700 bar Type IV H2 Pressure Vessel Cost Projections

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Department of Energy Physical-Based Hydrogen Storage Workshop:
Identifying Potential Pathways for Lower Cost 700 Bar Storage Vessels

24 August 2016

USCAR, Southfield, MI

Objective

- Overview assumptions & results of latest cost analyses
- Categorize potential pathways for cost reduction
- Provide framework and reference base for workshop discussions

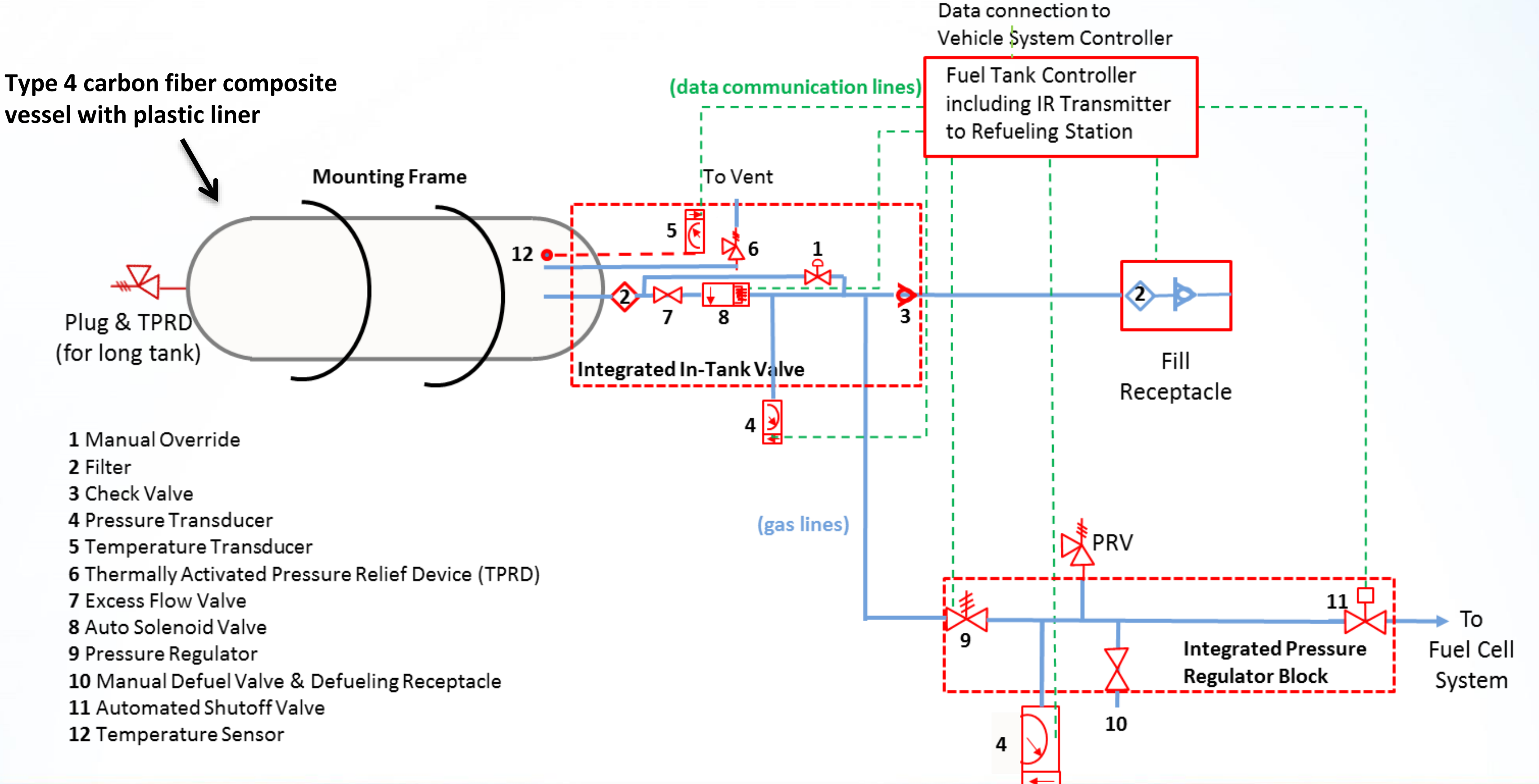
Outline

- System design
- Cost analysis methodology
- Cost projections
- Key opportunities for cost reduction
- Recent focus areas
  - Composites
  - BOP
  - Winding time

System Diagram

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

Cost Reduction Strategies:
- **System simplification**
- **Multi-functionality**
- **Part standardization**



Approach:
SA's DFMA® - Style Costing Methodology

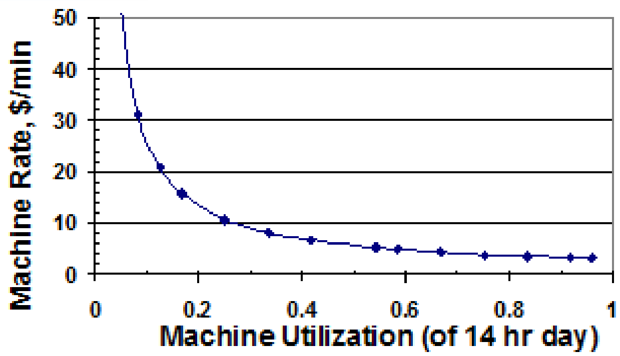
- DFMA® (Design for Manufacture & Assembly) is a registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Co. design/costing method for the past 20+ years
- SA practices are a blend of:
  - "Textbook" DFMA®, industry standards and practices,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

