Onboard Type IV Compressed Hydrogen Storage System Cost Analysis

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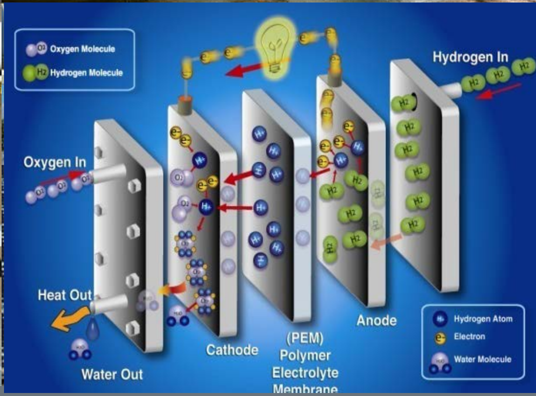

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U.S. Department of Energy
Fuel Cell Technologies Office
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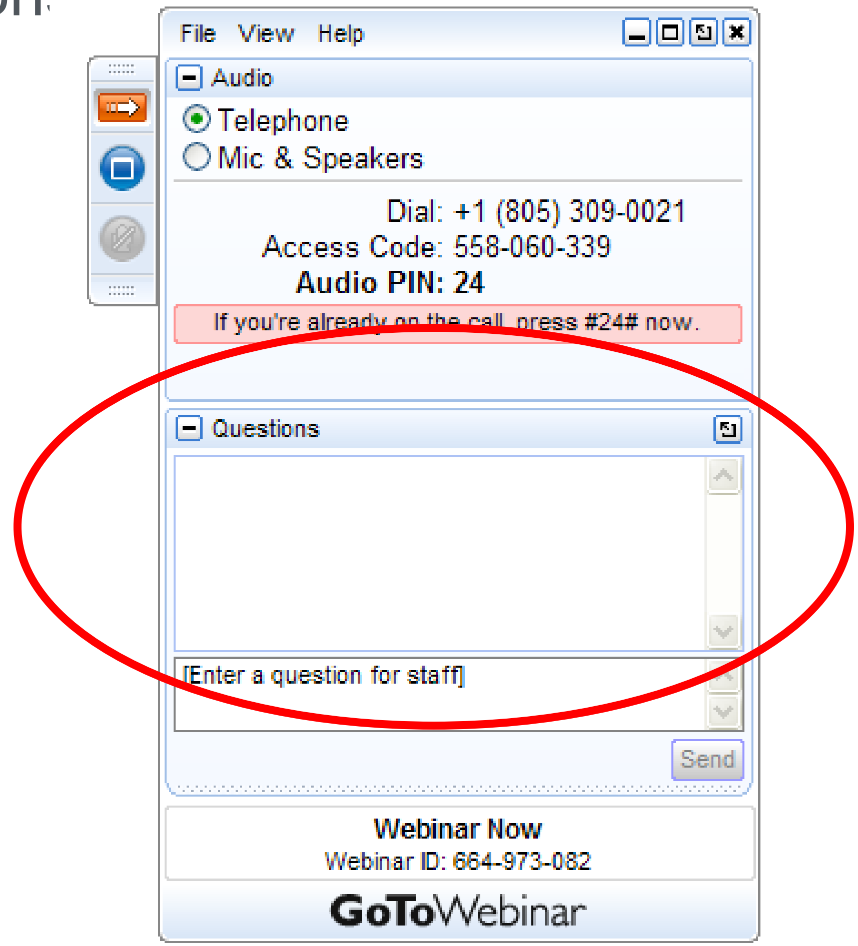
- Please type your questions into the question box



Onboard Type IV Compressed Hydrogen Storage System Cost Analysis

Funded by the U.S. Department of Energy's Fuel Cell Technologies Office

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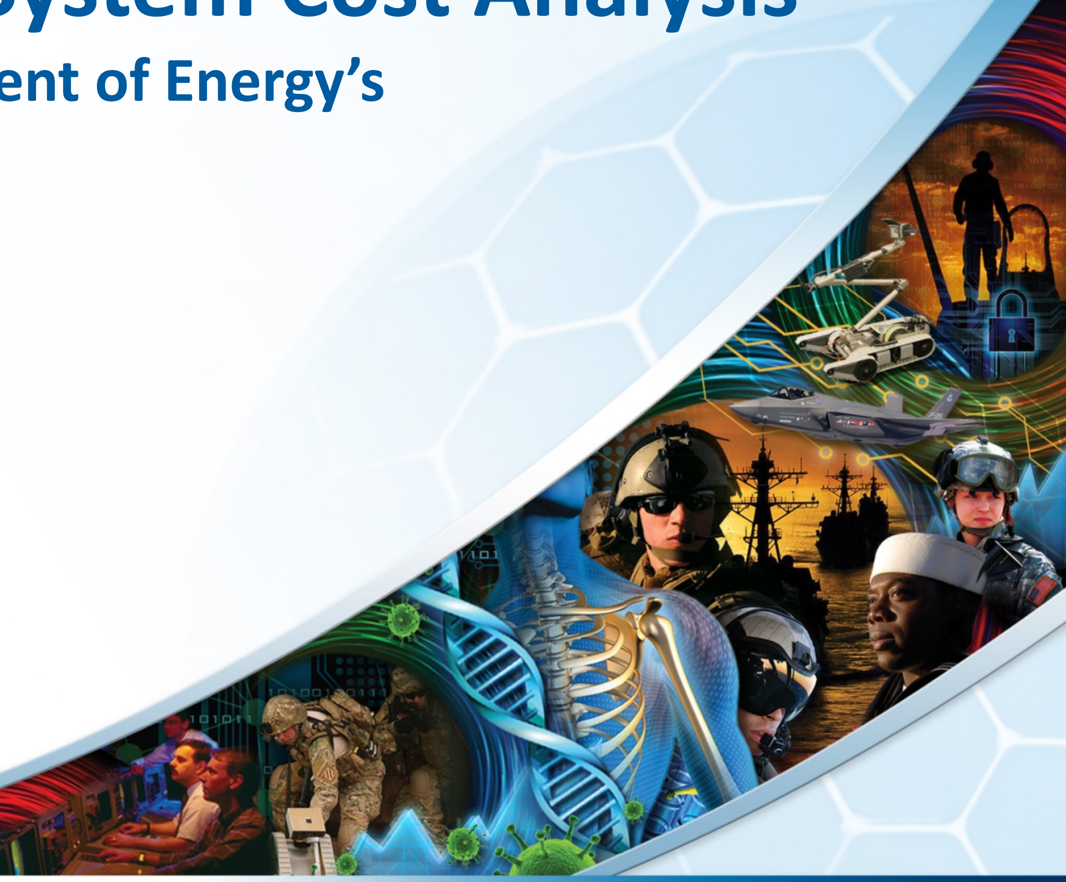
FCTO Webinar
1/26/2016



Overview

- Cost methodology—DFMA® primer
- System diagram
- System cost status comparison between 2013 and 2015
- Cost reductions
  - Balance of Plant
  - Resin with lower density and cost
  - Carbon fiber from high volume process
- Cost increases
  - Doily removal
  - Manufacturing variations

SA's DFMA® - Style Costing Methodology

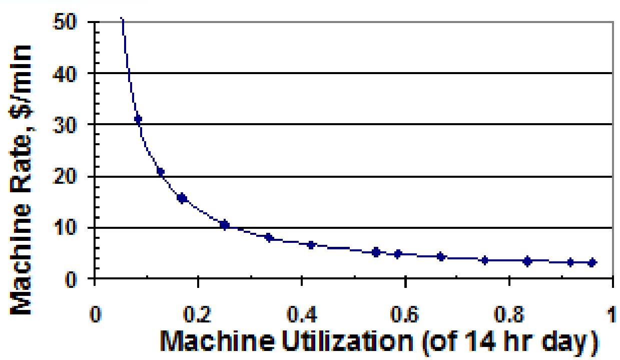
- DFMA® (Design for Manufacture & Assembly) is a registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Co. design/costing method for the past 20+ years
- SA practices are a blend of:
  - "Textbook" DFMA®, industry standards and practices, 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**

