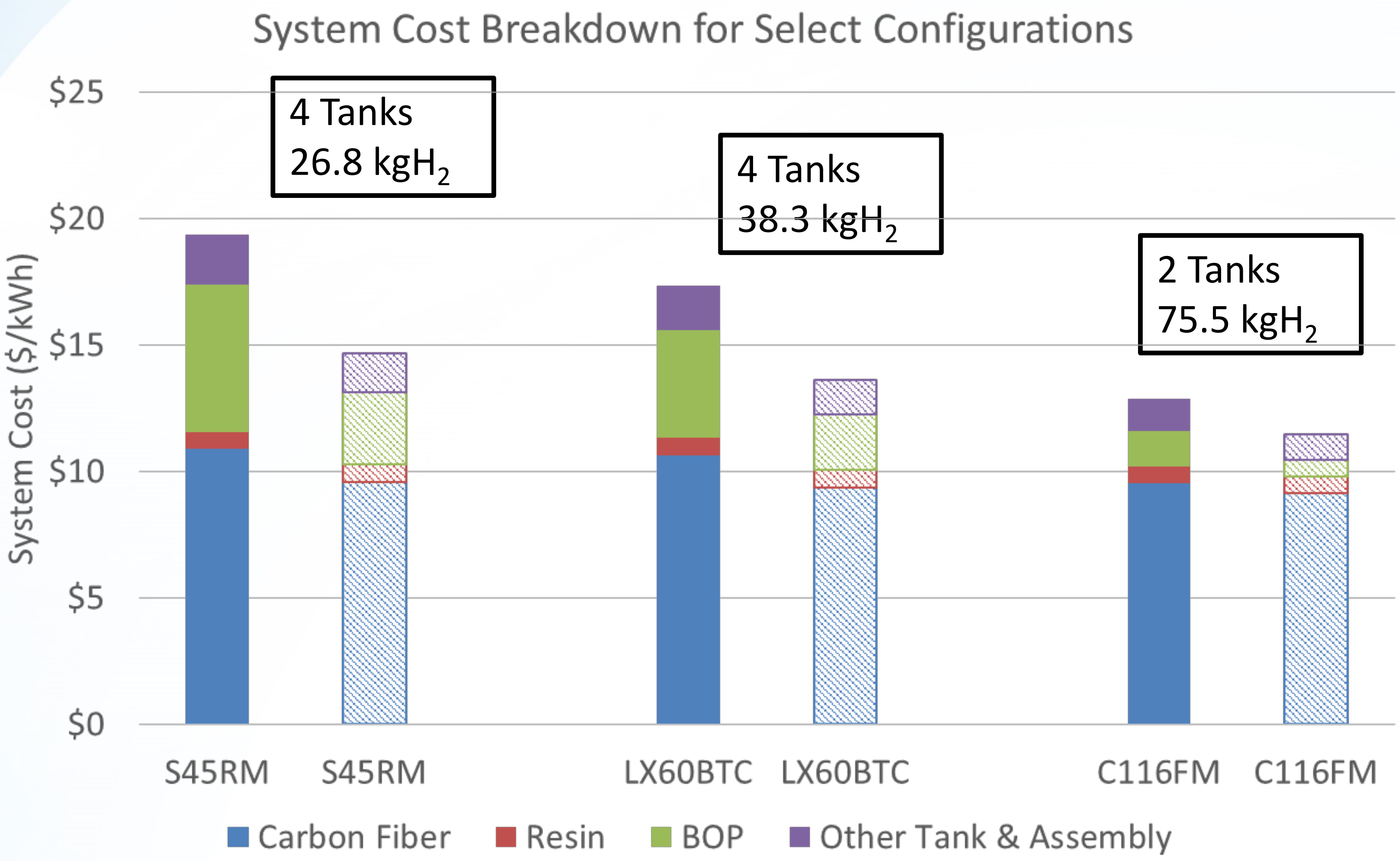
*http://www.a1autoelectric.com/alternative-home/fuel-systems-integration/

Survey of System Cost



- System costs are normalized to total energy content (33.33 kWh/kgH_2)
- Range System cost is a function of
  - Storage system volume (total kgH2)
  - Number of tanks (valves)
  - Production rate dependence strongly depends on system size driven by annual carbon fiber purchasing power.