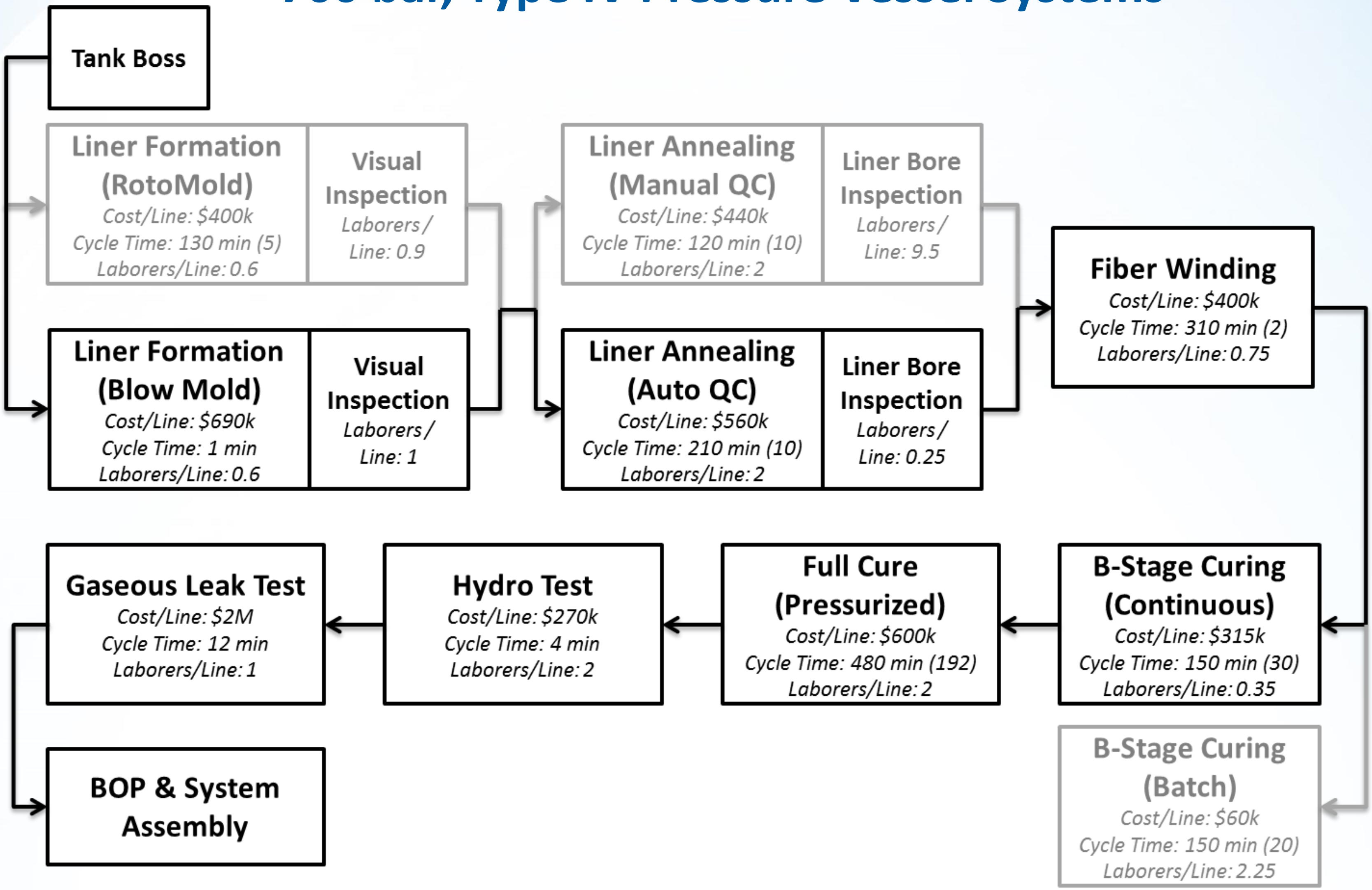
$$\frac{\text{Annual Capital Repayment} + \text{Annual Operating Payments}}{\text{Annual Minutes of Equipment Operation}} = \text{Machine Rate (\$/min)}$$

Production Volume Range of Analysis:

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

Manufacturing Flow Diagram

700 bar, Type IV Pressure Vessel Systems



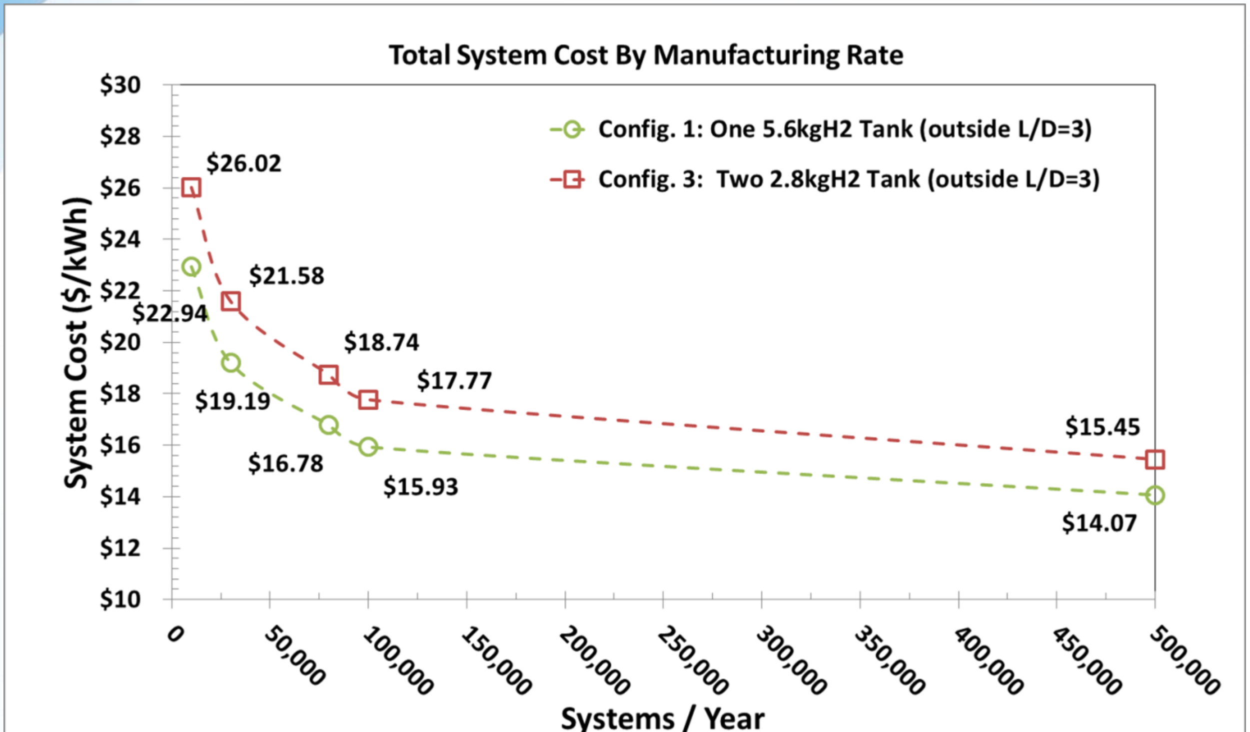
*Black indicates processes assumed for production at 500k systems/year

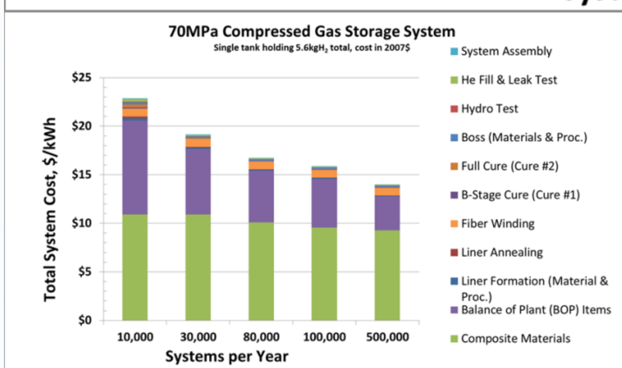
System Bill of Materials

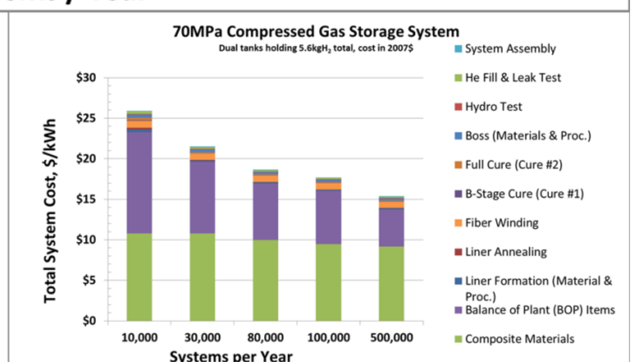
(700 bar, 5.6kgH_2 usable, Single Vessel)