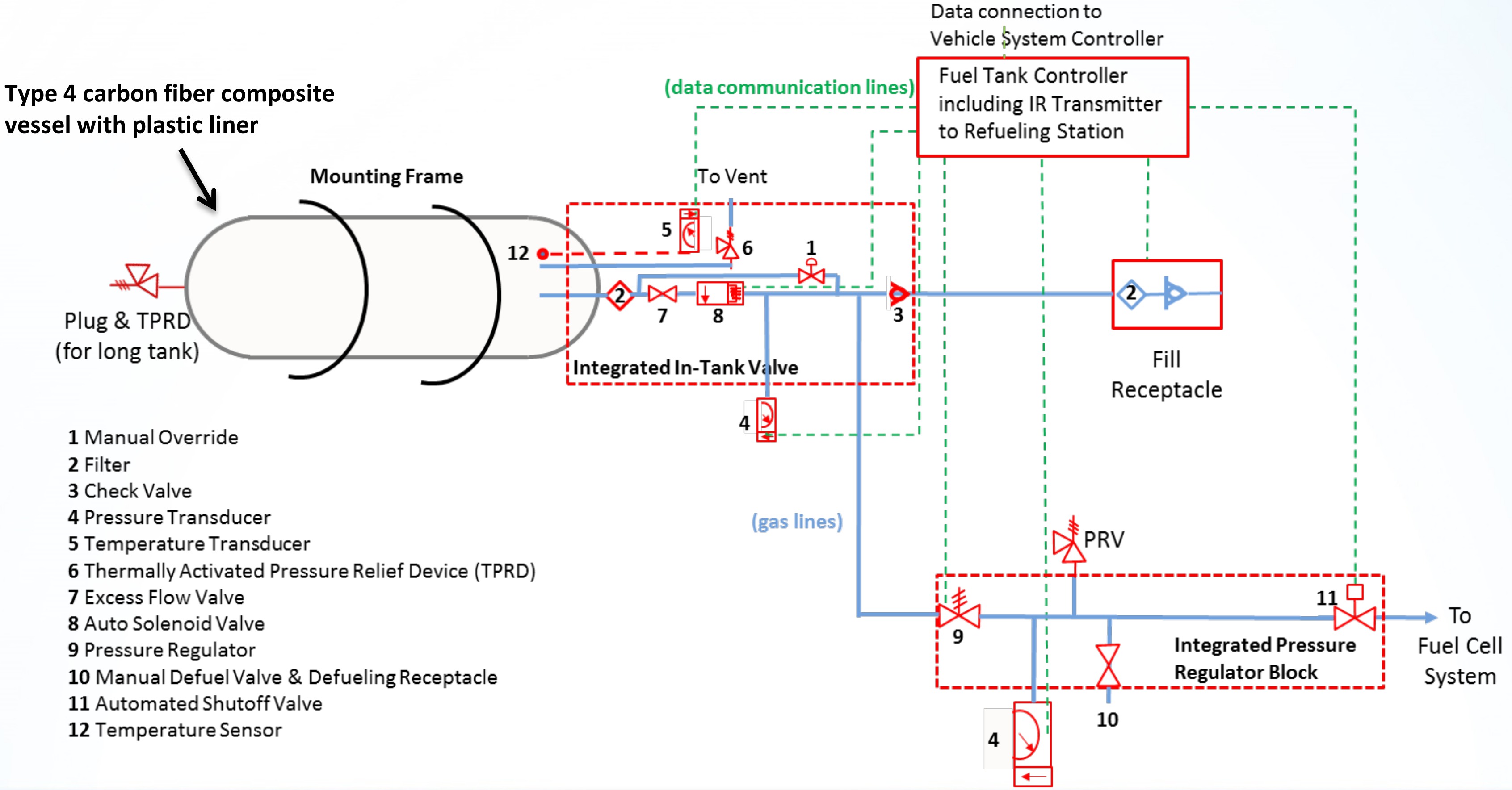
$$\frac{\left(\text{Annual Capital Repayment} + \text{Annual Operating Payments}\right)}{\left(\text{Annual Minutes of Equipment Operation}\right)} = \text{Machine Rate (\$/min)}$$

Production Volume Range of Analysis:

10,000 to 500,000 H_2 storage systems per year

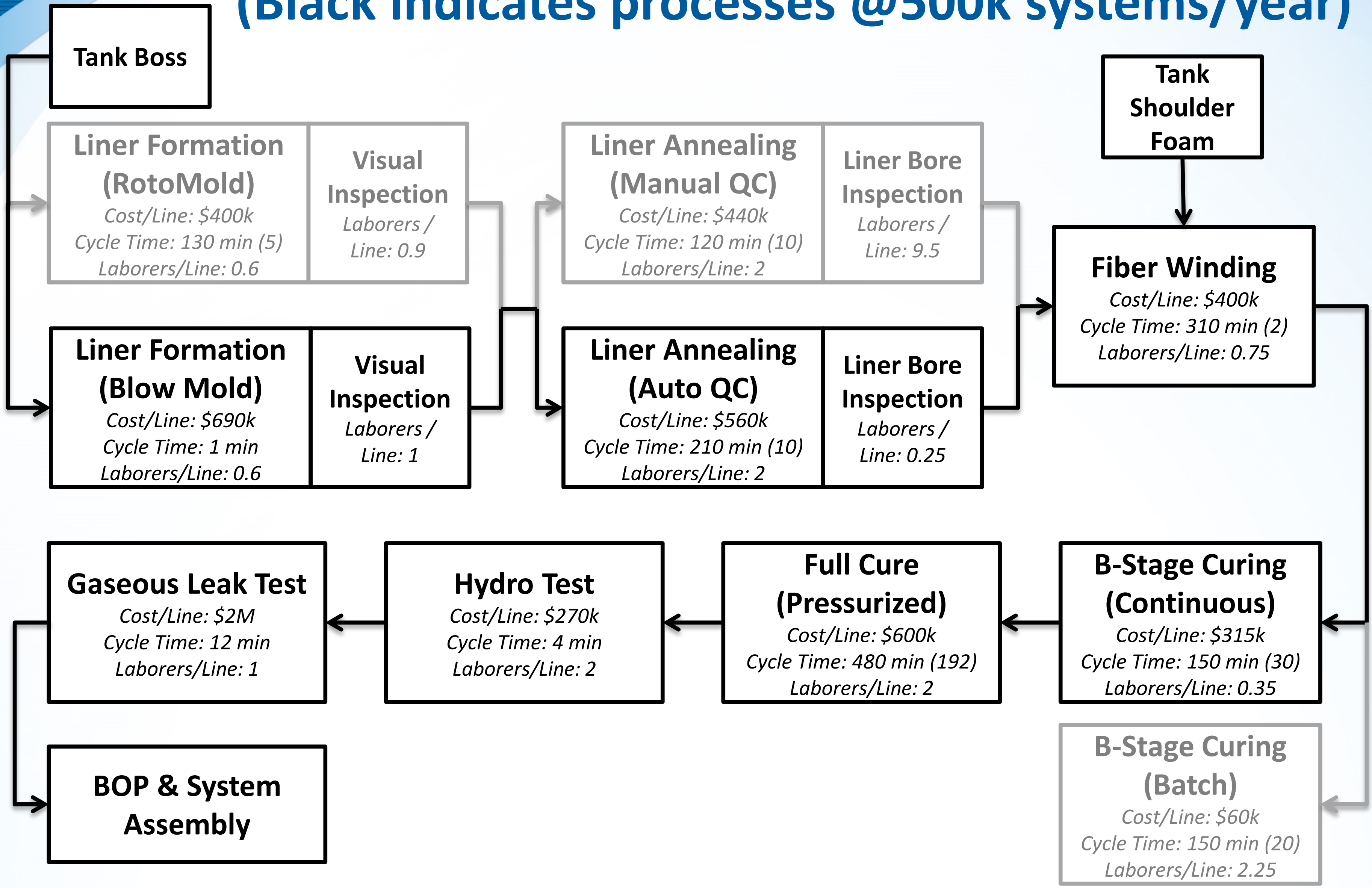
System Diagram

- System cost based on a single tank configuration
- Balance of tank includes:
  - Integrated in-tank valve
  - Integrated pressure regulator block

