Final Report: Hydrogen Storage System Cost Analysis

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Disclaimer

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Table of Abbreviations

AMR	Annual Merit Review (meeting)
ANL	Argonne National Laboratory
CC	Capital Cost
CF	Carbon Fiber
COPV	Composite Overwrapped Pressure Vessel
CNG	Compressed Natural Gas
DFMA	Design for Manufacture and Assembly
DOE	Department of Energy
EHC	Electrochemical Hydrogen Compression
FEA	Finite Element Analysis
FCTO	Fuel Cell Technologies Office
G&A	General and Administrative
HDPE	High Density Polyethylene
HP	High Pressure
HSECoE	Hydrogen Storage Engineering Center of Excellence
kWh	kilowatt-hours
LP	Low Pressure
MATI	Modular Adsorption Tank Insert
MOF	Metal Organic Framework
MT	Metric tons, tonnes (i.e. 1,000 kg)
NRE	Non-Recurring expense
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
psi	Pounds per Square Inch
R&D	Research and Development
ROI	Return on Investment
SA	Strategic Analysis, Inc.
SRNL	Savannah River National Laboratory
T-PRD	Thermal-Pressure Relief Device

1 Background, Objectives, and Tasks

The Fuel Cell Technologies Office (FCTO) has identified hydrogen storage as a key enabling technology for advancing hydrogen and fuel cell power technologies in transportation, stationary, and portable applications. Consequently, FCTO has established targets to chart the progress of developing and demonstrating viable hydrogen storage technologies for transportation and stationary applications. This cost assessment project supports the overall FCTO goals by identifying the current technology system components, performance levels, and manufacturing/assembly techniques most likely to lead to the lowest system storage cost. Furthermore, the project forecasts the cost of these systems at a variety of annual manufacturing rates to allow comparison to the overall 2017 and "Ultimate" DOE cost targets. The cost breakdown of the system components and manufacturing steps can then be used to guide future research and development (R&D) decisions.

The project was led by Strategic Analysis Inc. (SA) and aided by Rajesh Ahluwalia and Thanh Hua from Argonne National Laboratory (ANL) and Lin Simpson at the National Renewable Energy Laboratory (NREL). Since SA coordinated the project activities of all three organizations, this report includes a technical description of all project activity.

This report represents a summary of contract activities and findings under SA's five year contract to the US Department of Energy (Award No. DE-EE0005253) and constitutes the "Final Scientific Report" deliverable. Project publications and presentations are listed in the Appendix.

1.1 Project Objectives

The objectives of this project were to:

- Identify and update the configuration and performance of a variety of hydrogen (H_2) storage systems for both vehicular and stationary applications on an annual basis.
- Rigorously analyze the manufacturing cost of multiple H_2 storage systems to reflect optimized components for the specific application and manufacturing processes at various rates of production.
- Explore cost parameter sensitivity to gain an understanding of system cost drivers and future pathways to lower system cost.
- Document all analysis results and assumptions in a comprehensive annual report.

1.2 Tasks

The project was organized around five main tasks:

- Task 1: Literature Review
- Task 2: Review and down-select of systems to be examined
- Task 3: System definition and bill of materials
- Task 4: Manufacturing process definition and DFMA cost estimation
- Task 5: Reporting

A brief description of each of the tasks as defined in the statement of work follows.

1.2.1 Task 1.0 Literature Review

Strategic Analysis (SA) conducted a continuous literature review throughout the project to stay apprised of the latest developments in on-board H_2 storage system concepts, configurations, materials, and associated manufacturing technology. The review was more intensive during the first three months of the project to establish a base of information. The review included reviews of the status of selected storage technologies as directed by DOE's Hydrogen Storage Team and included the status of storage material properties and characterization, system level designs, safety analysis/testing of the storage options, schematics identifying the need for all subsystems, and balance of plant (BOP) requirements for practical operation. After the initial review, the literature review focused on staying abreast of ongoing developments. Literature sources included journal articles, conference proceedings, DOE contractor reports, company reports, patents, and newspaper articles.

1.2.2 Task 2.0 Review and down-select of system to be examined

SA down-selected specific storage methods and applications for cost analysis. Storage system options analyzed were: 350 bar pressurized hydrogen gas, 700 bar pressurized hydrogen gas, and adsorbent materials. The primary application considered was H_2 storage for light-duty fuel cell automobiles.