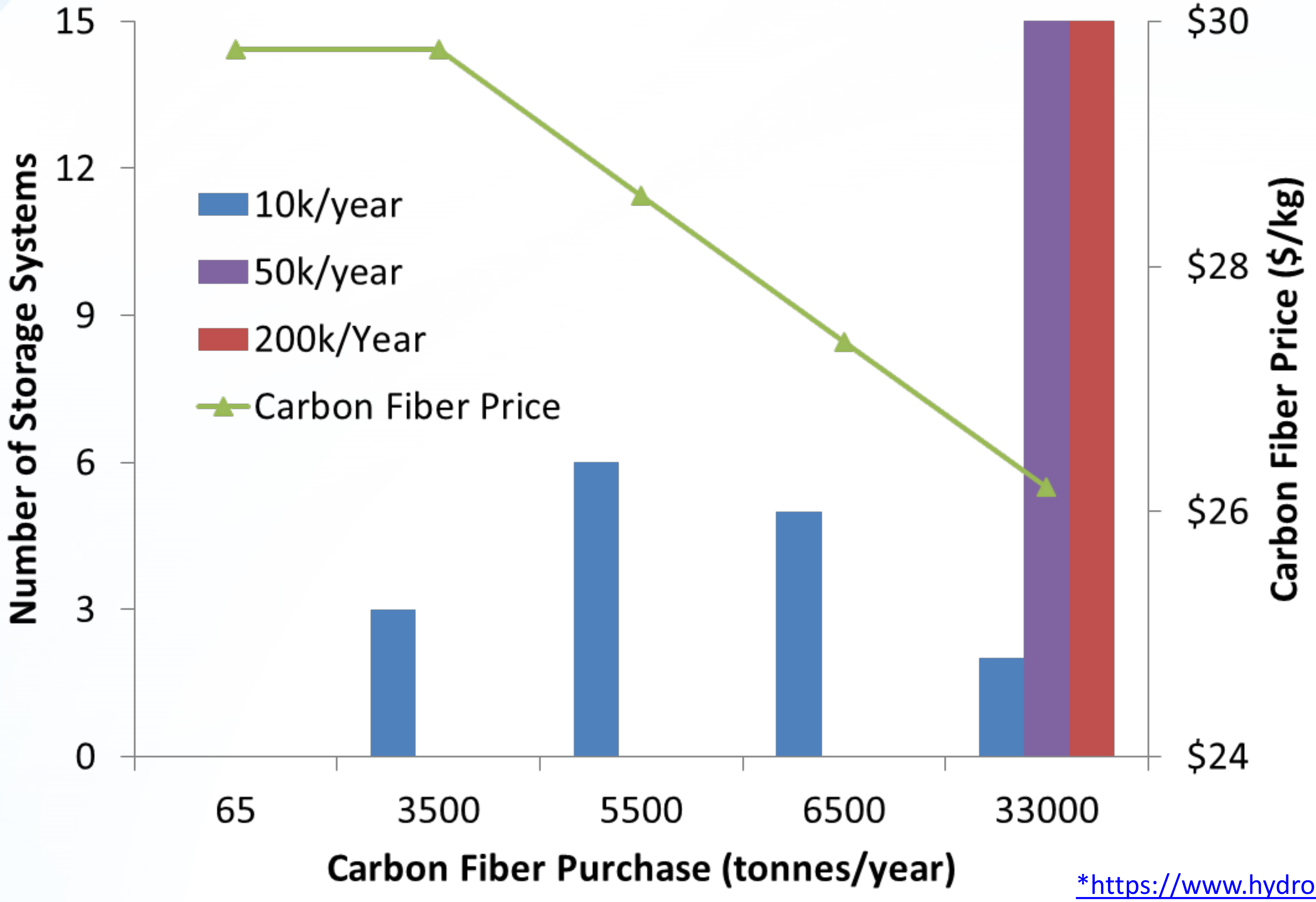
System Cost Breakdown Comparisons



- Breakdowns for three configurations: roof-mounted, behind-the-cab, and frame-mounted.
- Carbon fiber mass is (mostly) invariant with tank dimensions
- BOP cost (per kWh) is relatively smaller for larger storage volumes

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

Significant Carbon Fiber Purchasing Power is Possible at 'Low' Numbers of Storage System Production Rates