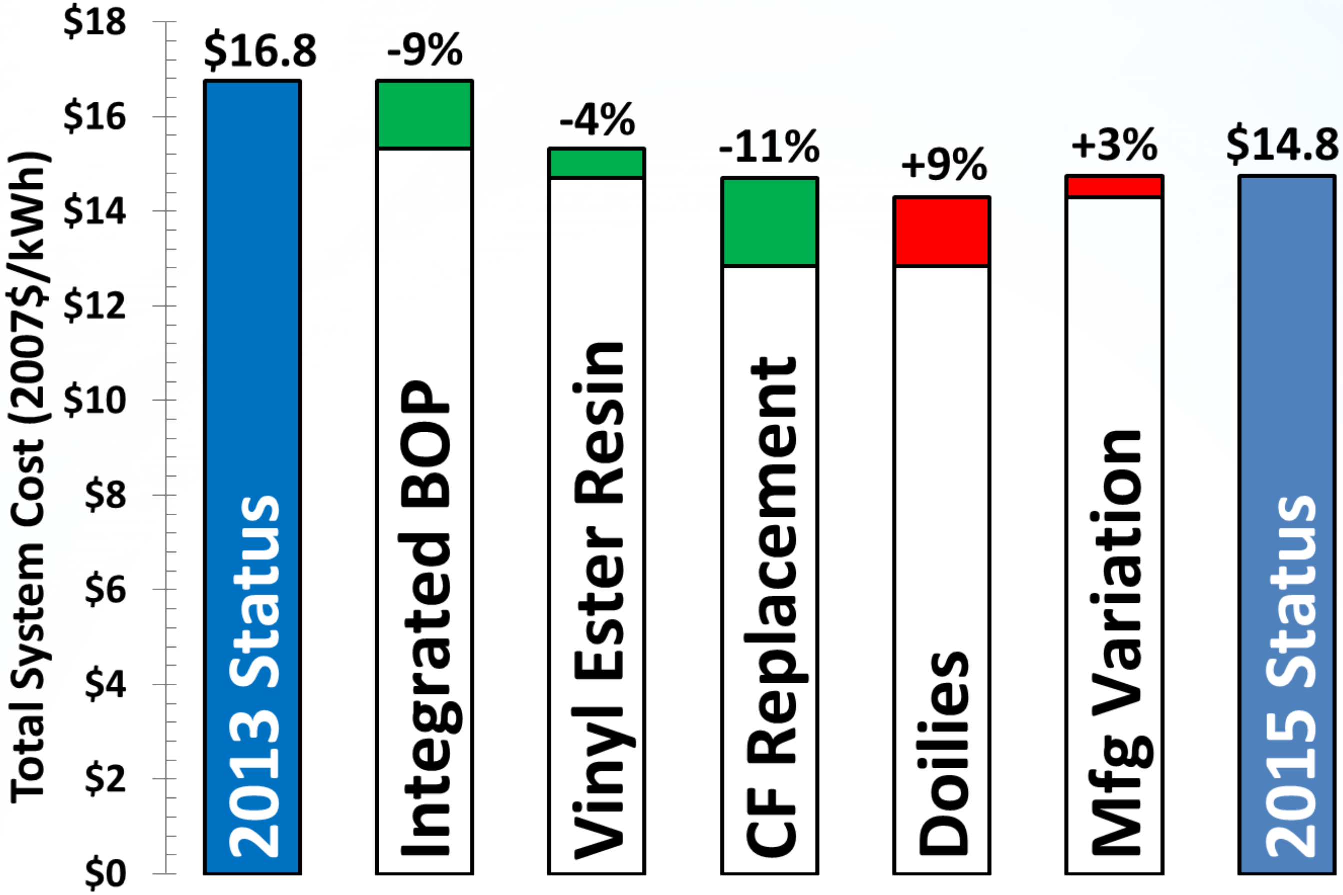


Process Flow Schematic

(Black indicates processes @500k systems/year)



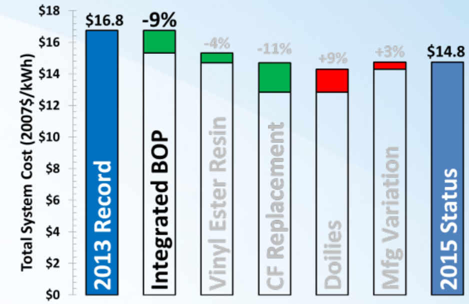
Storage System Cost Reduced by 12%



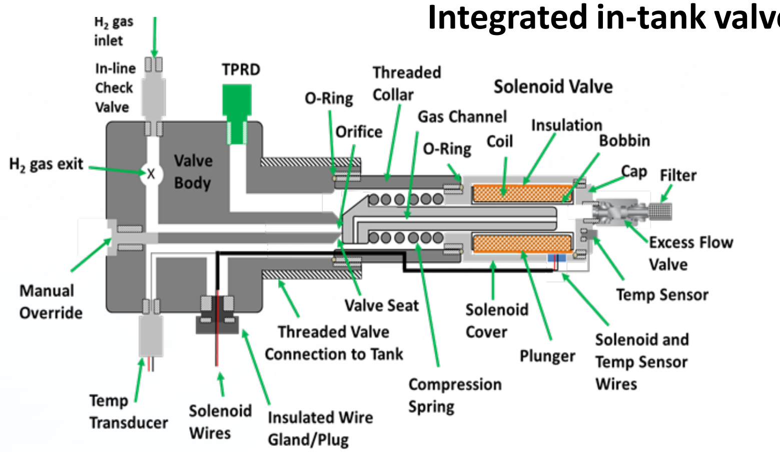
*Cost at 500,000 systems per year

Integrated BOP

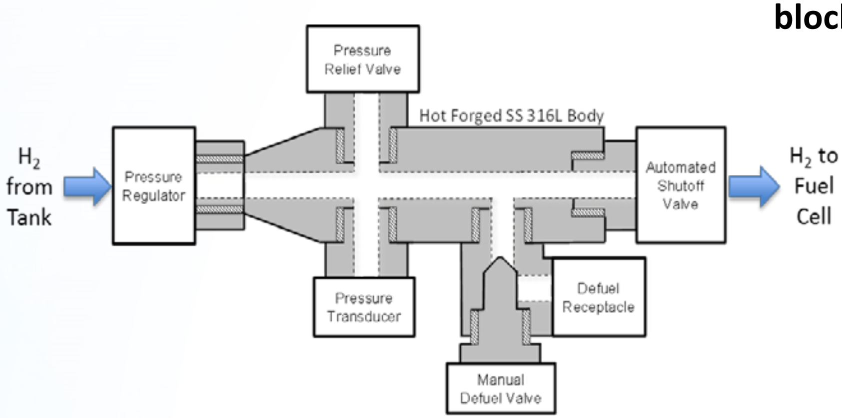
Integration of functionality reduces system cost



Integrated in-tank valve



Integrated pressure regulator block



Analysis Year	BOP Assumptions/Changes	BOP Cost (2007$/kWh)
2013 (DOE Record)	Majority of vendor quotations, limited by product availability	$4.98/kWh
2014	DFMA® analysis of integrated in-tank valve and pressure regulator quotation update	$4.37/kWh
2015	Integrated pressure regulator block will reduce number of fittings (translates to other H_2 storage systems)	$3.64/kWh

(projected 9% system cost savings)

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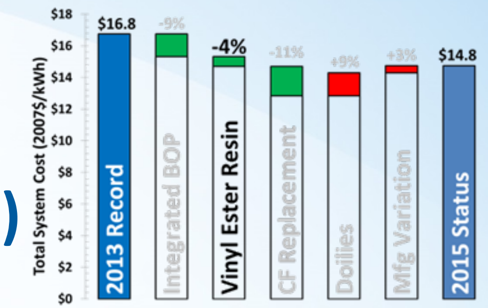
Lower-Cost, Low-Density Resin

(as replacement for epoxy resin in pressure vessel)



PNNL, Hexagon Lincoln, and Ford Collaboration

- Alternative lower-cost and lower-density vinyl ester resin
- Used alternate fiber sizing

