2016 DOE Hydrogen and Fuel Cells Program Review

Hydrogen Storage Cost Analysis

PI: Brian D. James

Strategic Analysis Inc.

8 June 2016

Project ID# ST100

Overview

Timeline

- Project Start Date: 9/30/11
- Project End Date: 9/29/16
- % complete: 85% (in year 5 of 5)

Barriers

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

Budget

- Total Project Budget: $1,448,441
  - Total DOE Funds Spent*: $847,000
- *As of 31 Mar 2016

Partners

- Project Lead: Strategic Analysis Inc.
- National Renewable Energy Laboratory (NREL)
- Argonne National Lab (ANL)

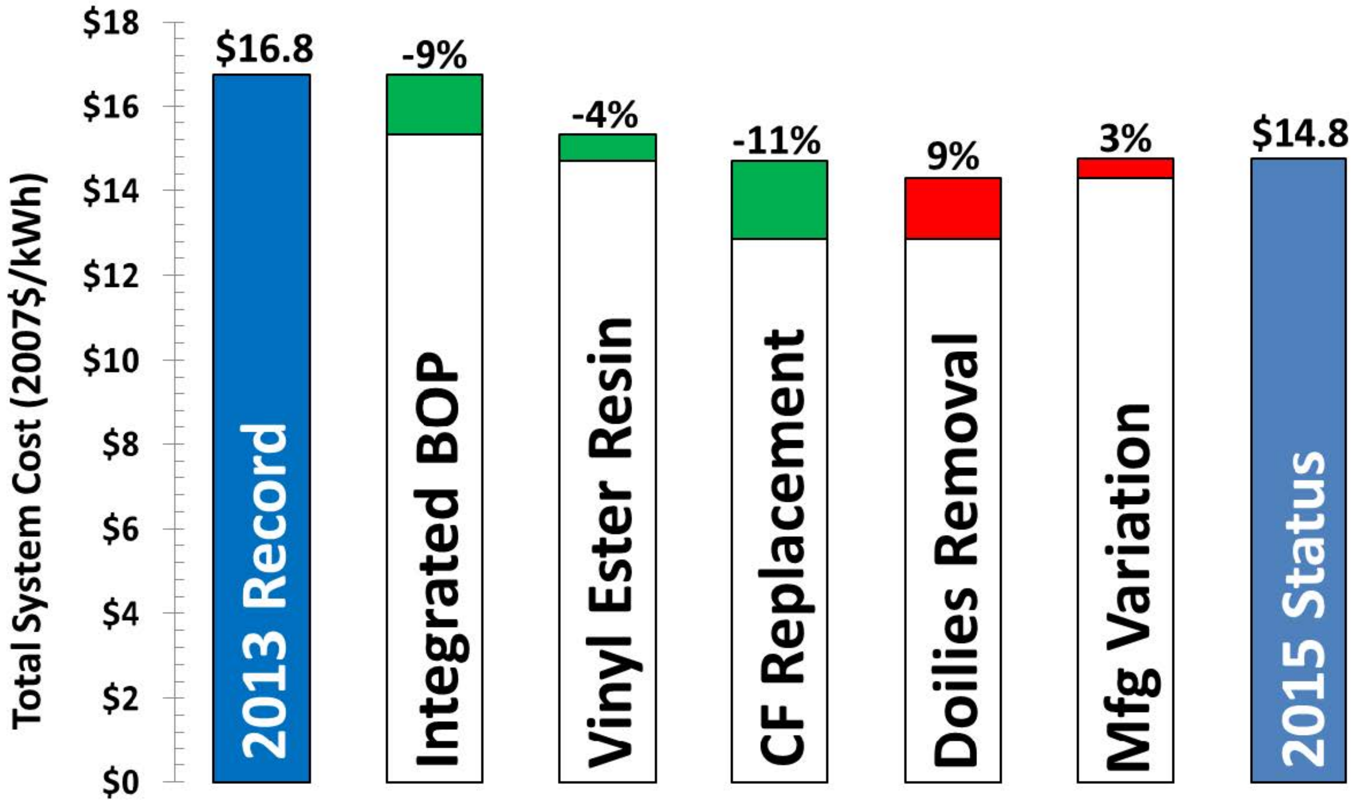
Relevance

- Conduct independent DFMA cost analysis of on-board hydrogen storage systems
- Assess/evaluate cost reduction strategies
- Target:
  - Identify pathways to reduce the cost of on-board hydrogen storage systems by 15% compared to DOE's 2013 record.
  - DOE 2017 target of $12/kWh (2007$) for onboard hydrogen storage for light-duty fuel cell vehicles.

Approach/Activities In Last year

- **Updated status of 700 bar Type IV tanks (2015 status)**
  - Summarize 2015 status
  - Explicitly account for manufacturing variations
  - Uncertainty analysis
    - Capacity uncertainty
    - Cost uncertainty
- **2016 Updates and Analysis**
  - Updated 2016 Balance of Plant (BOP) cost
  - Updating process assumptions
  - Winding times analysis
    - Motivated partly by cost, but also realistic manufacturing concerns (space, number of winders, etc.)
    - Baseline winding time assumptions
    - Parameterized winding model and implications for pre-preg
    - Vacuum infiltration – preliminary Materia analysis
  - Toyota Winding Patterns
  - Revisit PAN-MA low cost carbon fiber

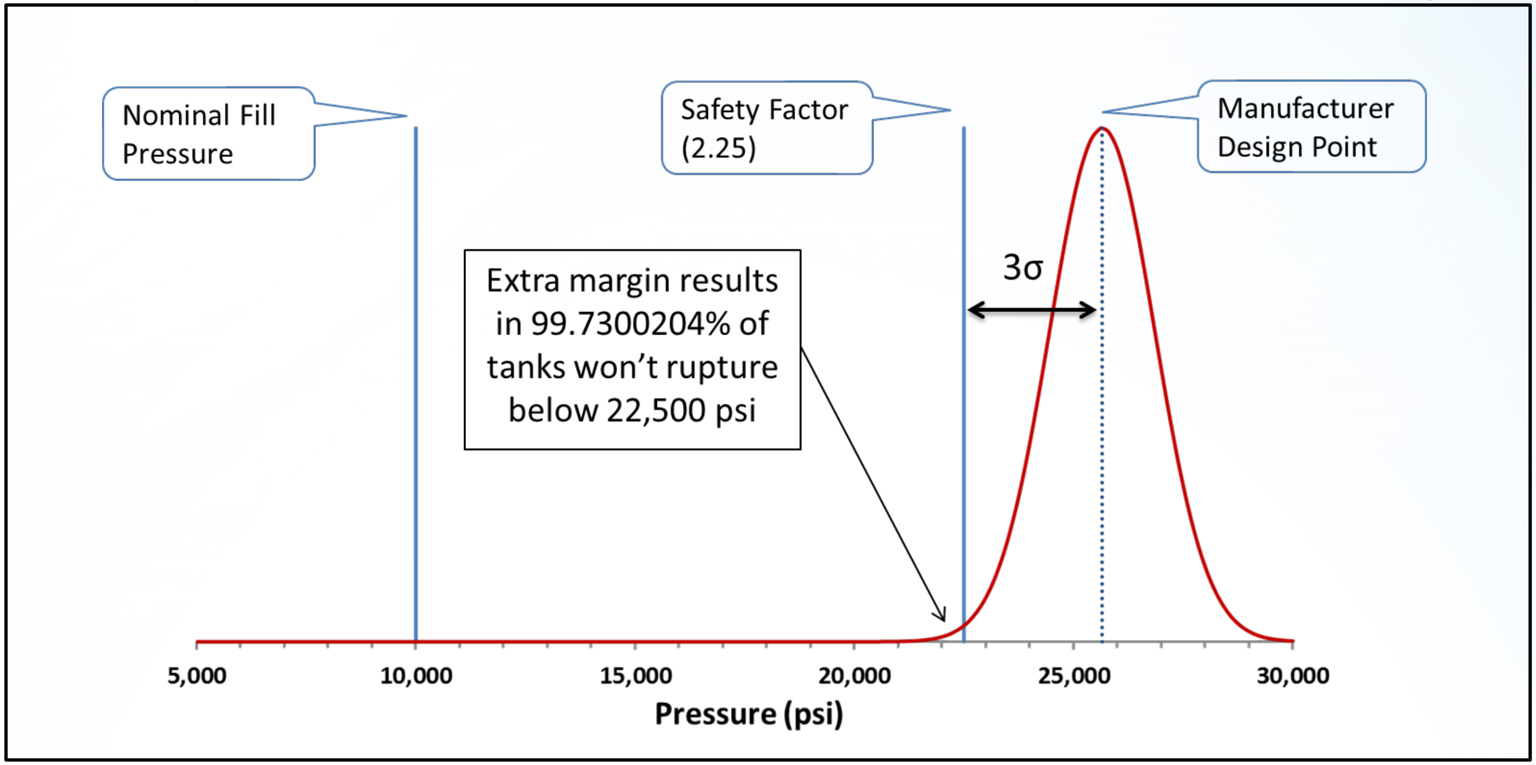
Accomplishments & Progress:
700 bar type IV H_2 storage system cost reduction identified