		Single-Tank Configuration					Dual-Tank Configuration				
		10,000	30,000	80,000	100,000	500,000	10,000	30,000	80,000	100,000	500,000
Liner Blow Mold	**$/kWh**	**$0.27**	**$0.15**	**$0.11**	**$0.10**	**$0.10**	**$0.31**	**$0.18**	**$0.14**	**$0.14**	**$0.14**
Cost/tank	**$/tank**	*$51.38*	*$27.60*	*$20.16*	*$19.27*	*$17.84*	*$28.61*	*$16.72*	*$13.01*	*$12.67*	*$12.64*
Liner Annealing	**$/kWh**	**$0.17**	**$0.06**	**$0.03**	**$0.04**	**$0.03**	**$0.24**	**$0.07**	**$0.06**	**$0.05**	**$0.05**
Cost/tank	**$/tank**	*$31.40*	*$11.39*	*$5.78*	*$7.74*	*$5.65*	*$22.51*	*$6.59*	*$5.36*	*$4.71*	*$4.42*
Fiber Winding (Wet Winding)	**$/kWh**	**$11.72**	**$11.70**	**$10.86**	**$10.35**	**$10.04**	**$11.64**	**$11.62**	**$10.79**	**$10.28**	**$9.96**
Cost/tank	**$/tank**	*$2,192.19*	*$2,187.45*	*$2,030.42*	*$1,934.75*	*$1,877.09*	*$1,088.37*	*$1,086.00*	*$1,009.18*	*$960.93*	*$930.97*
B-Stage Cure (Cure #1)	**$/kWh**	**$0.09**	**$0.03**	**$0.02**	**$0.03**	**$0.02**	**$0.08**	**$0.05**	**$0.04**	**$0.04**	**$0.04**
Cost/tank	**$/tank**	*$16.59*	*$5.16*	*$4.23*	*$4.79*	*$4.34*	*$7.09*	*$4.92*	*$3.99*	*$3.99*	*$3.38*
Tank Shoulder Foam	**$/kWh**	**$0.09**	**$0.07**	**$0.06**	**$0.06**	**$0.06**	**$0.10**	**$0.08**	**$0.07**	**$0.07**	**$0.07**
Cost/tank	**$/tank**	*$16.00*	*$12.28*	*$11.12*	*$10.98*	*$10.76*	*$9.25*	*$7.39*	*$6.81*	*$6.74*	*$6.67*
Full Cure	**$/kWh**	**$0.34**	**$0.06**	**$0.04**	**$0.05**	**$0.04**	**$0.31**	**$0.08**	**$0.07**	**$0.07**	**$0.06**
Cost/tank	**$/tank**	*$63.95*	*$12.09*	*$6.94*	*$8.79*	*$7.31*	*$28.64*	*$7.34*	*$6.31*	*$6.93*	*$5.61*
Boss	**$/kWh**	**$0.19**	**$0.15**	**$0.14**	**$0.13**	**$0.13**	**$0.38**	**$0.31**	**$0.28**	**$0.27**	**$0.27**
Cost/tank	**$/tank**	*$35.68*	*$28.90*	*$25.91*	*$25.21*	*$24.90*	*$35.68*	*$28.90*	*$25.91*	*$25.21*	*$24.90*
Hydro Test	**$/kWh**	**$0.08**	**$0.05**	**$0.04**	**$0.04**	**$0.04**	**$0.11**	**$0.09**	**$0.09**	**$0.08**	**$0.08**
Cost/tank	**$/tank**	*$14.92*	*$8.76*	*$7.99*	*$7.52*	*$7.52*	*$10.30*	*$8.76*	*$7.99*	*$7.52*	*$7.49*
He Fill & Leak Test	**$/kWh**	**$0.28**	**$0.11**	**$0.09**	**$0.08**	**$0.08**	**$0.31**	**$0.23**	**$0.18**	**$0.16**	**$0.15**
Cost/tank	**$/tank**	*$52.68*	*$21.17*	*$17.23*	*$14.86*	*$14.86*	*$29.05*	*$21.17*	*$17.23*	*$14.86*	*$13.60*
Balance of Plant (BOP) Items	**$/kWh**	**$9.65**	**$6.76**	**$5.33**	**$5.01**	**$3.48**	**$12.49**	**$8.82**	**$6.95**	**$6.54**	**$4.59**
Cost/system	**$/system**	*$1,804.23*	*$1,264.37*	*$997.47*	*$935.88*	*$650.62*	*$2,334.70*	*$1,648.40*	*$1,300.24*	*$1,223.52*	*$857.41*
System Assembly	**$/kWh**	**$0.06**	**$0.05**	**$0.05**	**$0.05**	**$0.05**	**$0.06**	**$0.06**	**$0.06**	**$0.06**	**$0.06**
Cost/system	**$/system**	*$10.47*	*$9.61*	*$9.50*	*$9.44*	*$9.33*	*$12.00*	*$12.00*	*$12.00*	*$12.00*	*$12.00*
Total System Cost	**$/kWh**	**$22.94**	**$19.19**	**$16.78**	**$15.93**	**$14.07**	**$26.02**	**$21.58**	**$18.74**	**$17.77**	**$15.45**
Total System Cost	$/system	$4,289.49	$3,588.77	$3,136.75	$2,979.23	$2,630.22	$4,865.70	$4,035.98	$3,503.80	$3,322.66	$2,888.76
Tank Cost	$/kWh	$13.24	$12.38	$11.39	$10.88	$10.54	$13.47	$12.70	$11.72	$11.16	$10.80
Cost per Tank	$/tank	$2,474.80	$2,314.79	$2,129.77	$2,033.92	$1,970.27	$1,259.50	$1,187.79	$1,095.78	$1,043.57	$1,009.67

System Cost vs. Manufacturing Rate



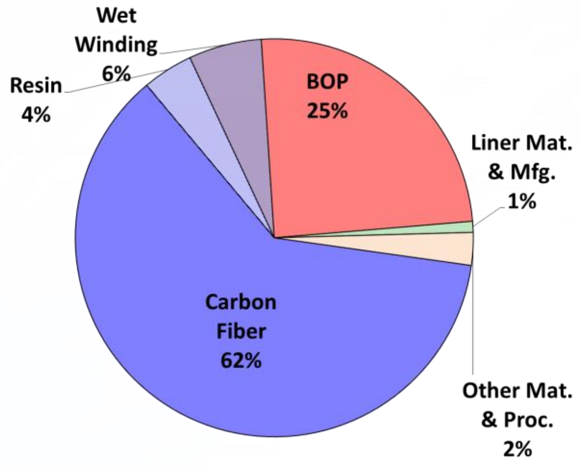




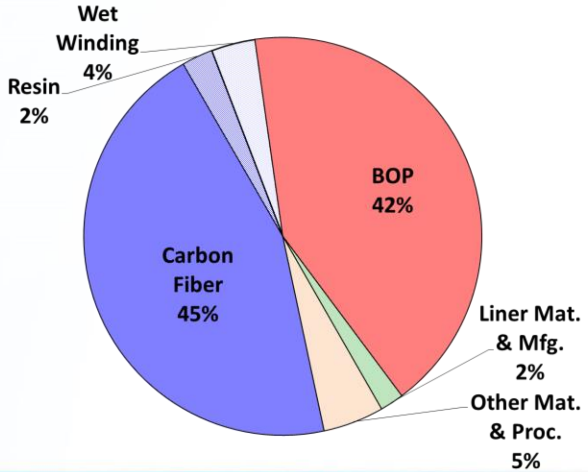
Cost Reduction Strategies:
- **Increase production rate**
- **Single tank instead of multiple tanks**