Sub-scale experimental burst test results used to calibrate finite element model

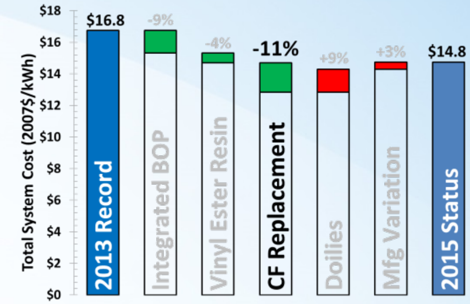
- Vinyl ester resin reduced composite mass by 6.6%
- Vinyl ester resin + alt sizing reduced composite mass by 9.0%
- Lower density resin and lower volume fraction largely responsible
- But some reduction in CF due to higher translation efficiency

	Weight (kg)				
	Hoop	Helical	Doilies	Total	Cost
2013 Baseline (with doilies)	40.2	48.0	2.8	91.0	$16.76/kWh
Calibrated Performance Model (no doilies)	34.3	72.3	N/A	106.6	
Calibrated Model + Low-Cost Resin	31.4	68.2	N/A	99.6	
Calibrated Model + Low-Cost Resin + Alternate Sizing	30.3	66.7	N/A	97.0	$16.17/kWh

(projected 4% system cost savings)

ORNL Low Cost Fiber

Textile precursor process projected to reduce cost of CF by enabling higher volume CF manufacturing



Approach to applying CF cost reduction to total system cost

Established baseline of T700S CF <u>cost (not price)</u> from ORNL's report
Increased CF production volume
→ Baseline established: $\$11.61/\text{lb}_{CF}$

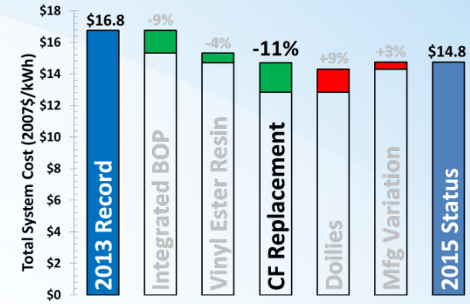
Switch to ORNL PAN MA CF
Reduced CF processing cost
→ <u>Cost</u> reduced to $\$11.16/\text{lb}_{CF}$

Switch to higher precursor production volumes (41k tonnes/yr)
Reduced precursor processing cost
→ <u>Cost</u> reduced to $\$9.49/\text{lb}_{CF}$ (Total cost reduction of 18.3%)

Applied <u>cost</u> ratio to 2013 DOE record <u>price</u> (assuming same markup for price)
→ New <u>price</u> of CF: $\$10.63/\text{lb}_{CF}$ (2007$)

Inserted new price into DFMA model to get total system cost
→ $15.04/kWh (2007$)

All costs in current year dollars, unless otherwise specified



ORNL Low Cost Fiber

ORNL CF has similar tensile strength to conventional T700S but is less expensive to produce due to economies of scale.

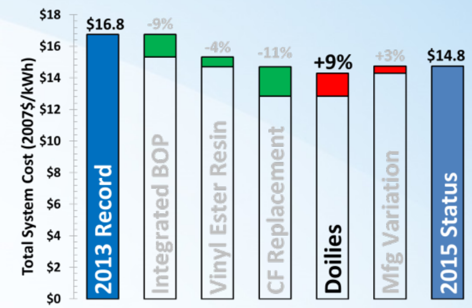
Parameter	2013 Baseline System (T-700S)	Reported ORNL Textile PAN MA CF	Textile PAN MA CF as used in SA's System Cost Model
Ultimate Tensile Strength	711 KSI	577 KSI (in 2014 AMR[1]) 655 to 750+ KSI (ORNL[2])	711 KSI
Modulus	33 MSI	39.8 MSI (2014 AMR)	NA
TOW	24k	24K	24K
Filament diameter	7 micron	7 micron	7 micron
CF Density (dry)	1.8 g/cc	1.78-1.81 g/cc	1.8 g/cc
CF Price (2007$)	$13/lb (at 25,000 tonnes/year)	Price NA (2014$ cost as reference: $9.49/lb, at 25,000 tonnes/year)	$10.63/lb (at 25,000 tonnes/year)
System Cost (5.6kg H2 usable, single tank, 500ksys/year, 2007$)	$16.76/kWh	NA	$15.04/kWh

18.3% cost reduction from $13/lb

projected 11% system cost savings

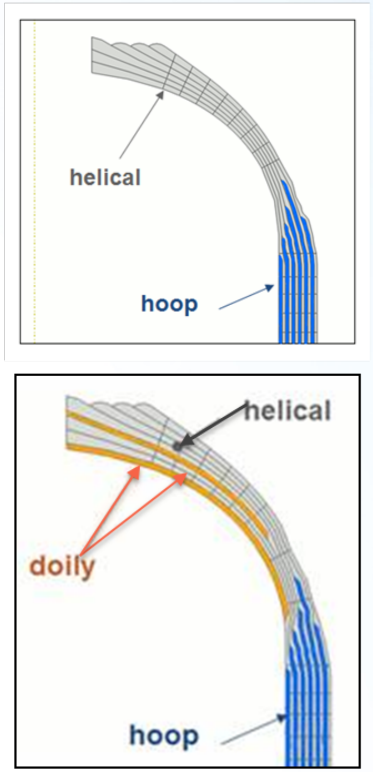
[1] "Development of Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)", C. David (Dave) Warren, Oak Ridge National Laboratory, presentation at 2014 DOE Hydrogen and Fuel Cells Program Annual Merit Review Meeting, Washington, D.C., June 2014.
[2] Personal communication with Dave Warren, ORNL, 19 September 2014. Results not yet published.

Vessel/Manufacturing Design Change—Doily Removal



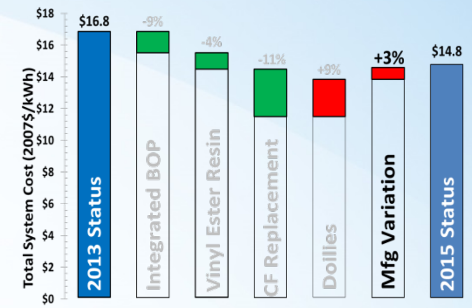
- Doilies are strips of CF applied to the dome to provide local reinforcement
  - Reduce number of helical windings
  - Transfers load to hoop windings
  - Reduces composite materials which reduces total cost
- Doilies introduce High Vol. Prod. challenges
  - Increases manufacturing complexity
  - Creates possibility for single-point failures
- Doilies removed from 2015 design after input from vessel manufacturers resulting in $1.36/kWh increase
  - May still be useful in reducing composite mass in the future but R&D needed