*Cost at 500,000 systems per year

Accomplishment & Progress:

COV was updated to account for both fiber and manufacturing variations



- Previous analysis: $3\sigma = 3\sqrt{COV_{Fiber}^2} = \mathbf{10\%}$
- Added explicit manufacturing variation (COV_{mfg}) to cost model
  - Updated analysis: $3\sigma = 3\sqrt{COV_{Manufacturing}^2 + COV_{Fiber}^2} = \mathbf{14\%}$
- $COV_{Manufacturing} = COV_{Fiber} =$ **3.3%**

STRATEGIC ANALYSIS INC

Accomplishments & Progress:

Uncertainties in capacity were estimated for 700 bar Type IV systems

Process

- Liner and composite were calculated from tank samples provided by PNNL
- Reported 90% confidence interval to be consistent with cost uncertainty reporting, i.e. $\mu \pm 1.645\sigma$
- BOP uncertainty estimated to 10% to reflect uncertain design/degree of component integration

Observations

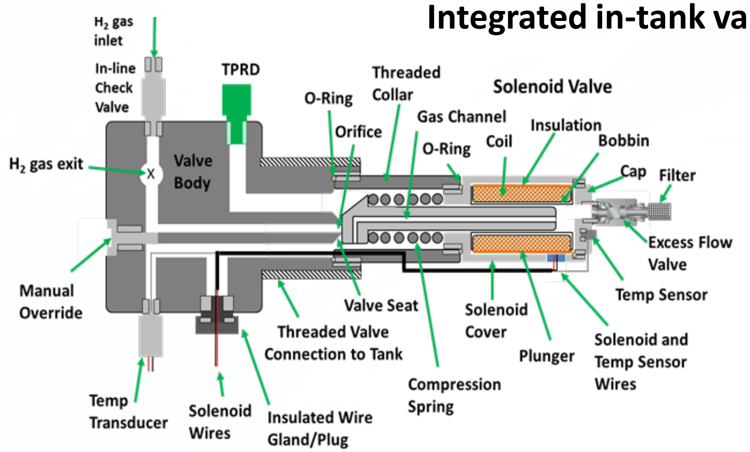
- At COV_{mfg} = 3.3% ± 1% to account for manufacturer-to-manufacturer variations, the gravimetric capacity uncertainty increases to 1.42 ± 0.07 kWh/kg
- Capacity uncertainties are smaller (0.04) than DOE target precision (1.5 kWh/kg)

Component	Nominal Value	COV	90% Confidence Interval	
	kg	%	Low	High
Hydrogen	5.84	1	5.74	5.94
Liner	7.84	0.2	7.81	7.87
Dome Protection	4.06	1	3.99	4.13
Composite	97.02	1.23	95.06	98.98
BOP	16.59	10	13.86	19.32

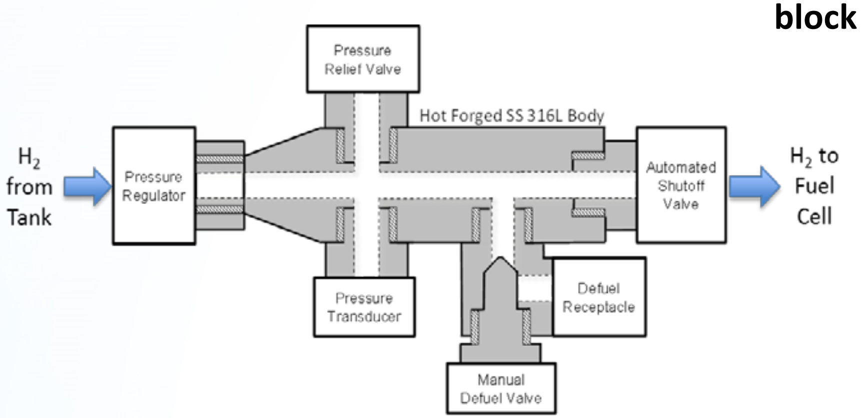
System Mass (kg_{system})	**131 ± 4 kg**
Capacity (kgH_2/kg_{system})	**4.3 ± 0.1 wt.%**
Capacity (kWh/kg_{system})	**1.42 ± 0.04 kWh/kg**

Accomplishments & Progress:
Integration of functionality and switching to aluminum valve and regulator bodies reduces system cost