1.2.3 Task 3.0 System definition and Bill of Materials

SA prepared system definitions corresponding to each of the systems identified in Task 2. System definitions were developed based on third-party designs and augmented by SA to the extent necessary for cost analysis. The systems were defined in flow schematics that identified all components of the system as well as a visual listing of relevant parameters (storage amount, mass flow, pressure, temperature, materials, etc.) System definitions were supported by system performance modeling calculations supplied by the DOE Storage Team and/or third-party vendors when possible, and supplemented with Excel and/or Hysys performance modeling conducted by SA and its team members. From the system definitions, a bill of materials (BOM) was created for each system tabulating all system components and subsystems contained in the storage systems. The BOM served as the master index of each system and was further detailed during Task 4. The flow schematics and BOM reflect changes in the systems between applications and the various annual manufacturing rates considered. The system definitions and bills of materials were reviewed with the Storage Team and industry for accuracy and completeness.

1.2.4 Task 4.0 Manufacturing process definition and DFMA cost estimation

SA conducted rigorous DFMA analysis based on 2015 (and beyond) storage technology projections. Estimated total storage system costs were predicted for up to five annual manufacturing rates ranging from initial market penetration volume through high volume. Manufacturing volumes ranged from 1,000 systems per year to 500,000 systems per year. To accomplish this, the following analyses were conducted as part of the overall task effort: enumeration of all manufacturing/assembly/testing steps and identification of all cost and fabrication assumptions used in the cost analysis, investigation and detailed specification of quality control equipment to ensure high yields and low costs, mathematical functions to scale system component costs, Tornado sensitivity analysis based on performance variations and key manufacturing or design changes, and recommendations for a feasible path forward to reduce total system cost. The cost analyses were based on H_2 storage system measurements, from DOE or third-parties, which were previously verified. All analysis results were documented in reports to DOE. The viewgraphs and reports were circulated to the DOE, H_2 storage community, and the manufacturing community for feedback as to technical and cost realism. Project methodology, key assumptions, and results were briefed to the DOE Storage Team and at the Annual Merit Review (AMR) (plus other groups as requested by DOE). To validate the cost models, a currently produced storage system were cost modeled and the resulting predictions compared against the known factory costs. The DOE Hydrogen Storage Team facilitated the definition of this baseline system and obtaining the factory cost values. SA worked closely with the third-party vendor to validate the model and compare system costs. This task was repeated in each budget period.

1.2.5 Task 5.0 Reporting

Reports and other deliverables were provided in accordance with the Federal Assistance Reporting Checklist following the instructions included therein. Clear, concise, assessable, and referenceable reporting of the methodology, assumptions, and results was a key objective of the project. For maximum accuracy and usefulness, the assumptions and results for the project were vetted by a wide range of individuals and groups. Reports were generated and presented at the:

- Hydrogen Storage Systems Analysis Working Group (SSAWG) Meetings
- USCAR and Fuel Hydrogen Storage Technical Team Meetings
- DOE Hydrogen Program Merit Review and Peer Evaluation (AMR) meeting

2 Analyses

The analyses conducted during this contract are described in the following section. Cost analysis of emerging technologies is inherently an iterative process as the technology, designs, and performance is rapidly changing. Consequently, some of the analyses in this report are marked as preliminary to denote their interim status as of the report date, due to either on-going areas of investigation or a shifting of DOE priorities. However, these preliminary analyses have significant value and are included to provide both status reporting and identification of cost drivers and manufacturing requirements.

2.1 Cost Analysis Methodology

SA uses a Design for Manufacture and Assembly® (DFMA®) cost methodology approach to project the cost to manufacture hydrogen storage systems. DFMA® is a process-based cost analysis methodology which projects material and manufacturing cost of the complete system by modeling specific manufacturing steps. Consequently, the first steps in performing cost analysis are to define the system design and the specific manufacturing and assembly steps required to achieve the specified design. Once the system and manufacturing/assembly steps are specified, the material inputs, capital equipment costs, and operating expenses are computed. The estimated cost is the sum of the material, manufacturing, and assembly costs. Material costs are based on the actual gross material cost consumed in each step (i.e. including scrap or other wastage). Manufacturing and assembly costs are defined as the product of machine rate (in $/min) and processing time (i.e. minutes to conduct that particular operation). Machine rate is defined as:

$$machine\ rate = \frac{Annual\ Capital\ Repayment + Annual\ Operating\ Payments}{Annual\ Minutes\ of\ Equipment\ Operation}.$$