Cross-section of dome with and without doilies

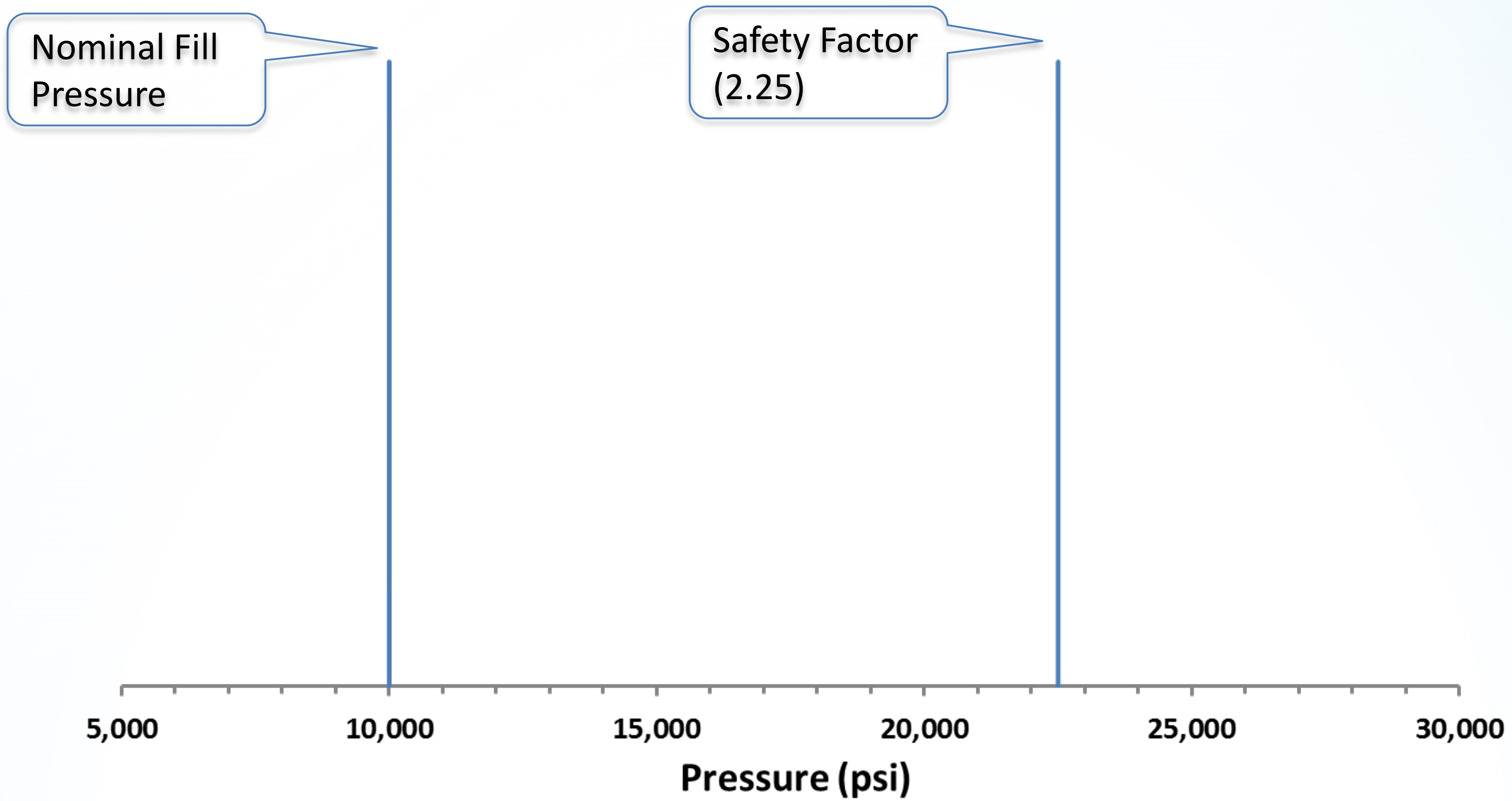


projected 9% system cost increase

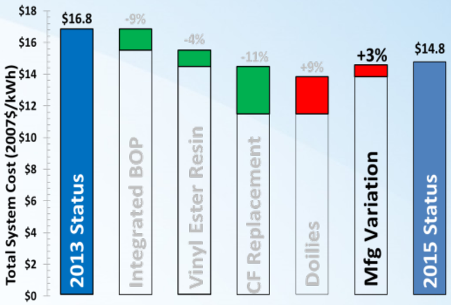
Addition of Explicit Manufacturing Variation COV (COV = Coefficient of Variation)



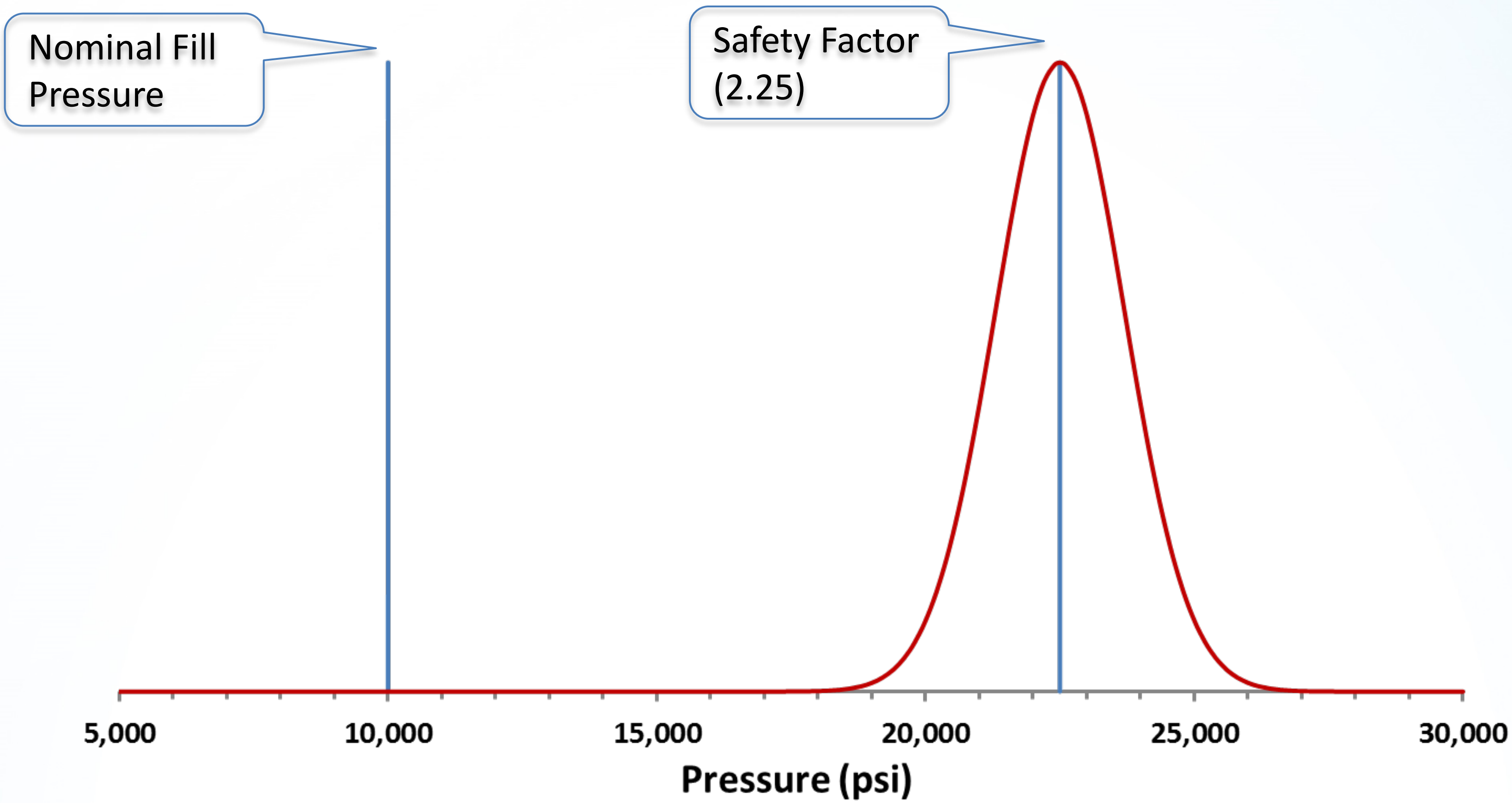
Pressure vessels are designed to withstand pressures with a safety factor 2.25 greater than the nominal fill pressure.



Addition of Explicit Manufacturing Variation COV
(COV = Coefficient of Variation)



In high volume manufacturing, tank burst pressures are normally distributed (shown in red) due to statistical variations in carbon strength fiber and manufacturing process