Integrated in-tank valve

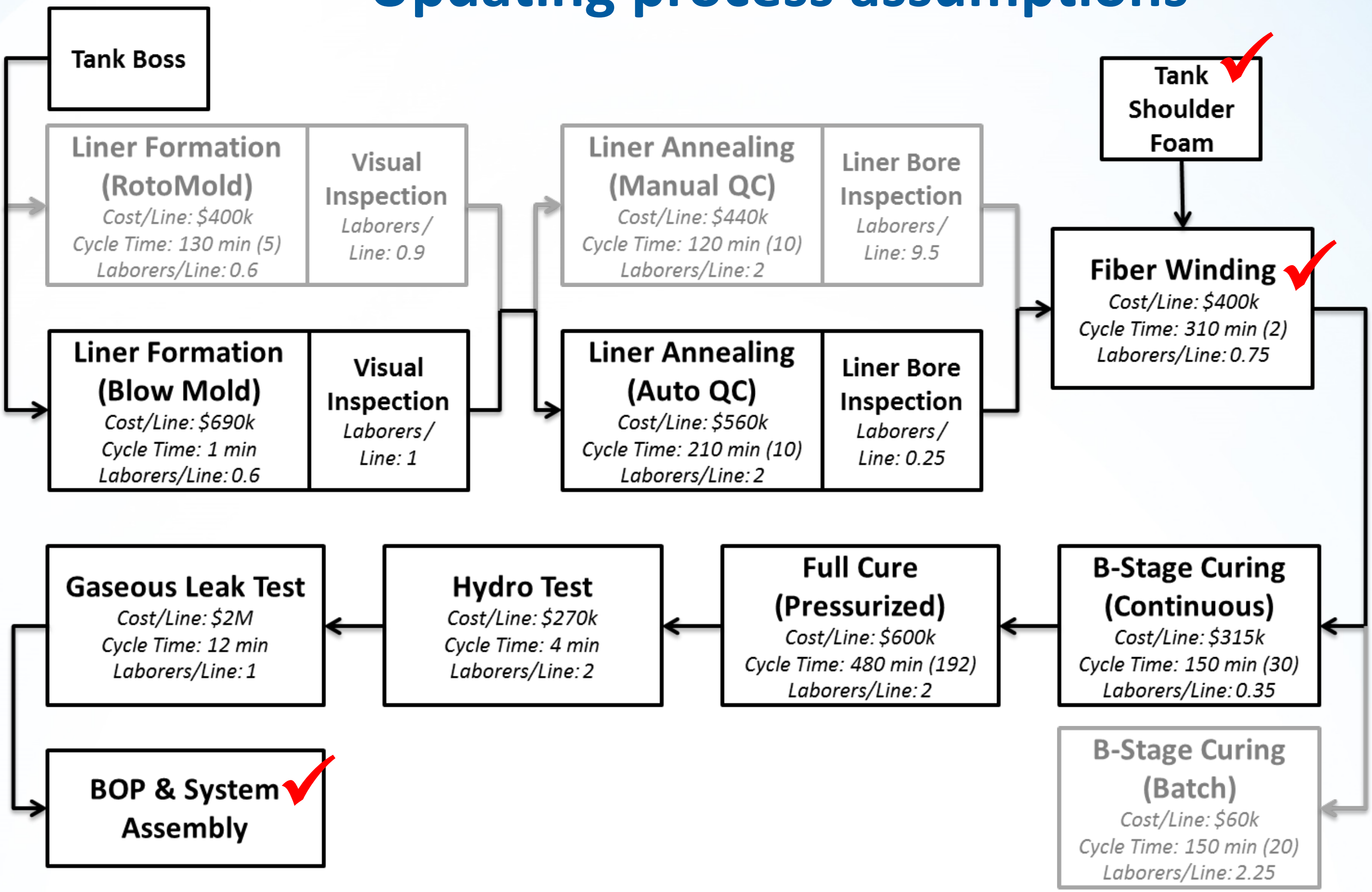


Integrated pressure regulator block



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 (DOE Record)	Integrated pressure regulator block will reduce number of fittings (translates to other H_2 storage systems)	$3.64/kWh
2016	Switched from SS to Al regulator and valve bodies	-$0.16/kWh ($3.48/kWh)

Accomplishments & Progress :
Updating process assumptions



*Black indicates processes assumed for production at 500k systems/year

✓ Indicates process has been updated in model

STRATEGIC ANALYSIS INC

Accomplishments & Progress:
Investigating alternatives to wet winding

- **Wet winding (baseline)**
  - Slow, relatively inexpensive materials, high resin wastage (est. 25%)
- **Pre-preg** (pre-impregnation of resin into fiber in contrast to wet-winding)
  - Faster than wet winding, premium paid for pre-preg, low material wastage
- **Vacuum infusion** (of resin in composite after winding on tank)
  - Similar materials costs as wet winding, faster (dry) winding time offset by long infusion time, possibly higher translation efficiency leading to lower CF usage
- **Braided CF/Vacuum Infusion** (pre-braided net of dry fiber place around tank)
  - Higher CF price due to braiding, faster wrapping time, potentially long infusion time, translation efficiency impact unclear

	Material Costs	Winding Time	Resin Impreg. Time	Strength of Composite Material	Notes
Wet Winding	--	--	--	--	**Model baseline winding method**
Pre-Preg	↑	↓	--	↑	
Dry Winding/Vacuum Infusion	=	↑	↑	↑	**Materia (ST114) approach**
Braided CF/Vacuum Infusion	↑	↓	↑	↓	**Past work**

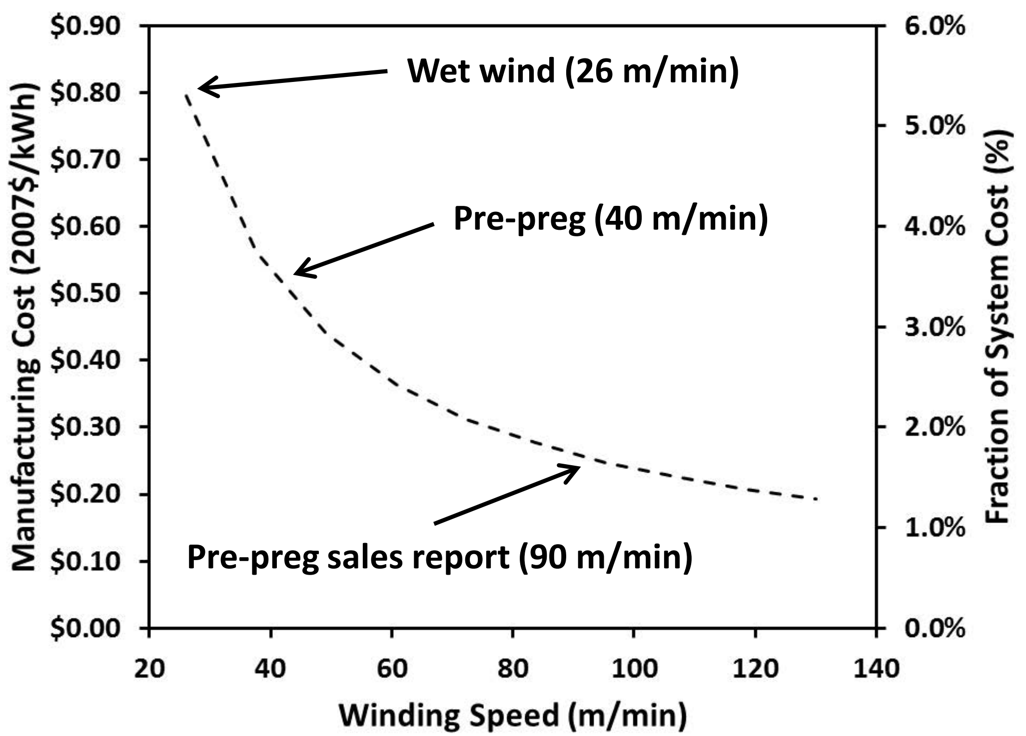
Accomplishments & Progress:

Small savings possible from increasing winding speed

- Winding is ~5.5% of system cost for current model at 26 m/min
- System cost reductions possible (~2-4%) by increasing winding speed

Assumptions

- 500k systems/year (single 147L tank)
- 25% resin wastage
- $343k/line (2007$)
- 2 spool winder (for large diam. vessels)
- 24k tows



Accomplishments & Progress:

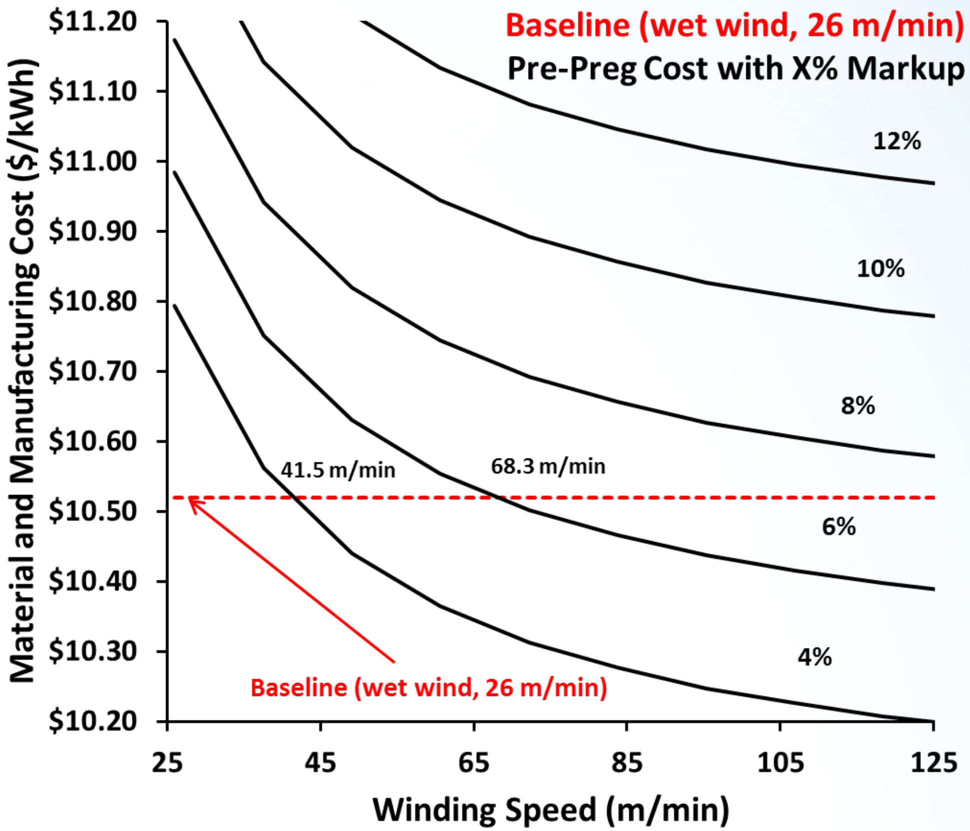
Tradeoff study pre-preg markup vs. winding speed

- Pre-preg is cost competitive at <6% markup with increased winding speed
- However, ~8% markup suggested by proprietary industry report

Based on
3.3% $COV_{Manufacturing}$

Assumptions

- 3.3% $COV_{Manufacturing}$
- 1% resin wastage
- 500k systems/year (single 147L tank)
- $343k/line (2007$)
- 2 spool winder (for large diam. vessels)
- 24k tows

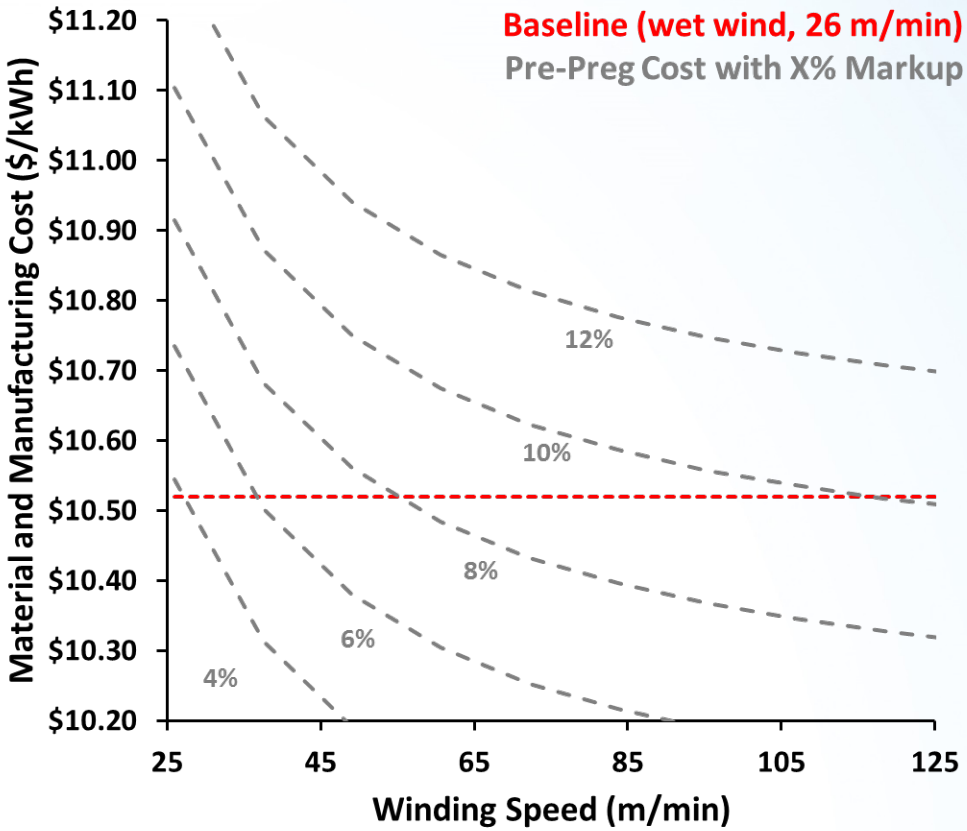


Accomplishments & Progress:
Tradeoff study of markup, winding speed, and COV

- However, pre-preg is reported to have a reduced $COV_{Manufacturing}$
- With lower COV, it becomes competitive at 8% markup

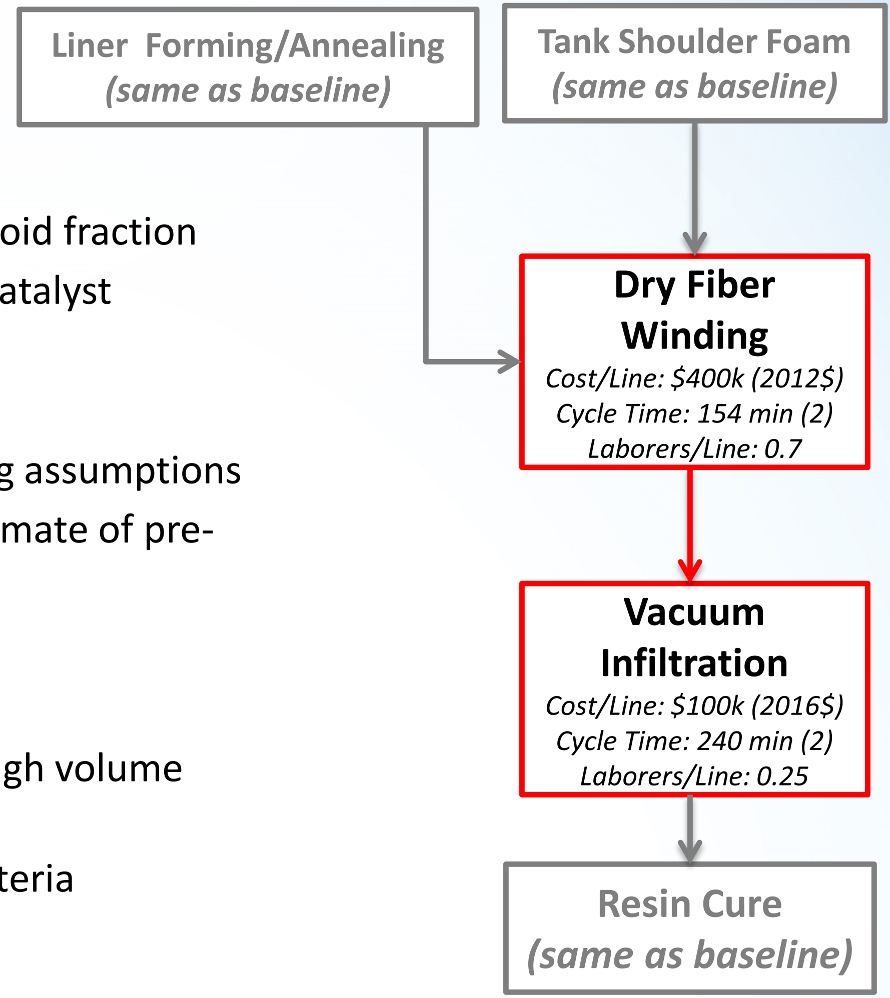
Based on
1.6% $COV_{Manufacturing}$

Assumptions
- 1.6% $COV_{Manufacturing}$
- 1% resin wastage
- 500k systems/year (single 147L tank)
- $343k/line (2007$)
- 2 spool winder (for large diam. vessels)
- 24k tows