Status and Key Areas for Cost Reduction

500k Systems per year: $14.07/kWh



10k Systems per year: $22.94/kWh



– Fiber and BOP costs dominate

– Cost reductions should address:
- **Carbon Fiber**
  - Reduced CF costs (e.g. precursor or processing cost reductions)
  - Improved material utilization (e.g. winding patterns)
- **BOP**
  - Increased component integration
  - Parts reduction
- Winding time not a large cost contributor

Carbon Fiber Production Costs

	Units	20k vehicles per year	350k vehicles per year
Precursor Production Capacity (single large plant)	tonnes/year	7,500	7,500
Precursor Required for CF Production Volume	tonnes/year	3,300	55,000
Precursor Cost (spun PAN fibers)	$/kg	$6.42	$6.42
Ratio of Precursor to CF	kg/kg	2.2	2.2
CF Production Volume	tonnes/year	1,500	25,000
Cost of Precursor per kg CF	$/kg CF	$14.12	$14.12
CF Processing Cost	$/kg CF	$15.32	$11.49
CF Cost (no markup)	$/kg	$29.44	$25.61

- Precursor production is under-sized at high CF production volume
- Precursor cost contributes ~50% of the total CF cost

Cost Reduction Strategies:

- Reduce precursor material cost **($/kg)**
- Increasing precursor to CF conversion efficiency (**$kg_{precursor}/kg_{CF}$**)
- Increase production volumes **(economies of scale)**

Composite Reduction Through Material Utilization

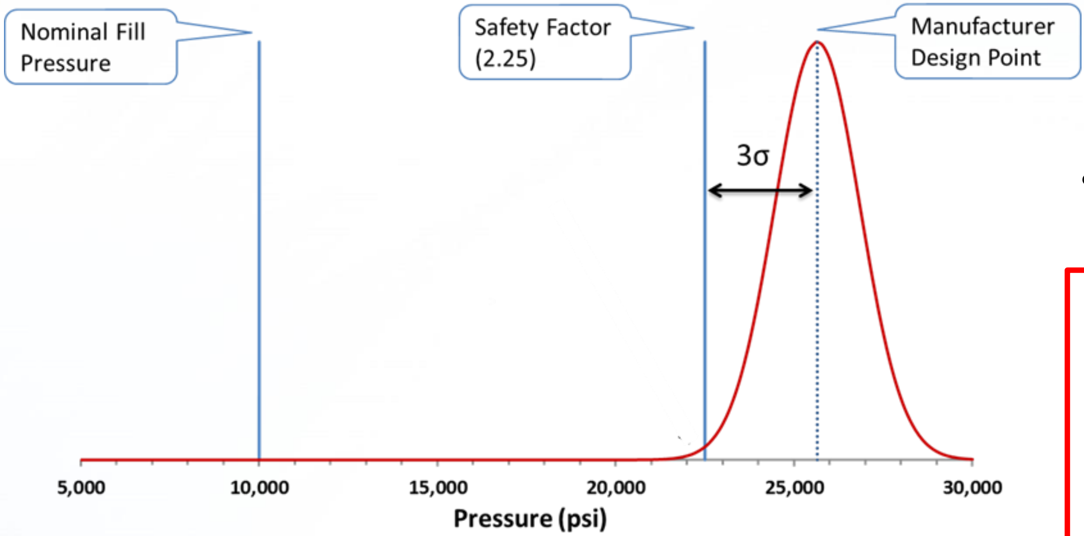
Winding Pattern	Resin	CF Volume Fraction [%]	Composite Mass [kg]	Tank Cost [$/kWh]	BOP& Assembly [$/kWh]	Total Cost [$/kWh]	
PNNL/HL	Epoxy	60	106.6	12.06	3.53	15.59	-4.7%
Toyota	Epoxy	60	99.9	11.33	3.53	14.86	
PNNL/HL	Vinyl Ester	64.7	97.0	11.04	3.53	14.57	-3.4%
Toyota	Vinyl Ester	64.7	92.3	10.54	3.53	14.07	

Toyota cost reduction strategies:

- Eliminate high-angle helical windings using an alternate liner geometry with sharp transitions from cylinder to dome
- Alternate winding scheme with
  - One helical layer over the entire liner
  - Concentrated hoop winding over the cylinder
  - Hoop/helical winding over cylinder and dome
- Alternate boss design with a smaller diameter boss and longer flange
- Higher strength T720 vs T700 CF (cost impact not currently modeled)

Composite Reduction Through Reduced Fiber and Manufacturing Variations

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



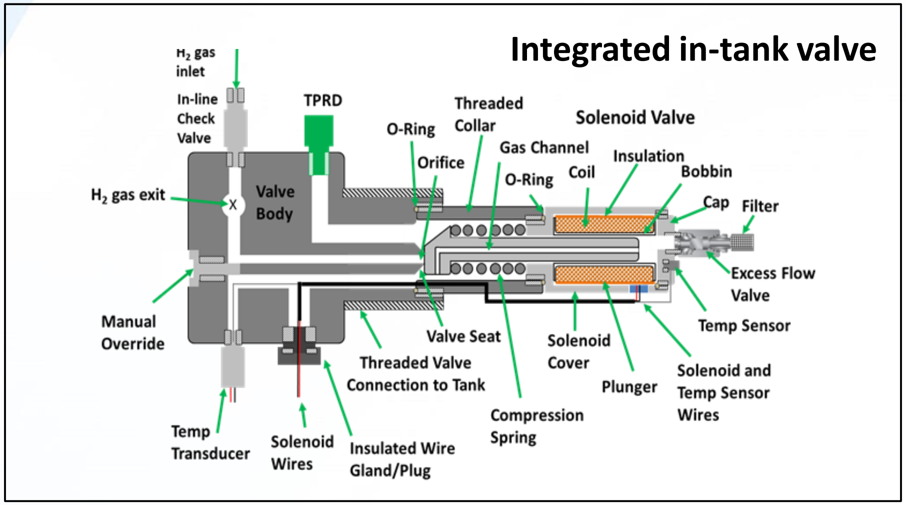
- T-700 has a COV_{fiber} of 3.3%
- Limited test samples from pilot line production have shown high fiber COVs of 7% adding almost 6 kg of CF ($0.85/kWh)
- Fiber variations are expected to be lower at full production scale