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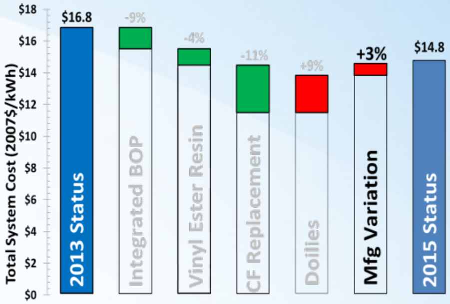
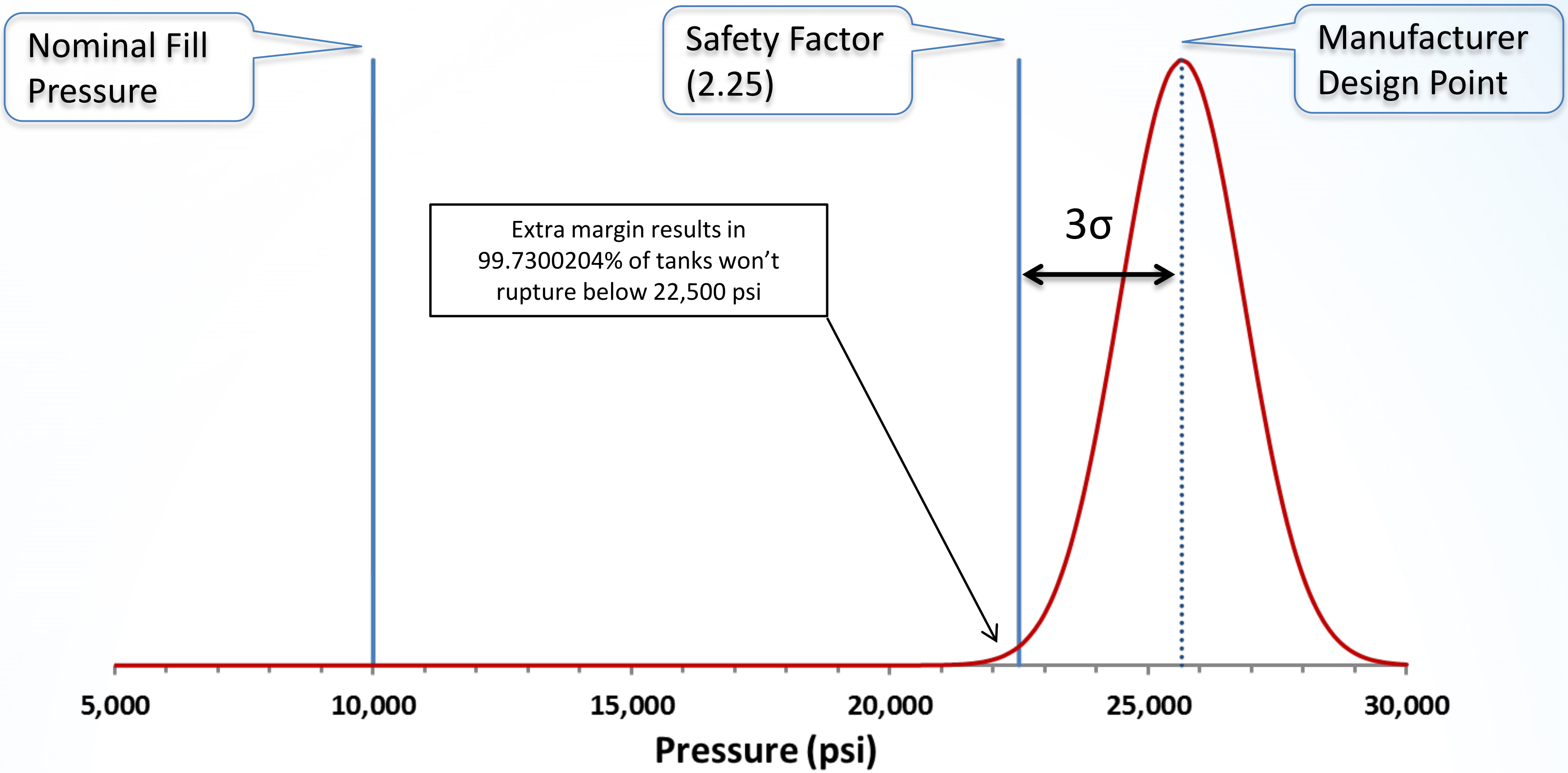


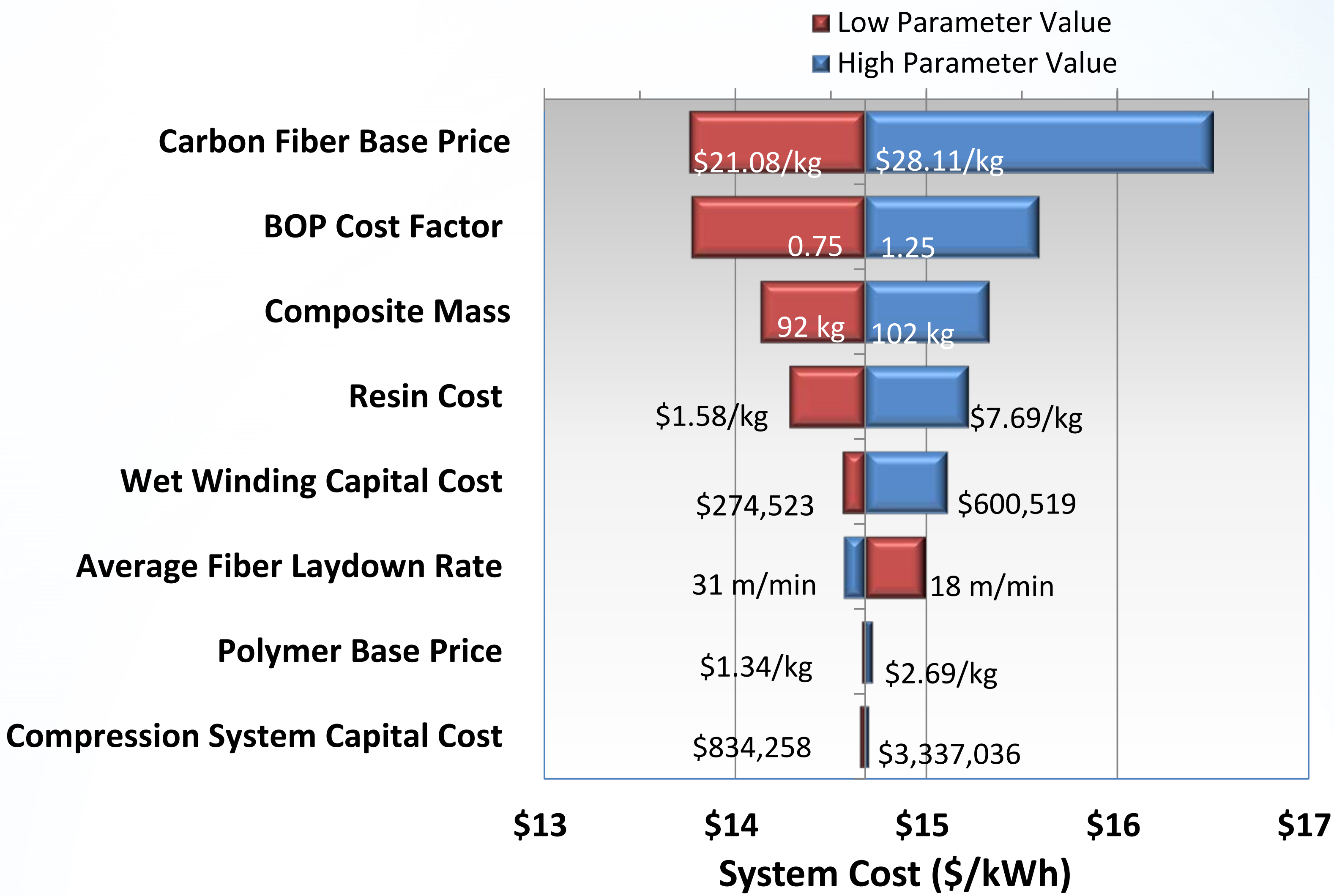
To ensure tanks are designed to meet the 2.25 safety factor, manufacturers design tanks with additional carbon fiber to meet 3σ quality standards



Uncertainty Analysis

	Unit	Low	Most Probable	High	Rationale
CF Composite Mass	kg	92	97	102	Based on the difference of 5 kg between the 2013 PNNL/Ford and ANL analyses. The distribution was assumed to be symmetric with a range of ±5 kg.
Polymer Base Price	$/kg	1.34	1.79	2.69	Assumed -25% to +50%. Baseline is approximately commodity pricing.
Carbon Fiber Base Price	$/kg	21.08	23.43	28.11	Assumed -10% to +20%. Baseline is SA projection of CF fiber using ORNL low-cost precursor.
Blow Molding Capital Cost	$	443,955	591,940	739,925	Assumed ±25%. Baseline is approximate equipment cost.
Blow Molding Cycle Time		0.5	1	2	Assumed -50% to +100%. Range based on our level of uncertainty in cycle time.
Wet Winding Capital Cost	$	274,523	343,154	600,519	Assumed -50% to +100%. Baseline is average of several vendor price quotes.
Average Fiber Laydown Rate	m/min	18	26	32	Assumed -8 m/min to +6 m/min. Range and average taken from informal survey of winding literature and discussions with PNNL regarding winding times.
Curing Oven Capital Cost	$/ft	1,506	2,008	2,511	Assumed ±25%. Baseline is based on vendor quotation.
Conveyor Capital Cost		0.20	1.00	1.50	Assumed -80% to +50%. Range is deliberately wide as conveyor costs are relatively low and thus % uncertainty is high.
B-Stage Dwell Time	hrs	2	2.5	3	Assumed ±0.5 hrs. Baseline from vendor input. Range based on eng. judgement.
Full Cure Dwell Time	hrs	4	8	12	Assumed ±50%. Baseline from vendor input. Range based on eng. judgement.
Compr. System Capital Cost	$	834,258	1,668,518	3,337,036	Assumed -50% to +100%. Baseline from vendor input. Range based on eng. judgement.
BOP Cost Factor		0.75	1.00	1.25	Assumed ±25%. Range based on eng. judgement.
Resin Cost	$/kg	1.58	4.52	7.69	Assumed -65%/+70%. Range based on same ±% used in 2013 DOE Record. Baseline based on vendor quote of PNNL low-cost resin at high production quantity, inclusive of 25% overage for winding wastage.
Foam Dome Protection	$/kg	1.25	2.50	5.00	Baseline from online pricing for polyurethane foam. Assumed -50% and +100% based on ranges in price and eng. judgement.