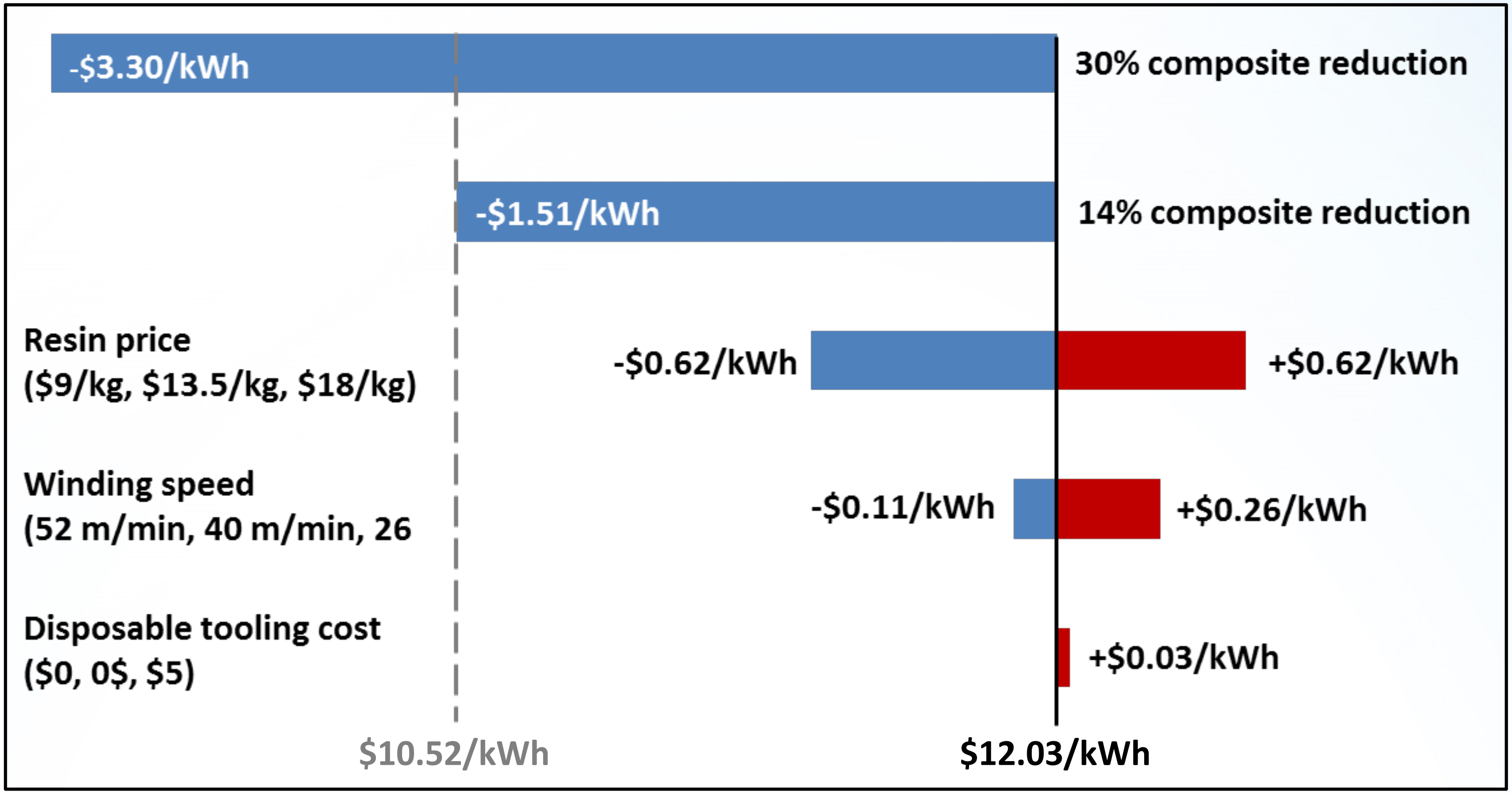
Accomplishment & Progress:
Preliminary Materia Cost Analysis Results

- **Overview**
  - Based on Materia project
  - Expected to result in reduced CF usage by reducing void fraction
  - Resin is dicyclopentadiene with a ruthenium-based catalyst (Grubb's catalyst) suspended in mineral oil
- **Winding Assumptions**
  - Capital cost, power, labor modeled using wet winding assumptions
  - Winding speed = 40 m/min analogous to current estimate of pre-preg winding speed
- **Infiltration Assumptions**
  - Capital cost = $100k (2016$)
  - Reusable clamshell infiltration station assumed for high volume production
  - Infiltration time = 4 hr based on discussions with Materia
  - One laborer operating 4 infiltration stations
  - 2 tanks per station
  - Resin cost $9-$18/kg (modeled as $13.5/kg in 2016$)



Accomplishment & Progress

Preliminary Materia process cost analysis



- Material and manufacturing cost of dry winding and vacuum infiltration is $12.03/kWh
  - With no composite reduction
  - Driven by resin cost and increased processing time for vacuum infiltration
- Targeted 30% composite reduction projected to reduce system cost by $1.79/kWh

Accomplishment & Progress:
Two-Tank System Based on Toyota Design

- Two-Tank configurations are more expensive than single-tank configurations due to repeat parts
- Toyota Mirai tanks includes a number of design changes that are different from the SA baseline
  - Higher tensile strength T-720 CF
  - A front tank and a rear tank with different aspect ratios (L/D = 2.8 and 1.7, respectively)
  - Boss and liner geometries that eliminate high-angle helical winds
  - 5 kg total H_2
- Cost reductions are due to CF mass reductions predicted by ANL from ABAQUS simulations
  - Improved winding resulted in 7.2% composite mass reduction for T-700
  - Results for tanks wound with T-720 showed much higher composite mass reduction, 21%
  - Low aspect ratio rear tank did not benefit from improved winding (i.e. no mass reduction predicted)

	Available H_2 (kg)	L/D	Cost/tank ($/kWh)	CF Reduction (%)	BOP & Assembly ($/kWh)*	Total ($/kWh)
SA Baseline (single tank)	5.6	3	11.05	--	3.54	14.59
SA Two-Tank Configuration	5.6	3	11.28	--	4.66	15.94
SA Two-Tank w/Toyota winding pattern	5.6	2.8	10.53	-7.2%	4.66	15.19

Accomplishment & Progress:
Two-Tank System Based on Toyota Design

- Two-Tank configurations are more expensive than single-tank configurations due to repeat parts
- Toyota Mirai tanks includes a number of design changes that are different from the SA baseline
  - Higher tensile strength T-720 CF
  - A front tank and a rear tank with different aspect ratios (L/D = 2.8 and 1.7, respectively)
  - Boss and liner geometries that eliminate high-angle helical winds
  - 5 kg total H_2
- Cost reductions are due to CF mass reductions predicted by ANL from ABAQUS simulations
  - Improved winding resulted in 7.2% composite mass reduction for T-700
  - Results for tanks wound with T-720 showed much higher composite mass reduction, 21%
  - Low aspect ratio rear tank did not benefit from improved winding (i.e. no mass reduction predicted)