Thus machine rate varies with annual production rate since Annual Capital Repayment is an annual fixed charge: the higher the machine utilization, the lower the machine rate. Additionally Annual Capital Repayment reflects the repayment of principle (i.e. repayment of the purchase price of the processing equipment), loan or return on investment (ROI) payments (i.e. payment of interest on the equipment loan or equivalent ROI to the business for providing the capital), and taxes (i.e. an increase in payment to reflect that interest and ROI payments are paid with after-tax dollars). Annual operating payments include variable costs for labor, maintenance, repair, and utilities. Material and manufacturing costs are tabulated for each step in the production process and then summed to achieve a system cost projection.

Typically, SA projects the cost (not the price) of the system to the final system integrator (i.e. the company that sells the fully assembled storage system. Consequently, the projected cost only reports the materials/manufacturing/assembly costs and does not include markup for profit, one-time costs such as non-recurring engineering (NRE) costs, general and administrative (G&A) expenses, warranties, or advertising; however, components that are assumed to be purchased for the system (e.g. valves, gas lines, etc.) include vendor markup. (This reflects that fact that the "price" of the purchases component is a "cost" to the final system integrator.) Standard values are used in the analyses for interest rates, labor rates, etc. to provide a common, transparent framework. These are summarized in

Table 1.

Throughout the analysis, cost is normalized on a $/kWh to allow comparison with DOE targets and as a metric which refers to total available onboard fuel storage. The energy content of hydrogen was taken on a lower heating value (LHV) basis, i.e. the LHV of hydrogen is assumed to be 33.3 kWh/kgH_2.

Table 1: Standard DFMA® inputs

	Units	Values
Possible Runtime per Day	hrs/day	14
Work Days/Year	days/year	240
Possible Annual Runtime per Line	hrs/year	3,360
Default Machine Lifetime	Years	15
Discount Rate	%	10%
Corporate Income Tax Rate	%	40%
Average Equipment Installation Factor	--	1.4
Average Maint./Spare Parts (% of CC per year)	%/yr	10%
Average Misc. Expenses (% of CC per year)	%/yr	7%
Electric Utility Cost	$/kWh	$0.07
Average Labor Rate (inclusive of direct labor, benefits, employer taxes)	$/hr	$42

2.2 Physical Storage Cost Analysis

Physical storage approaches include ambient temperature compressed gas, cryo-compressed gas, and cryogenic storage. During this contract, the cost of ambient temperature hydrogen storage was analyzed.

2.2.1 Type IV 350 bar Compressed Natural Gas (CNG) Pressure Vessel Validation

A validation study of the H_2 pressure vessel cost model was completed in the first year by adapting the previously SA developed cost model to represent a CNG pressure vessel and then comparing the projected results to actual vendor high production CNG quotes. CNG pressure vessels are manufactured in a very similar way to compressed H_2 Type IV tanks: a polymer liner overwrapped by continuous carbon fiber filament. For this comparison, a 270 liter (internal water volume) CNG tank (sized for light duty trucks) was selected for modeling based on discussions with CNG industry professionals who suggested that such a tank is currently produced at (relatively) high manufacturing rates. While CNG tanks for light duty vehicles (120 liter water volume) are produced at higher manufacturing rates (5,000 systems/year) by Structural Composite Industries (SCI)/Worthington Cylinders, the vessels are Type III tanks (metal lined, waist wrapped) rather than the Type IV tanks assumed for current H_2 storage pressure vessels. Consequently, the SCI tanks were rejected as the CNG validation basis. Table 2 compares key parameters for CNG and H_2 pressure vessels.

The general manufacturing process used for composite overwrapped pressure vessel gas storage systems (CNG, 350 and 700 bar H_2 systems) is shown in Figure 1.