Sensitivity Study



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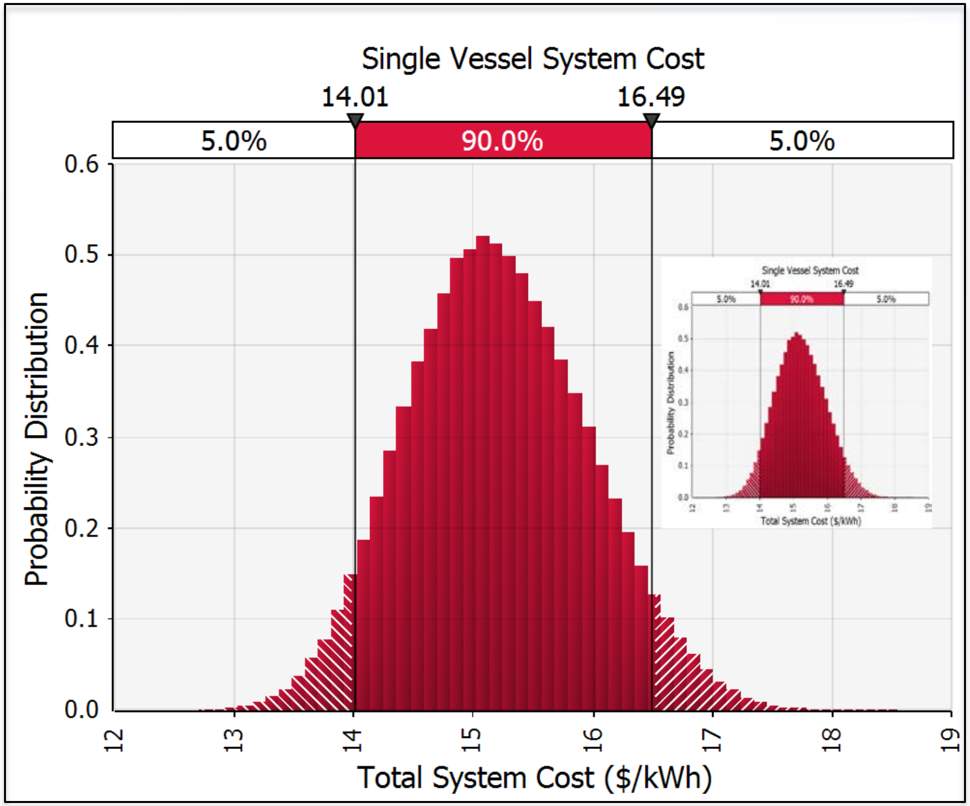
Monte Carlo Analysis Results (Stochastic multivariable error analysis)



90% confidence the cost will be between $14.01 and $16.49/kWh.

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Conclusions

- **Projected storage system costs decreased by a net 12% from 2013 baseline due to technology improvements and design adjustments**
  - Cost reductions identified result in a projected decrease in cost of 24%
    - Integrated balance of plant with reduced fittings and part counts
    - Low-density lower-cost vinyl ester resin
    - High volume textile processed carbon fiber precursor
  - Adjustments were made to the tank design that raised cost by a projected 12% but result in improved manufacturability and performance
    - Removed doilies to accommodate high volume manufacturing
    - Increased tank mass to account for manufacturing variation
- **CF usage reduction remains key system cost reduction strategy**
  - Mirai demonstrates feasibility of reduced CF mass from alternative winding patterns
  - Reduction in manufacturing variations could reduce CF mass and cost
  - Other approaches (e.g. vacuum infiltration of resin) are currently being considered
  - Alternative fibers (e.g. glass)
- **Further optimization of BOP components**

Acknowledgement

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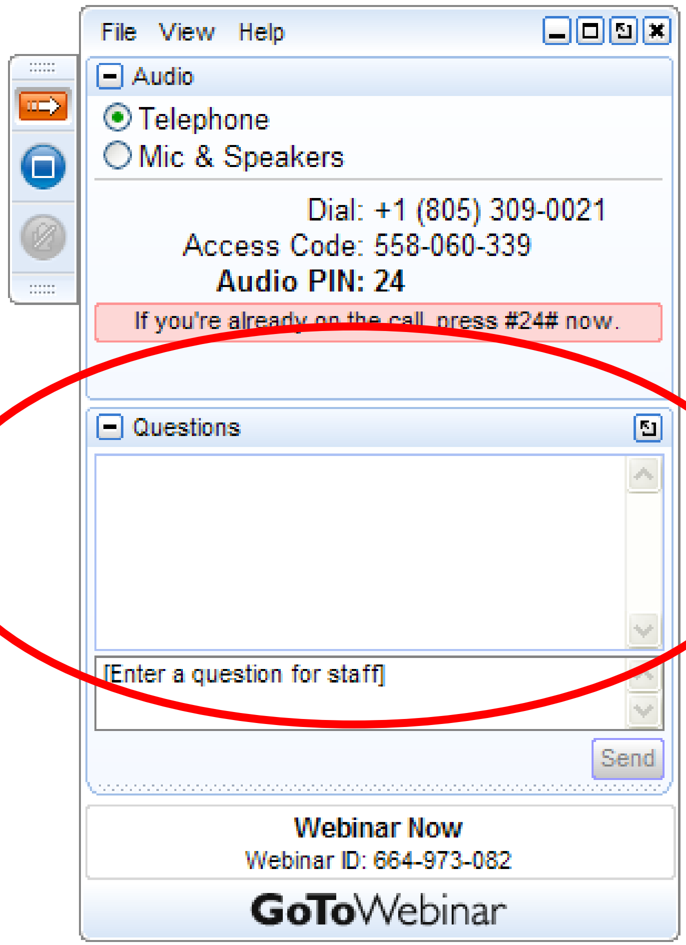
References

- G. Ordaz, C. Houchins, T. Hua, "Onboard Type IV Compressed Hydrogen Storage Systems-Cost and Performance Status 2015" DOE Hydrogen and Fuel Cells Program Record #15013. http://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf
- B.D. James, C. Houchins, J.M. Moton, D.D. DeSantis, "IV.A.2 Hydrogen Storage Cost Analysis," 2015 DOE Hydrogen and Fuel Cells Program Annual Progress Report. http://www.hydrogen.energy.gov/pdfs/progress15/iv_a_2_james_2015.pdf