	Available H_2 (kg)	L/D	Cost/tank ($/kWh)	CF Reduction (%)	BOP & Assembly ($/kWh)*	Total ($/kWh)
SA Baseline (single tank)	5.6	3	11.05	**Slight +Δ due to 2nd boss**	3.54	14.59
SA Two-Tank Configuration	5.6	3	11.28		4.66	15.94
SA Two-Tank w/Toyota winding pattern	5.6	2.8	10.53	-7.2%	4.66	15.19

Accomplishment & Progress:
Two-Tank System Based on Toyota Design

- Two-Tank configurations are more expensive than single-tank configurations due to repeat parts
- Toyota Mirai tanks includes a number of design changes that are different from the SA baseline
  - Higher tensile strength T-720 CF
  - A front tank and a rear tank with different aspect ratios (L/D = 2.8 and 1.7, respectively)
  - Boss and liner geometries that eliminate high-angle helical winds
  - 5 kg total H_2
- Cost reductions are due to CF mass reductions predicted by ANL from ABAQUS simulations
  - Improved winding resulted in 7.2% composite mass reduction for T-700
  - Results for tanks wound with T-720 showed much higher composite mass reduction, 21%
  - Low aspect ratio rear tank did not benefit from improved winding (i.e. no mass reduction predicted)

	Available H_2 (kg)	L/D	Cost/tank ($/kWh)	CF Reduction (%)	BOP & Assembly ($/kWh)*	Total ($/kWh)
SA Baseline (single tank)	5.6	3	11.05	--	3.54	**Large +Δ due to 2^{nd} valve**
SA Two-Tank Configuration	5.6	3	11.28	--	4.66	
SA Two-Tank w/Toyota winding pattern	5.6	2.8	10.53	-7.2%	4.66	15.19

Accomplishment & Progress:
Two-Tank System Based on Toyota Design

- Two-Tank configurations are more expensive than single-tank configurations due to repeat parts
- Toyota Mirai tanks includes a number of design changes that are different from the SA baseline
  - Higher tensile strength T-720 CF
  - A front tank and a rear tank with different aspect ratios (L/D = 2.8 and 1.7, respectively)
  - Boss and liner geometries that eliminate high-angle helical winds
  - 5 kg total H_2
- Cost reductions are due to CF mass reductions predicted by ANL from ABAQUS simulations
  - Improved winding resulted in 7.2% composite mass reduction for T-700
  - Results for tanks wound with T-720 showed much higher composite mass reduction, 21%
  - Low aspect ratio rear tank did not benefit from improved winding (i.e. no mass reduction predicted)

	Available H_2 (kg)	L/D	Cost/tank ($/kWh)	CF Reduction (%)	BOP & Assembly ($/kWh)*	Total ($/kWh)
SA Baseline (single tank)	5.6	3	11.05	--	3.54	14.59
SA Two-Tank Configuration	5.6	3	11.28	--	4.66	15.94
SA Two-Tank w/Toyota winding pattern			10.53	-7.2%	4.66	15.19

Large -Δ due to CF reduction

Accomplishments & Progress:
ORNL PAN-MA fiber strength variations revisited

	Fiber	COV (mfg)	COV (fiber)	3σ	System Cost
SA Baseline	ORNL CF from PAN-MA precursor	3.3%	3.3%	14.0%	$14.59/kWh
Observed COV_{Fiber}	ORNL CF from PAN-MA precursor	3.3%	7.0%	23.2%	$15.44/kWh
High COV_{Fiber}	ORNL CF from PAN-MA precursor	3.3%	11.5%	36.0%	$16.62/kWh
Tank with T-700	T-700	3.3%	3.3%	14.0%	$16.62/kWh

- Limited test samples lead to uncertain COV_{fiber}
  - Current baseline system cost assumes COV_{fiber} is comparable with T-700 (3.3%)
  - Observed COV_{Fiber} results in baseline increase of $0.85/kWh
- ORNL PAN-MA is cost competitive for fiber COVs less than 11.5%

$$3\sigma = 3\sqrt{COV^2_{Manufacturing} + COV^2_{Fiber}}$$

Accomplishments and Progress:
Responses to Previous Year's Reviewers' Comments

Reviewer's Comments	Response to Reviewer's Comment
The approach is generally effective but certainly can be improved. The cost analysis is based on single tank, and some assumptions are very optimistic.	Costs for two tank configurations were reported this year at the AMR and expanded to include analysis of a modeled Mirai storage system. SA is in the process of reviewing the processing assumptions to ensure they are realistic and consistent with current manufacturing capabilities
It would be nice to see inclusion (or at least mention) of other projects that might be generating data that could contribute to the overall big picture of the analysis.	SA is working with DOE supported projects (e.g. Materia, PPG, and CTC) to identify new materials and potential future savings.
The $/kWh should include uncertainty.	The 2015 status for 700 bar Type IV tanks is reported within the 90% confidence interval. In addition, uncertainty in the gravimetric and volumetric capacities were estimated for the first time in 2015.

Collaborations

Partner	Project Role
National Renewable Energy Laboratory (NREL) (sub on project)	Contributed information on developments within cyro-compressed H_2, and manufacturing variations
Argonne National Laboratory (ANL) (sub on project)	Conduct system analysis to determine the carbon fiber requirement for compressed gas Type-4 tanks. Support SA in cost analysis activities.
PNNL, Hexagon Lincoln, and Ford	Performing testing and advising on project for low cost carbon fiber tanks. Providing SA with burst test results.
Materia, Inc.	Provided feedback on manufacturing assumptions for vacuum infiltration, Grubb's catalyzed resin
Oak Ridge National Laboratory (ORNL)	Provided cost and information on projected cost reduction for low cost PAN MA textile precursor and fiber variations
Pittsburgh Plate and Glass (PPG)	Provided feedback on glass fiber manufacturing

Remaining Barriers and Challenges

700 bar Pressure Vessel System

- Carbon fiber composites
  - Carbon fiber remains expensive, primary cost driver for Type IV tanks
  - Accurate price quotes are difficult to obtain
  - Significant difference between apparent cost and price for carbon fiber
- BOP cost is spread over many components
  - High pressure fitting costs are widespread within industry due to high profit margin, testing/certifications, safety inspections, and/or verification/regulations
  - Integrated solenoid valve and pressure regulator

Proposed Future Work

- Exploring alternative fibers (e.g. glass) and resins (Grubb's catalyzed resin)
- Continue updating process assumptions
- Update quotes for T-700 and get new quotes for T-720
- Model alternative fiber (e.g. glass fiber) and carbon fiber for comparison
- Update BOP assumptions/validate against currently available components

Technology Transfer Activities

Not Applicable to SA's Cost Analysis

Summary (1/2)

- **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
- **Winding analysis shows potential for decreasing cost**
  - Baseline wet winding cost can be reduced by ~$0.40/kWh if winding speed is doubled
  - Pre-preg may be cost competitive due to potentially faster winding speeds
  - Vacuum infiltration with reduced resin void fraction has potential to significantly reduce costs if composite reductions are realized
  - Braided CF with vacuum infiltration offers an attractive short cycle time process and proofs of concept potential high production vacuum infiltration process

Summary (2/2)

- **Uncertainty analysis suggest high precision in mass and volume estimates**
  - Tank mass assumptions are based on a limited sample size corrected for small sample error
  - Small variation is consistent with good manufacturing practice
  - COV_{mfg} between manufacturers could increase the uncertainty
- **Preliminary analysis of Toyota composite tanks**
  - No savings in CF mass for small aspect ratio tank
  - Improved winding patterns demonstrate potential to reduce cost by ~5% for two-tank configuration with same aspect ratio
- **Parametric analysis of Toray T-720**
  - Lighter tank leads to increase in grav. capacity from 4.7 wt.% (T-700) vs. 5.6 wt.% (T-720)
  - Need accurate T-720 pricing data
  - Preliminary parametric cost analysis shows
    - Significant cost savings relative to T-700
    - Cost parity with T-700 at a price premium of ~30%
    - Not competitive with ORNL PAN-MA at prices higher than ~1.1*T-700
- **Variations in fiber strength variations**
  - Preliminary ORNL PAN-MA fiber variations of ~7% measured on lab-scale equipment result in a preliminary cost increase of 4.8%