Table 2: Comparison of CNG and H_2 pressure vessel nominal system parameters

	Units	CNG	H_2
Pressure	psi	3,600	10,000
Prod. Rate	units/year	100's-1,000's	1,000-500,000
Structural Fiber	--	T-700 carbon fiber	T-700 carbon fiber
Fiberglass	--	Outer Layer	None
Liner Material	--	HDPE	HDPE
Liner Formation Method	--	Roto-mold	Blow mold
Liner Thickness	cm	0.4	0.5

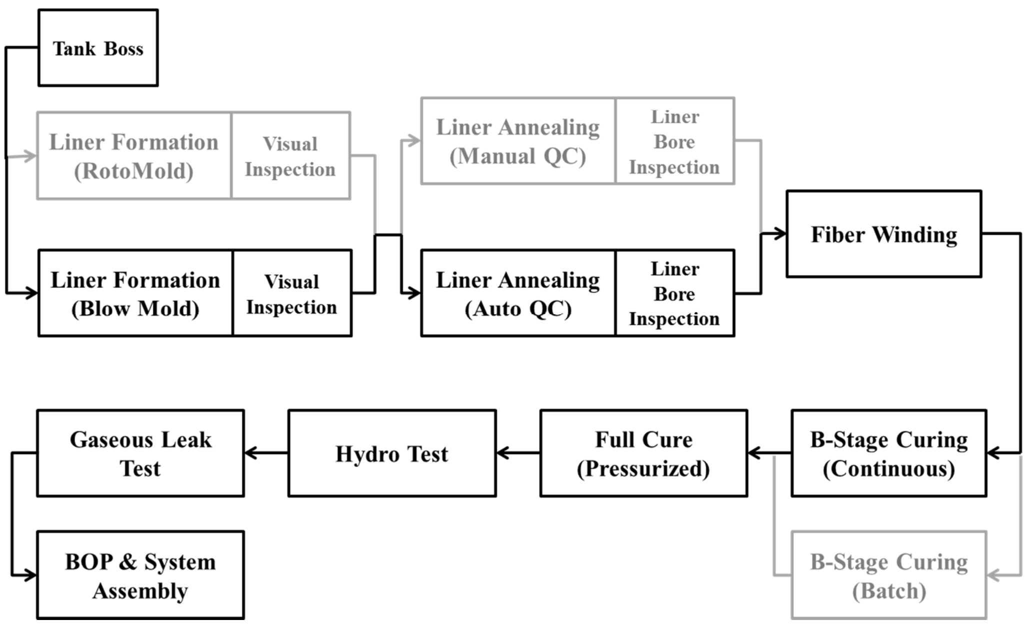

Figure 1: Generic process flow diagram for Type IV compressed gas storage. Steps in black indicate processes used at high volume manufacturing. Steps in gray indicate alternative forming processes that may be selected at low volume as appropriate to achieve a lower cost.

Argonne National Lab (ANL) used the ABAQUS™ finite element analysis (FEA) modeling tool to identify material masses and dimensions which were used as input values for SA's DFMA pressure vessel cost model. Results from the cost analysis were then marked up to allow direct comparison to price quotations provided by CNG tank manufacturers (Quantum Technologies, 3M, and Hexagon Lincoln) to validate the cost modeling approach. The final analysis results shown in Table 3 compare price quotations provided by manufacturers with the corresponding assumed markup schemes to allow assessment of the DFMA cost results. SA's results are in good agreement with Quantum and 3M quotations; however, Hexagon Lincoln prices are 15% lower than SA modeled prices. This difference is attributed to Hexagon Lincoln's higher actual total tank production volume compared to SA modeled production volume for a single vessel size: Hexagon Lincoln has lower costs because they have higher machine utilization due to producing multiple sizes of vessels, not just the DFMA modeled size). Additionally, Hexagon Lincoln's interior tank volume is slightly lower than the other manufacturers in part due to their addition of fiberglass to both the outer tank wrapping (for abrasion and chemical resistance) and to the inner fiber wrapping (for impact resistance). Quantum and 3M restrict fiberglass to the outside of the tank only, thereby providing a higher internal volume for the same outer tank dimensions. During this analysis, it was noted that the DFMA cost projection is quite sensitive to production rate. Thus, minor assumption differences in annual production rate can lead to significant changes in projected cost. Figure 2 shows the cost breakdown of modeled CNG tanks at several production volumes.