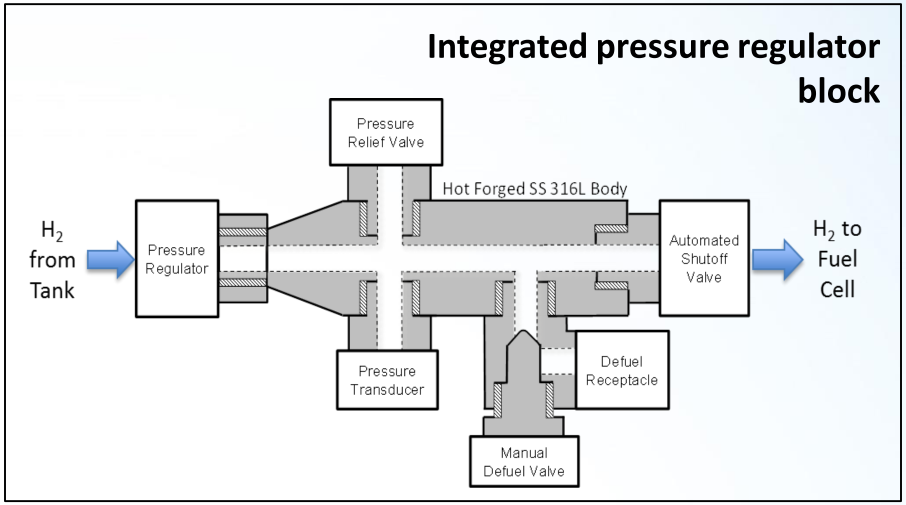
Cost Reduction Strategies:

- **R&D to lower COV during tank winding and/or during CF manufacture**
- **Lower Safety Factor**

	Fiber	COV (mfg)	COV (fiber)	3σ	System Cost
SA Baseline	ORNL CF from PAN-MA precursor	3.3%	3.3%	14.0%	$14.57/kWh
Observed COV_{Fiber}	ORNL CF from PAN-MA precursor	3.3%	7.0%	23.2%	$15.42/kWh
High COV_{Fiber}	ORNL CF from PAN-MA precursor	3.3%	11.6%	36.0%	$16.61/kWh
Tank with T-700	T-700	3.3%	3.3%	14.0%	$16.61/kWh

Integrated BOP functionality and lower cost materials reduce system cost





	Part Count	10k sys/yr [$/kWh]	500k sys/yr [$/kWh]
Integrated In-Tank Valve	9 (integrated into single unit)	2.40	0.96
Integrated Regulator	9 (integrated into single unit)	3.13	1.12
Other (tubing, mount, etc.)	15	4.12	1.40
Total	33	9.65	3.48

Additional BOP Adds ~$1.50/kWh for Two-Tank Configuration

	Single-Tank [$/kWh]	Two-Tank [$/kWh]
Integrated Regulator	$0.96	$1.75
Integrated In-Tank Valve	$1.12	$1.12
Other Components (Tubing, Fittings, Mounting Frame, TPRD)	$1.40	$1.72
Total	**$3.48**	**$4.59**

Cost Reduction Strategies:

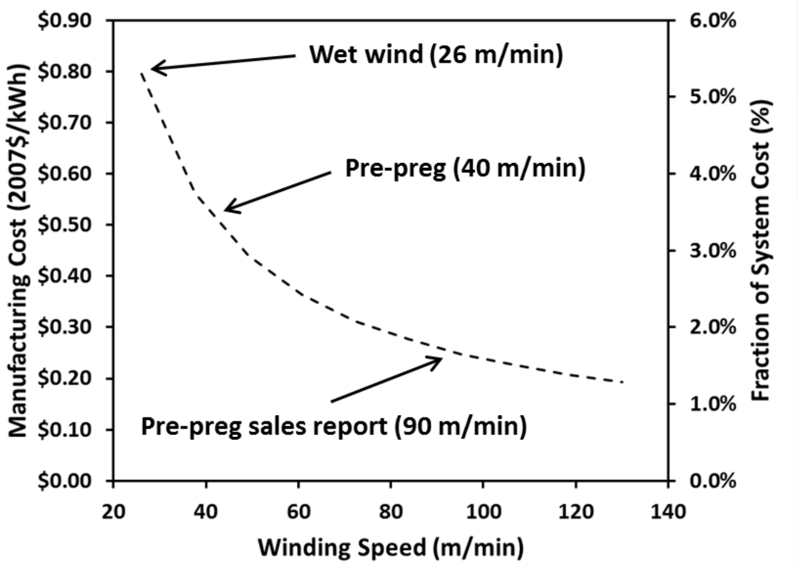
- System simplification
- Single vs. multiple tanks
- Multi-functionality
- Part standardization
- **Share valve among tanks**
- **Lower cost polymers/alloys**

Increasing Winding Speed Leads to Modest Cost Reductions

- Winding is ~5.5% of system cost for current model at 26 m/min
- System cost reductions possible (~2-4%) by increasing winding speed
- One winding line can supply around 1,500 tanks per year
  - 300 production lines required for 550k systems/year
  - Reduction in # of prod. lines is compelling reason alone to increase speed
- Manufacturing floor space and labor would be the main savings from improving winding speed

Cost Reduction Strategies:

- **Decrease winding time (limited savings)**
- **Advanced forming techniques (perhaps something radically different)**



Summary

- **Carbon fiber**
  - Largest single cost item at all volumes studied (45% - 62% of system cost)
  - The cost of precursor and of converting the precursor to carbon fiber contribute approximately equally to the finished carbon fiber cost
  - Strategies to address CF cost could include reduction in
    - Precursor cost
    - Time to convert precursor fibers to CF
    - Total precursor required
  - Fiber variations must be controlled in new fiber development programs
- **Balance of Plant**
  - Further part count reduction through component integration
  - Lower cost materials
- **Manufacturing**
  - Increased winding speed will not have a significant impact on system cost, but would address the significant time to manufacturing tanks

Summary of Cost Reduction Strategies

System		• System simplification to reduce part counts and reduce manufacturing cost

Pressure Vessel	**Carbon Fiber/Composite**	• Reduce CF precursor cost $/kg
		• New materials with lower $/kg
		• Reduce CF usage
		• **Increase strength/performance**
		    • **Stronger fibers**
		    • **Higher translation**
		• **High temperature resins to allow fast fill temperature rise**

	Manufacturing	• Advanced forming techniques • Something radically different • **Fast cure and/or low cost resins** • Lower manufacturing COV • Lower Safety Factor (demonstrate safety at lower SF) • Increase production rate, market size • Decrease winding time (limited savings) • **Multi-head winding, pre-preg, etc**.
Balance of Plant		• Multi-functional components • Lower cost metals/materials-of-construction • Standardized equipment • **Port sizes/diameters, connection type, material selection, etc.**
Refueling Infrastructure	**Functionality Placement**	• **Better utilization and lower cost if placed at station rather than placed on vehicle** • **Sensors, pumps, electronics, heat exchangers , etc.**
	Innov. Refueling Concepts	• **Systems that efficiently pre-cool hydrogen** • **Systems that can handle flow rate surge of fast filling**
	PV Insulation	• **Avoid vacuum insulation (that require gas tight welds and/or maintenance)** • **Develop low-k (and inexpensive) insulation** • **Develop automated insulation lay-up techniques** • **Load bearing vs. non-load bearing insulation**