Technical Backup Slides

Approach:
SA's DFMA® - Style Costing Methodology

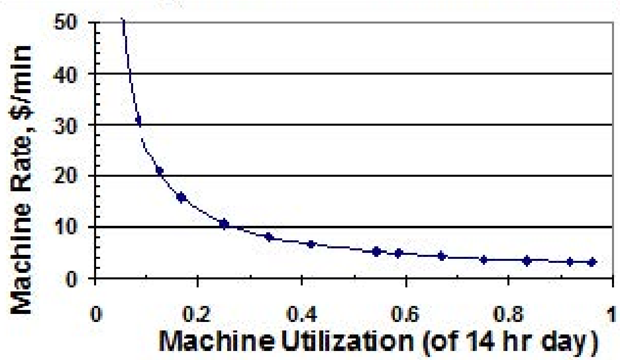
- DFMA® (Design for Manufacture & Assembly) is a registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Co. design/costing method for the past 20+ years
- SA practices are a blend of:
  - "Textbook" DFMA®, industry standards and practices,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

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

Production Volume Range of Analysis:

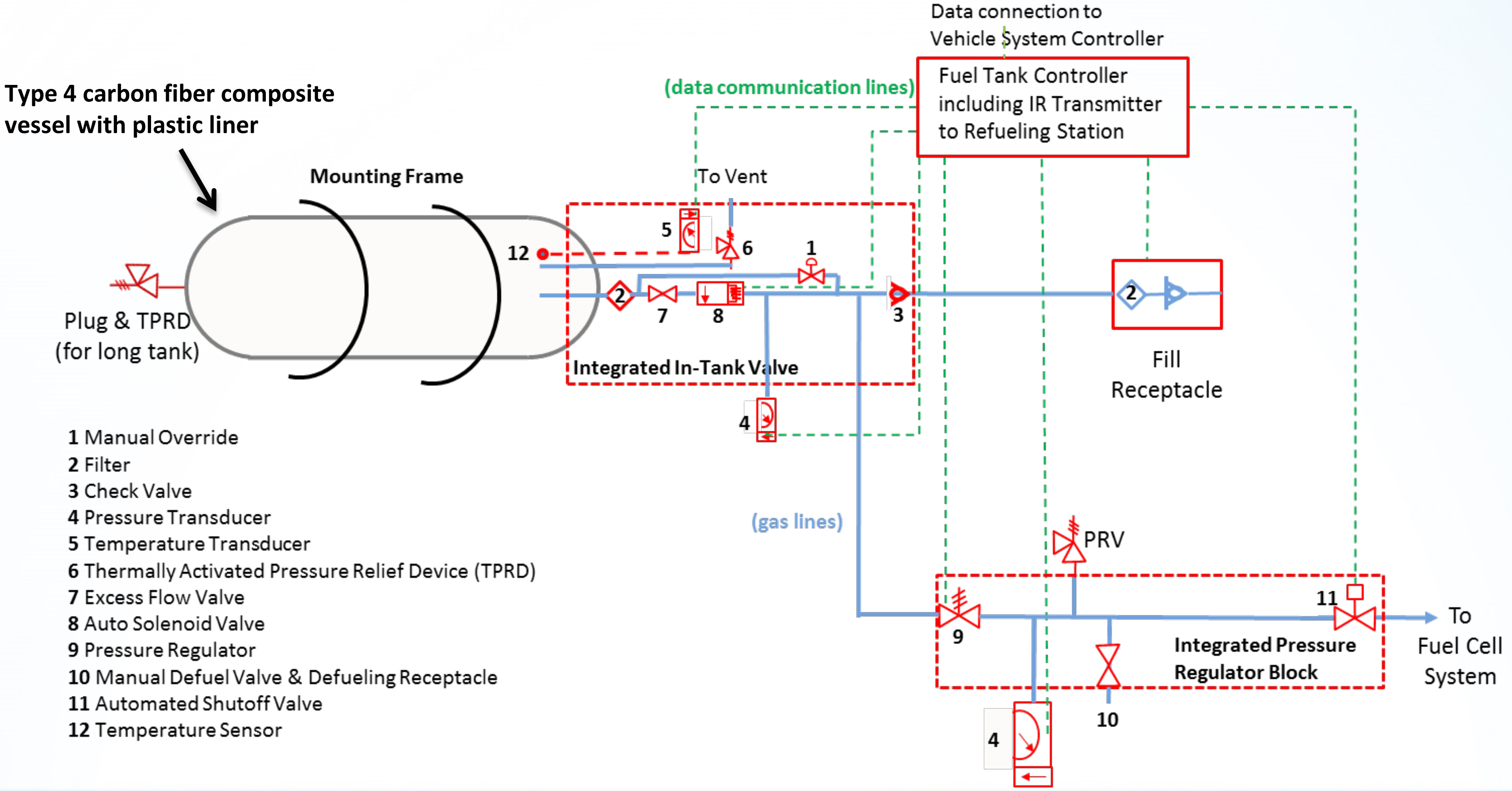
10,000 to 500,000 H_2 storage systems per year