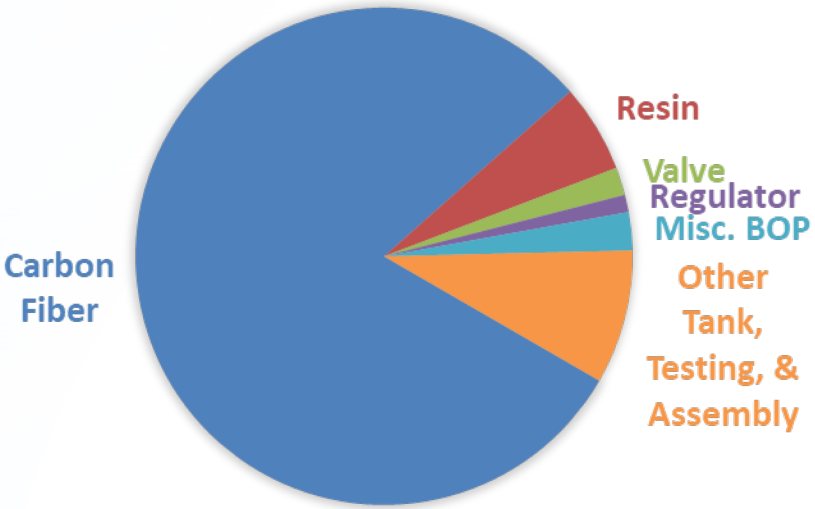
- Carbon fiber is based on T700S price curves reported in the 2019 DOE Record*
- Histogram shows number of systems from slide 8 that fall within the annual carbon fiber purchase volume bin (e.g. 3 storage systems fall within the 3500 tonnes/year bin when produced at 10k systems per year)
- Because the storage systems are relatively large and there are multiple tanks, the annual carbon fiber purchase quantity approaches the annual output of a single large carbon fiber processing line at around 50k systems per year
- For perspective, 50k is around 10% of the combined annual sales of medium and heavy-duty vehicle shown in slide 4

*https://www.hydrogen.energy.gov/pdfs/19008_onboard_storage_cost_performance_status.pdf.

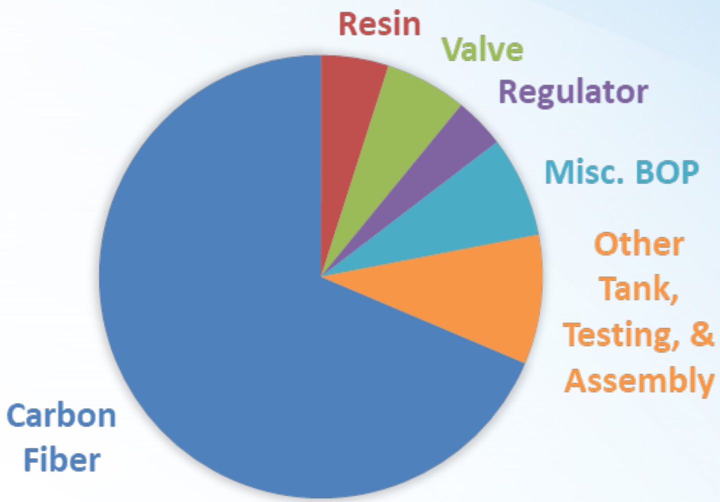
Some More Cost Breakdowns…

- Note relative fraction of total cost from Carbon Fiber for the frame-mounted (75.5 kgH_2) vs. behind-the-cab (20 kgH_2 and 40 kgH_2) storage systems
- Also note valve cost fraction (vs. regulator) for 2 vs. 4 tank BTC