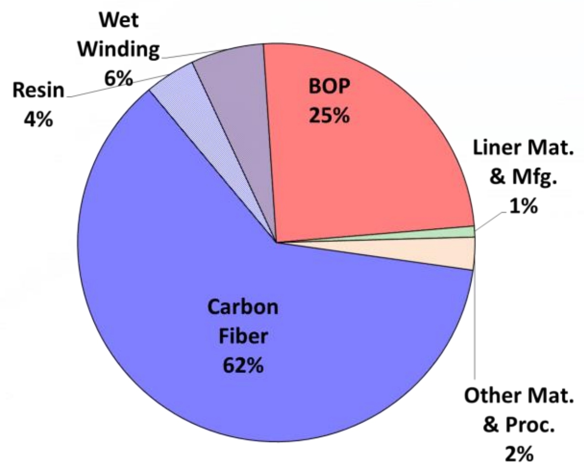
Backup Slides

System Cost Breakdown

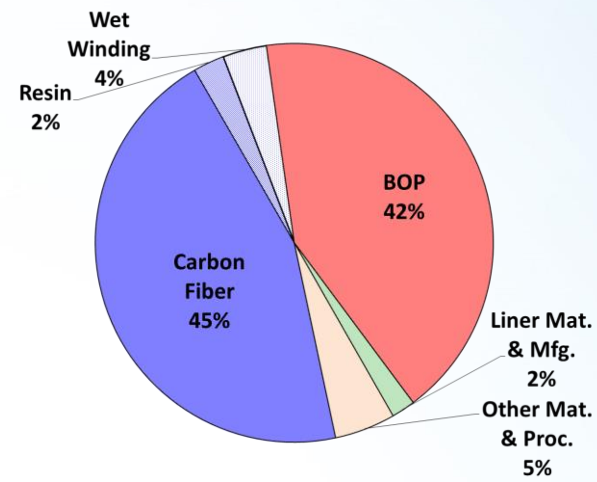
500k Systems per year | **10k Systems per year**

Single-Tank

500k Systems per year:

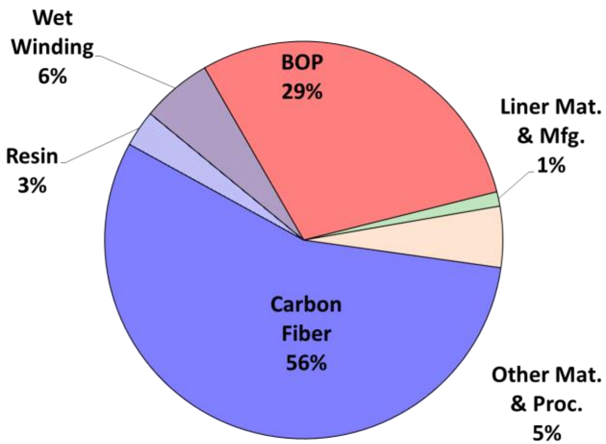


10k Systems per year:

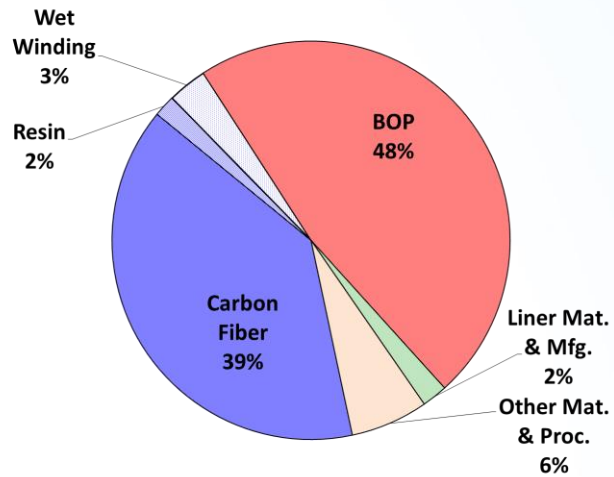


Two-Tank

500k Systems per year:



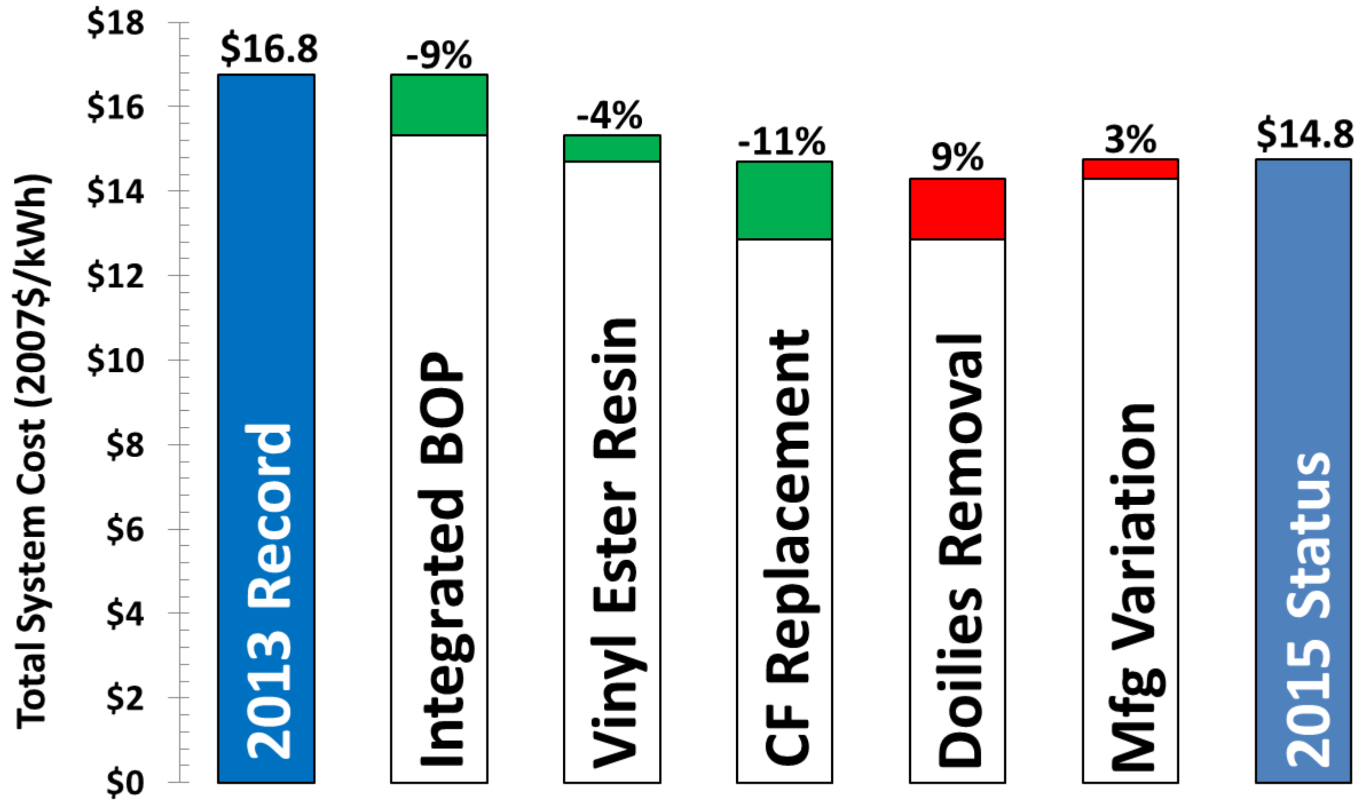
10k Systems per year:



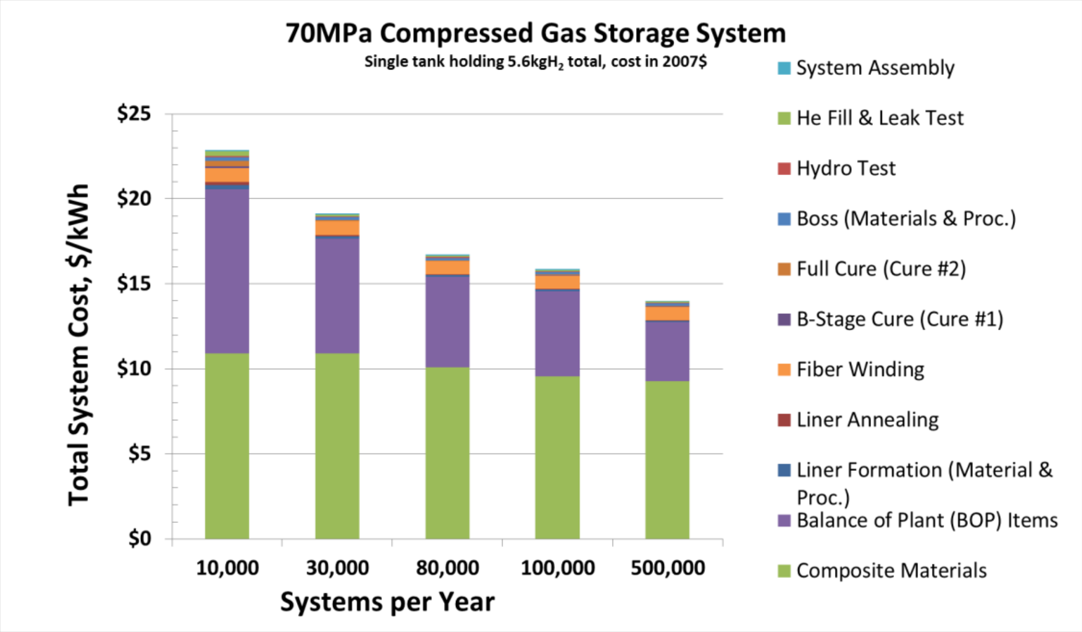
BOP Bill of Materials

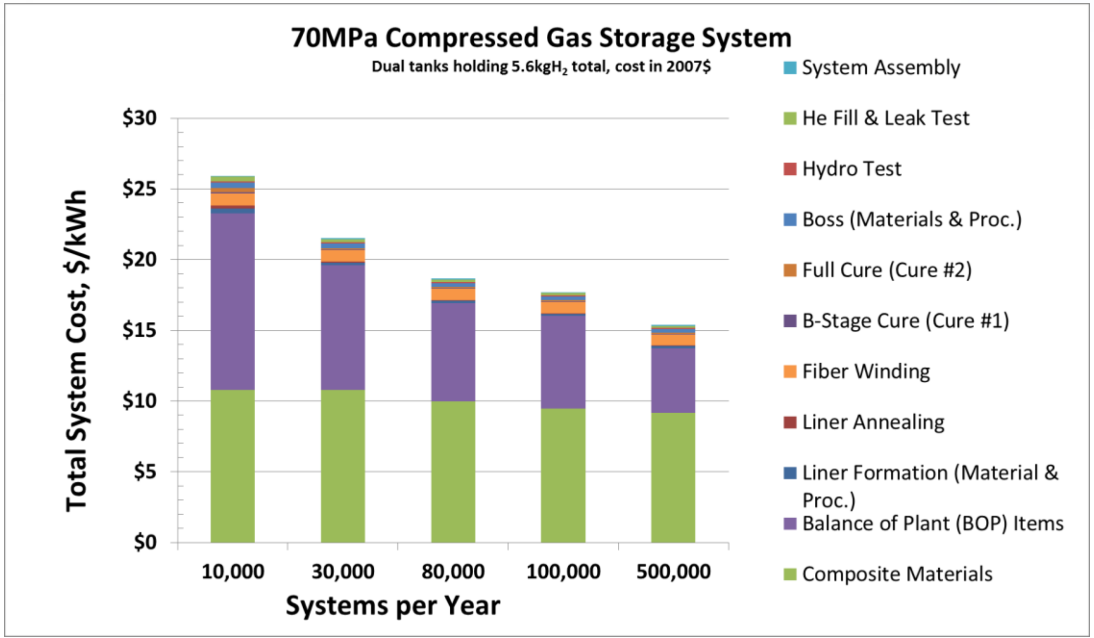
Annual Manufacturing Rate	Sys/Year	Single-Tank Configuration 10,000	30,000	80,000	100,000	500,000	Two-Tank Configuration 10,000	30,000	80,000	100,000	500,000
Integrated In-Tank Valve	**Per Tank**	**$447**	**$325**	**$261**	**$247**	**$178**	**$759**	**$563**	**$458**	**$437**	**$327**
TPRD (1)	Per Tank	$31	$27	$23	$22	$16	$62	$53	$46	$44	$33
Excess Flow Valve (1)	Per Tank	$40	$32	$28	$27	$21	$80	$64	$55	$53	$41
Filter (1)	Per Tank	$27	$22	$20	$19	$16	$54	$45	$40	$39	$32
Manual Override (1)	Per Tank	$6	$5	$5	$5	$5	$12	$11	$10	$10	$10
Temperature Sensor (1)	Per Tank	$43	$29	$21	$20	$12	$87	$58	$42	$39	$25
Auto Solenoid Valve (1)	Per Tank	$105	$77	$64	$62	$48	$211	$154	$128	$123	$97
Valve Body (1)	Per Tank	$19	$16	$15	$15	$14	$38	$32	$30	$30	$27
Insulated Leadwire Sealing Fitting (1)	Per Tank	$29	$20	$15	$13	$8	$59	$40	$29	$27	$16
Valve Integration and Test (1)	Per Tank	$9	$8	$8	$8	$7	$18	$17	$16	$16	$15
Check Valve (1)	Per System	$44	$29	$21	$19	$11	$44	$29	$21	$19	$11
High Pressure Transducer (1)	Per System	$94	$60	$41	$37	$20	$94	$60	$41	$37	$20
Integrated Pressure Regulator	**Per System**	**$586**	**$396**	**$327**	**$302**	**$209**	**$586**	**$396**	**$327**	**$302**	**$209**
Integrated Pressure Regulator Block	Per System	$33	$10	$12	$11	$8	$33	$10	$12	$11	$8
Pressure Regulator (1)	Per System	$204	$164	$164	$153	$127	$204	$164	$164	$153	$127
PRV (1)	Per System	$92	$58	$39	$35	$18	$92	$58	$39	$35	$18
Low Pressure Transducer (1)	Per System	$55	$35	$24	$22	$13	$55	$35	$24	$22	$13
Manual Defuel Valve incl. "Defuel Recep." (1)	Per System	$87	$55	$37	$34	$17	$87	$55	$37	$34	$17
Low Pressure Automated Shutoff Valve (1)	Per System	$115	$74	$51	$47	$26	$115	$74	$51	$47	$26
Other (tubing, mount, etc.)	**Per System**	**$770**	**$541**	**$413**	**$387**	**$262**	**$991**	**$688**	**$518**	**$485**	**$321**
Fuel Tank Controller (1)	Per System	$138	$117	$101	$97	$76	$138	$117	$101	$97	$76
Pipings/Fittings for first tank	Per System	$91	$68	$61	$59	$51	$91	$68	$61	$59	$51
Pipings/Fittings per additional tank	per addtl tank	$0	$0	$0	$0	$0	$35	$30	$27	$26	$23
Plug and TPRD (1)	Per tank	$140	$89	$59	$54	$28	$280	$177	$118	$108	$55
Fill Receptacle (incl. IR Transmitter) (1)	Per System	$195	$124	$83	$76	$40	$195	$124	$83	$76	$40
Mounting Frame (1)	Per Tank	$45	$29	$19	$17	$9	$91	$58	$38	$35	$18
Miscellaneous	Per System	$161	$114	$90	$84	$58	$161	$114	$90	$84	$58
BOP Subtotal	**$/System**	**$1,804**	**$1,264**	**$997**	**$936**	**$651**	**$2,335**	**$1,648**	**$1,300**	**$1,224**	**$857**
BOP Subtotal	**$/kWh**	**$9.65**	**$6.76**	**$5.33**	**$5.01**	**$3.48**	**$12.49**	**$8.82**	**$6.95**	**$6.54**	**$4.59**