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

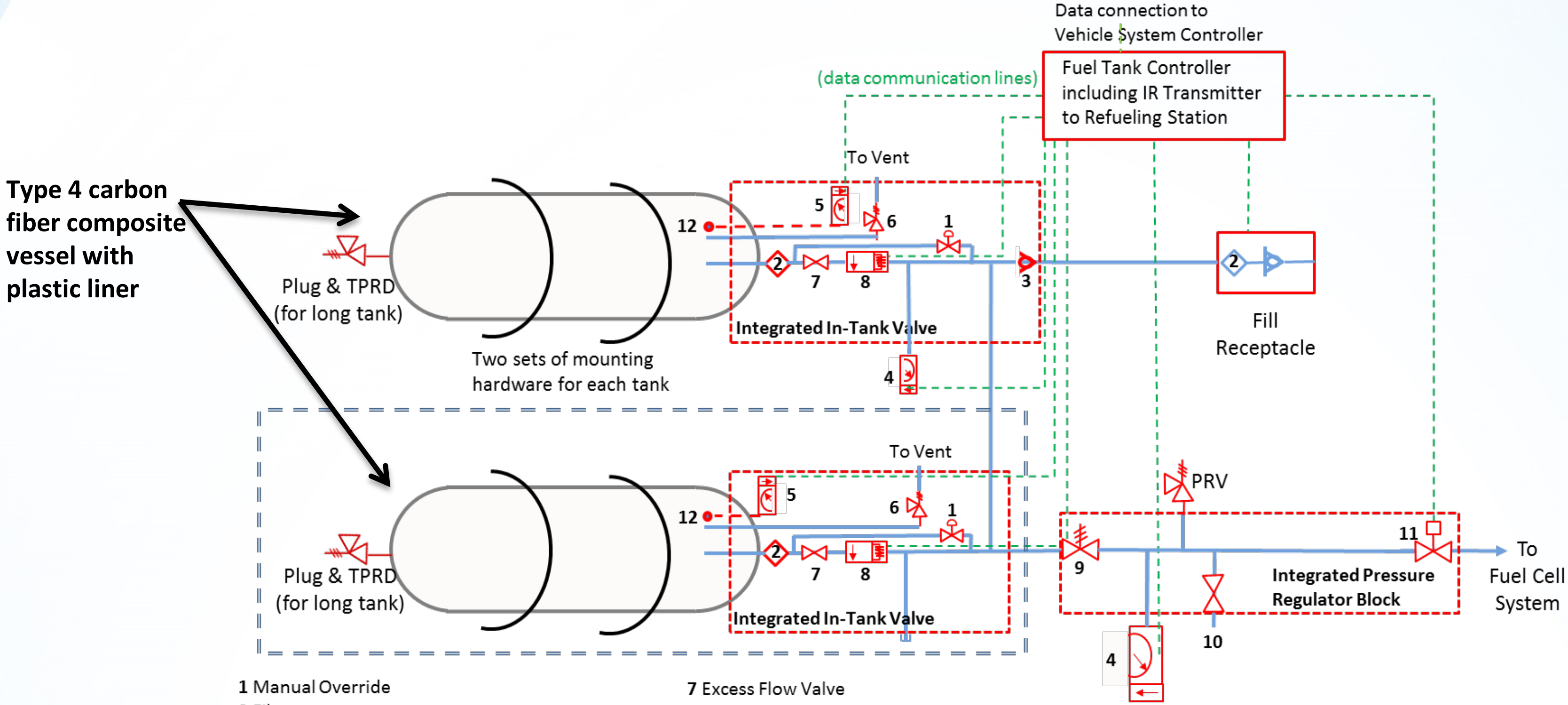
System Diagram

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



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



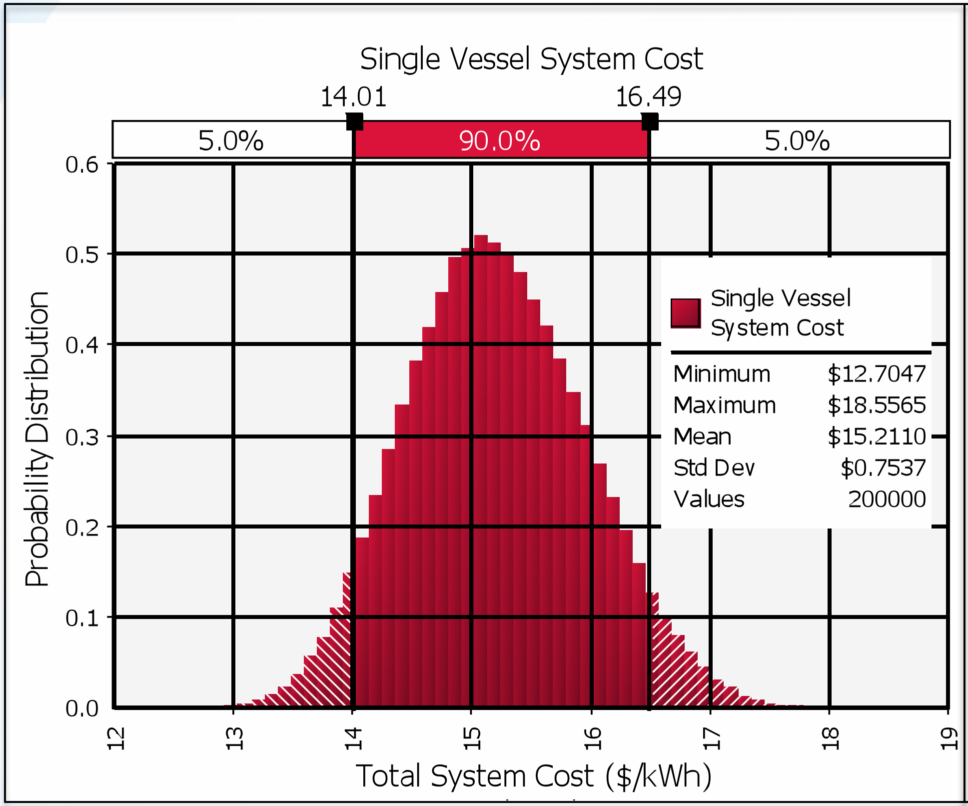
1 Manual Override
2 Filter
3 Check Valve
4 Pressure Transducer
5 Temperature Transducer
6 Thermally Activated Pressure Relief Device (TPRD)
7 Excess Flow Valve
8 Auto Solenoid Valve
9 Pressure Regulator
10 Manual Defuel Valve & Defueling Receptacle
11 Automated Shutoff Valve
12 Temperature Sensor

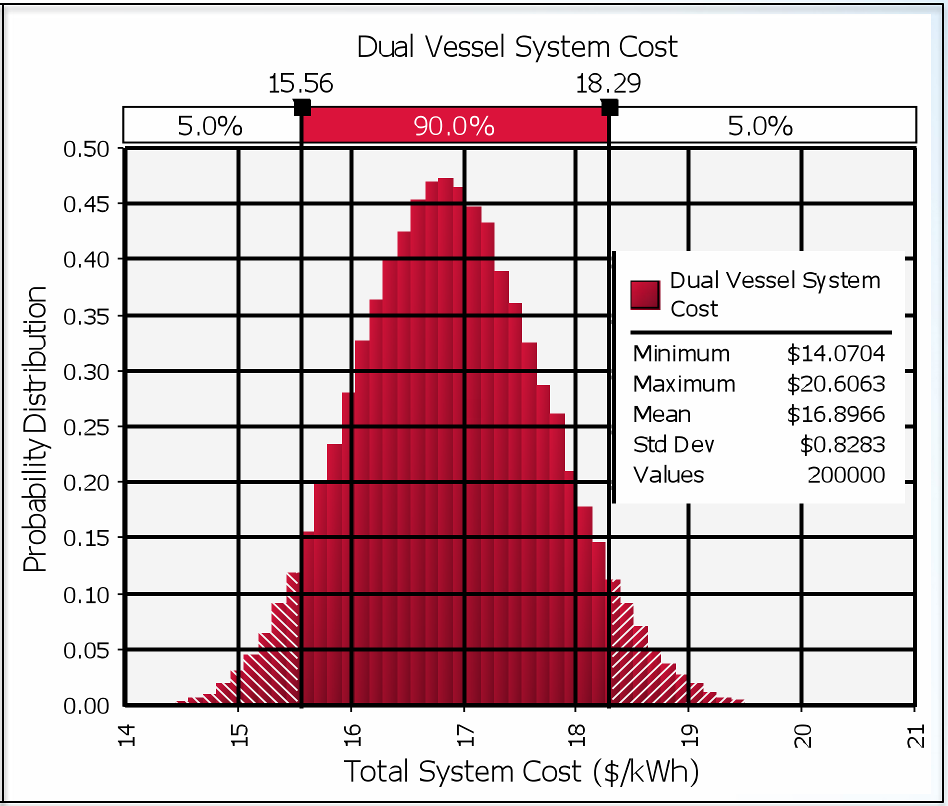
Accomplishment & Progress:
Uncertainty analysis expanded to include capacity for 700 bar Type IV Systems

	Units	2020 Target [1]	Ultimate Target [1]	2013 Status [2]	2015 Status
Gravimetric Capacity	kWh/kg system	1.8	2.5	1.5	1.40±0.04[a]
Volumetric Capacity	kWh/L system	1.3	2.3	0.8	0.81±0.01[a]
Cost at 500,000 units/year	2007$/kWh	10	8	16.8	14.7 [-0.8, +1.7][b]

- Uncertainty in capacity represents the 90% confidence interval
  - Tank mass ranges from PNNL (as detailed on previous slide)
  - Estimated 10% mass uncertainty in BOP components
- Cost uncertainty modeled using Monte Carlo analysis

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

Cost 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.