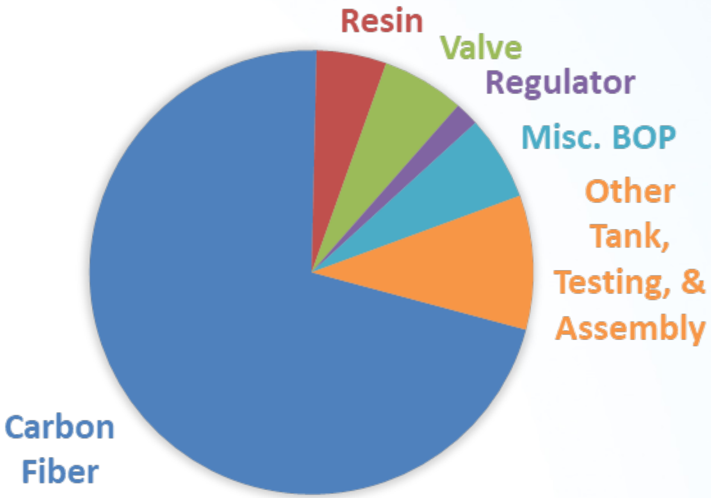
C116FM @200K/YEAR
2 TANK SYSTEM



LX30BTC @200K/YEAR
2 TANK SYSTEM

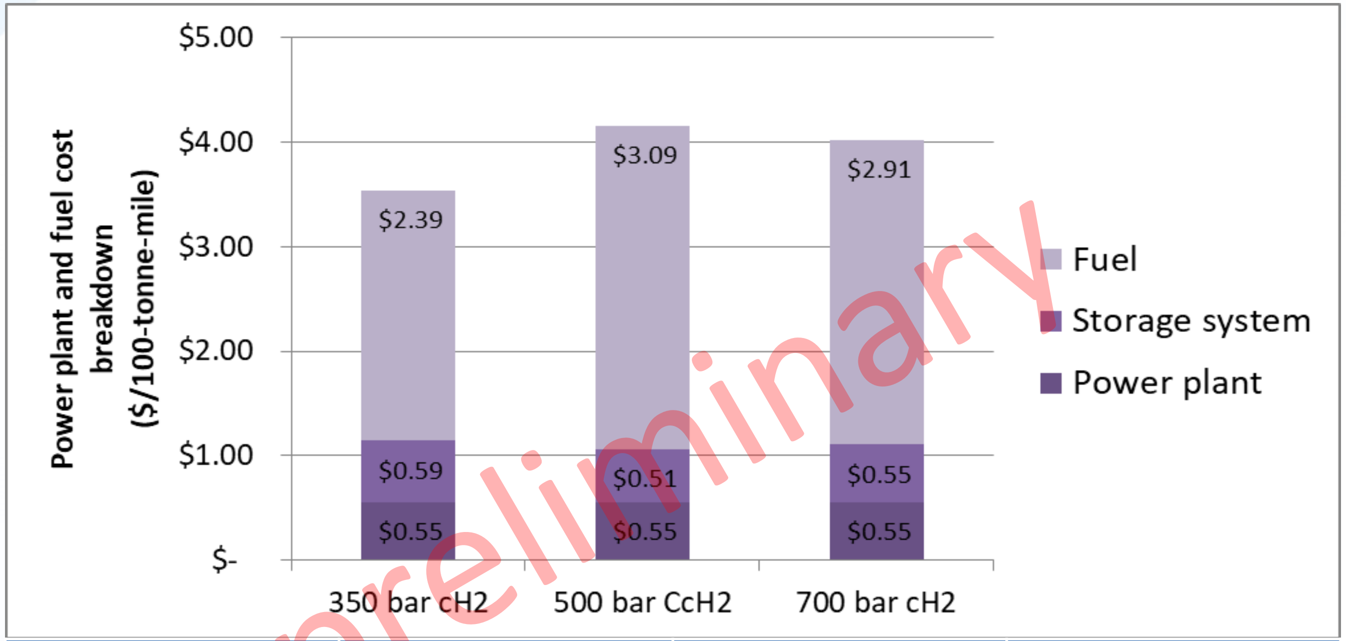


LX60BTC @200K/YEAR
4 TANK SYSTEM



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

Targets Need to Account for Operating Costs



Parameter	350 bar Type 3 cH_2	500 bar CcH_2	700 bar Type 4 cH_2
Fuel	$3.00/kg	$3.87/kg	$3.65/kg
Gravimetric Capacity	0.044 wt%	0.11 wt%	0.06 wt%
Storage System	$30/kWh	$26/kWh	$28/kWh
Battery	$500/kWh	$500/kWh	$500/kWh
Fuel Cell System	$100/kW	$100/kW	$100/kW

- Rough analysis of system operating costs for an 80 ton long haul truck comparing three on-board fueling options: 350 bar Type 3, 700 bar Type 4, and 500 bar cryo-compressed
- Goal is to estimate the operating costs on a tonne-mile basis by evaluating the lost freight capacity due the mass of the storage and power plant.
- The storage system, fuel cell system and battery estimates are based on the very conservative ranges from our analysis.
- Fuel costs are estimated from ANL*. Dispensing costs are from ANL analysis are for light-duty vehicle refueling

*https://www.hydrogen.energy.gov/pdfs/review19/sa170_elgowainy_2019_o.pdf

Conclusions

- For vehicles with very large fuel storage requirements, carbon fiber is the only effective cost reduction parameter.
- For vehicles with smaller on-board storage and multiple tanks, the repeated in-tank valve adds significant cost.
- Targets need to address operating expense of vehicle (reduce $/ton-mile).
  - Higher storage densities (e.g. cryo-compressed) may be an attractive option for improving the $/ton-mile opex **if** the refueling costs can be improved.
  - Improved fuel economy can reduce the total storage system size

Thanks!

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Storage 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		

Carbon Fiber Price Schedule (Based on T700S)