Questions?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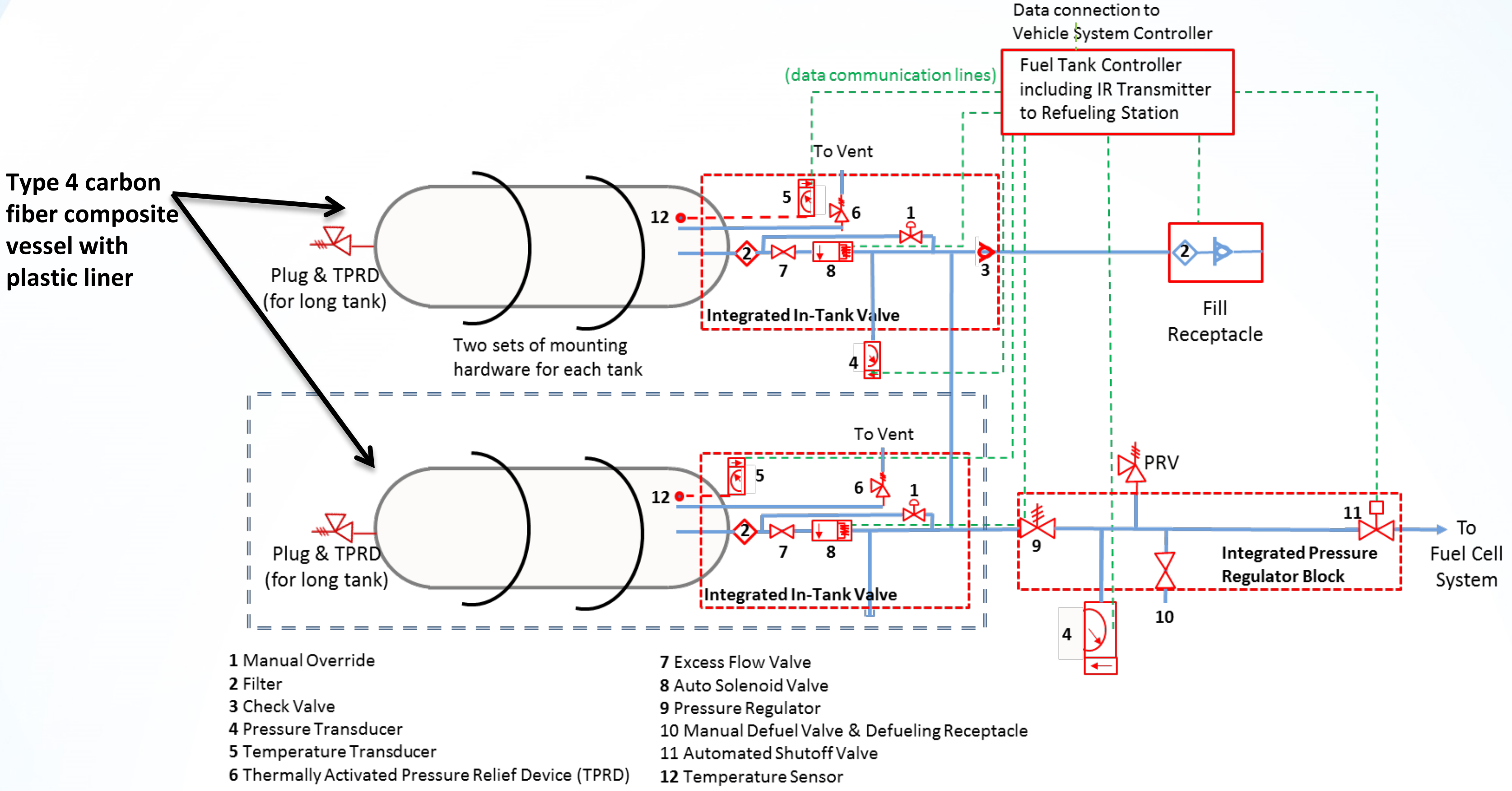
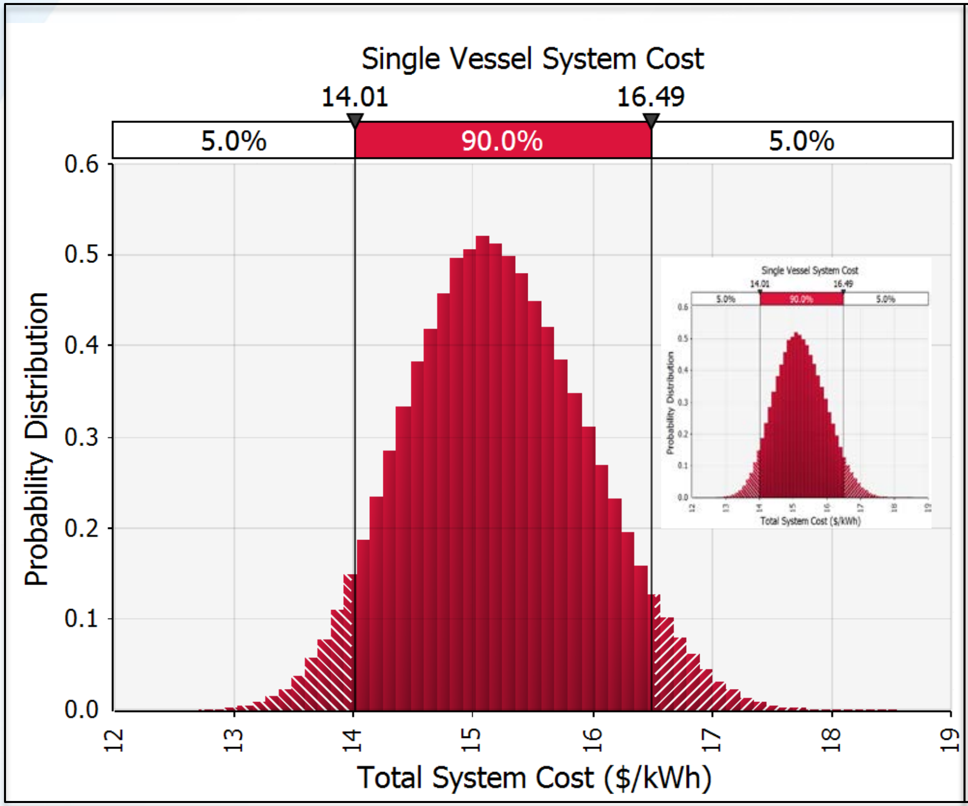
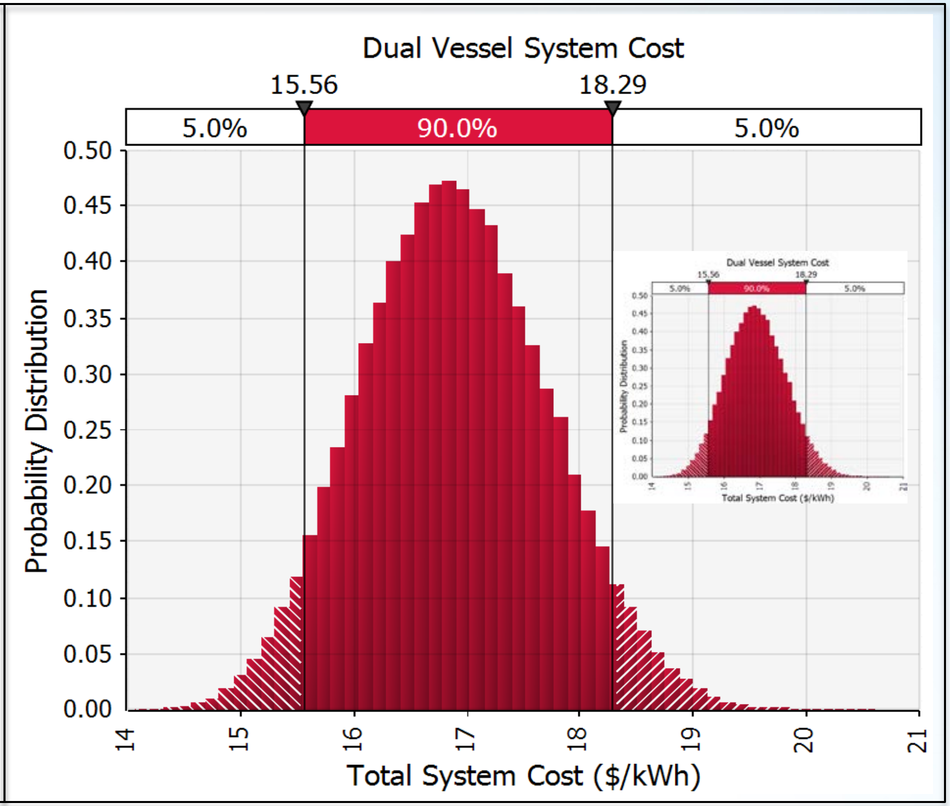
Two Tank Configuration

- System cost for two-tank configuration is higher than for single tank
- Two-tank configuration duplicates the integrated in-tank valve
- Overall carbon fiber mass is higher for two-tank configuration



Monte Carlo Analysis Results (Stochastic multivariable error analysis)





Single Vessel: 90% confidence the cost will be between $14.01 and $16.49/kWh
Dual Vessel: 90% confidence the cost will be between $15.56 and $18.29/kWh