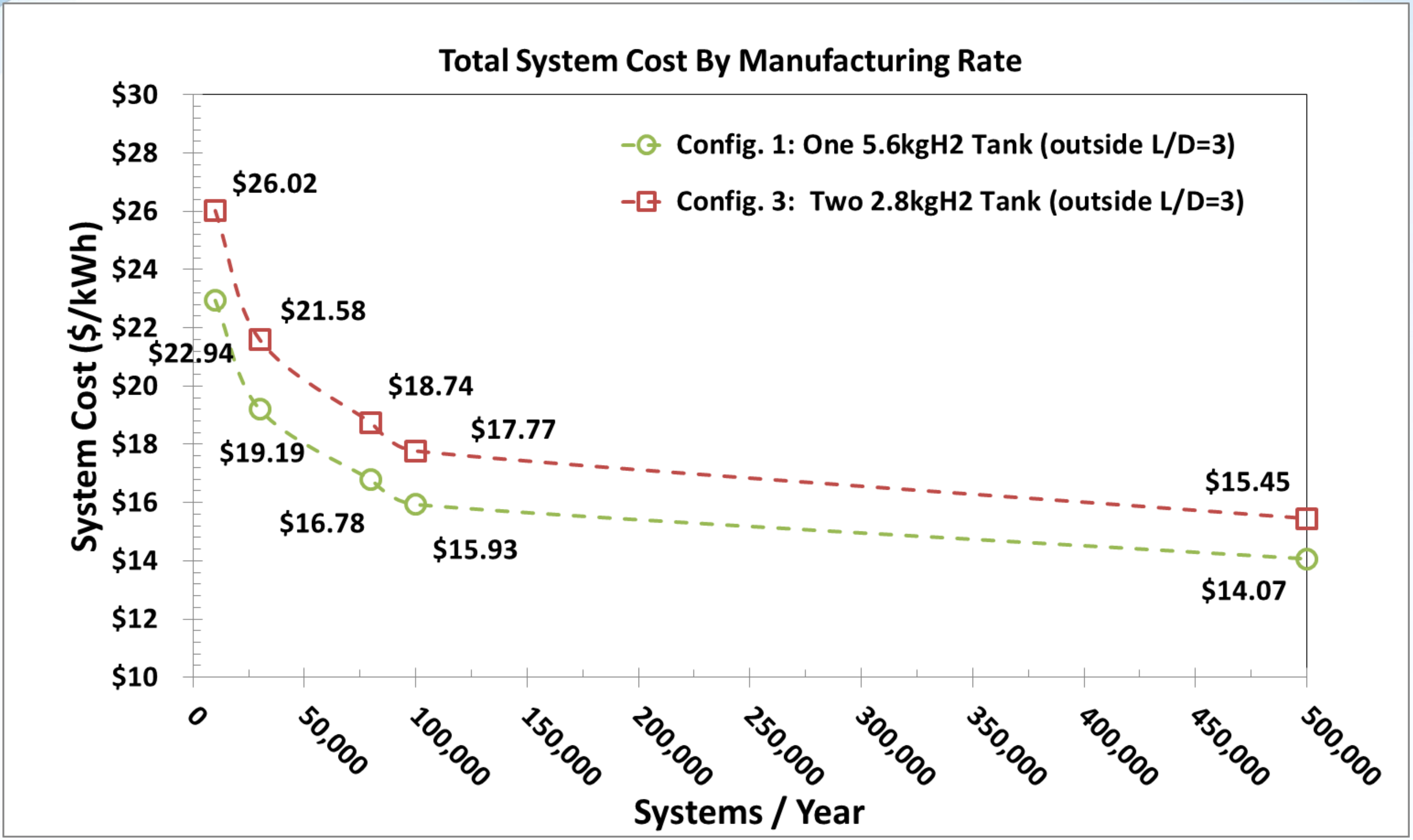
Accomplishments & Progress:
700 bar type IV H_2 storage system cost reduction identified



*Cost at 500,000 systems per year


70MPa Compressed Gas Storage System
Single tank holding 5.6kgH2 total, cost in 2007$
Total System Cost, $/kWh
$0
$5
$10
$15
$20
$25
10,000
30,000
80,000
100,000
500,000
Systems per Year
System Assembly
He Fill & Leak Test
Hydro Test
Boss (Materials & Proc.)
Full Cure (Cure #2)
B-Stage Cure (Cure #1)
Fiber Winding
Liner Annealing
Liner Formation (Material & Proc.)
Balance of Plant (BOP) Items
Composite Materials


70MPa Compressed Gas Storage System
Dual tanks holding 5.6kgH2 total, cost in 2007$
Total System Cost, $/kWh
$0
$5
$10
$15
$20
$25
$30
10,000
30,000
80,000
100,000
500,000
Systems per Year
System Assembly
He Fill & Leak Test
Hydro Test
Boss (Materials & Proc.)
Full Cure (Cure #2)
B-Stage Cure (Cure #1)
Fiber Winding
Liner Annealing
Liner Formation (Material & Proc.)
Balance of Plant (BOP) Items
Composite Materials



Total System Cost By Manufacturing Rate
System Cost ($/kWh)
$30
$28
$26
$24
$22
$20
$18
$16
$14
$12
$10
Config. 1: One 5.6kgH2 Tank (outside L/D=3)
Config. 3: Two 2.8kgH2 Tank (outside L/D=3)
$26.02
$21.58
$18.74
$17.77
$15.45
$22.94
$19.19
$16.78
$15.93
$14.07
0
50,000
100,000
150,000
200,000
250,000
300,000
350,000
400,000
450,000
500,000
Systems / Year