Table 3: **Comparison of average commercial natural gas system parameters and cost with model.**

	Units	Commercial System[1]	Modeled System
Annual Production[2]	units/year	1,000	1,000
Interior Volume	L	268	275
Tank Mass	kg	70.8	67.7
Tank Cost[3]	$	2,587	2,852
Manufacturers Markup[4]	%	15	15
Installer Markup[4]	%	10	10
Tank Price	$	3,272	3,607

[1] Values are the average from vendors polled
[2] Commercial production volumes are estimated
[3] Estimated from assumed markups for commercial systems
[4] Estimated for manufacturer and installer

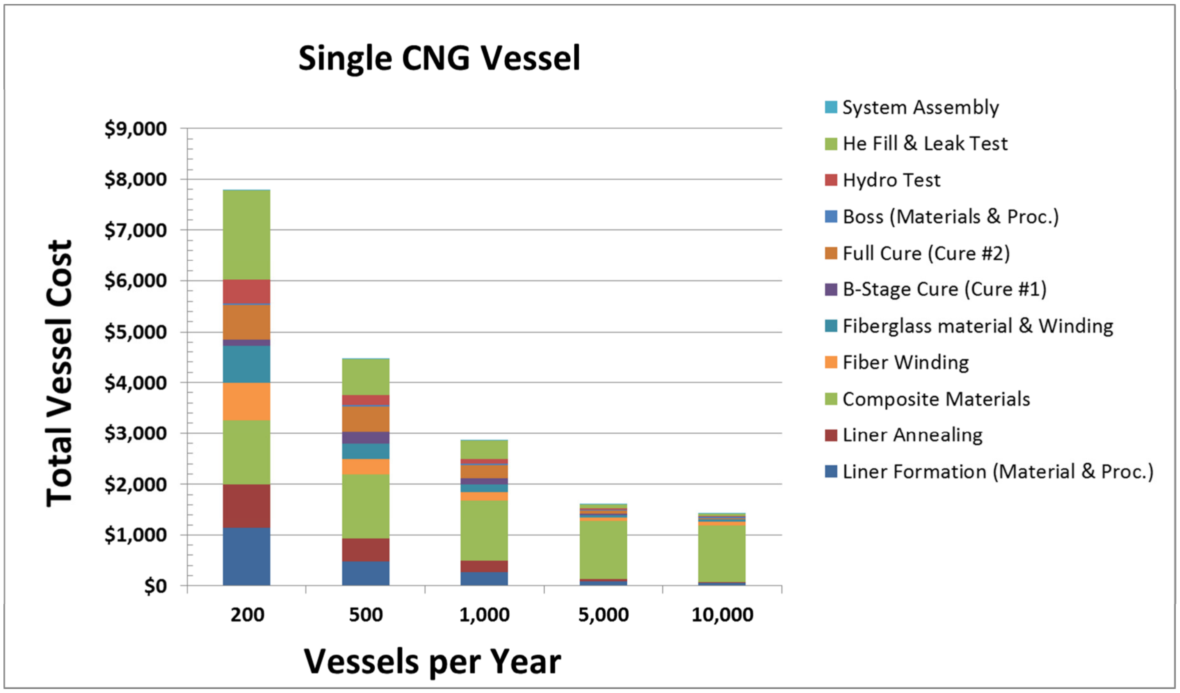

Figure 2: Cost breakdown for modeled 275 L 250 bar type IV CNG pressure vessels at multiple production volumes.

2.2.2 Type IV 350 bar H_2 Pressure Vessel Analysis

The validated CNG cost model was used to analyze the costs of 350 bar Type IV H_2 storage systems. The manufacturing process flow is the same as shown in Figure 1 with differences in system size, pressure, and production volume. Figure 3 shows a cost breakdown of 350 bar type IV H_2 storage systems. In contrast to the CNG system, H_2 storage system costs are dominated by balance of plant (BOP) and composite at all volumes. Due to the higher pressures being considered for H_2 storage (350 bar and 700 bar vs. 250 bar for CNG), significantly more carbon fiber composite is required to achieve the design pressure. For 250 bar CNG tanks, around 50 kg of composite is required for a 275 L pressure vessel, while 62 kg of composite is required for a 245 L H_2 pressure vessel at 350 bar [1]. It is also noteworthy that the production volumes analyzed for the H_2 storage begin at the upper range of the CNG production volume (10,000 systems per year).

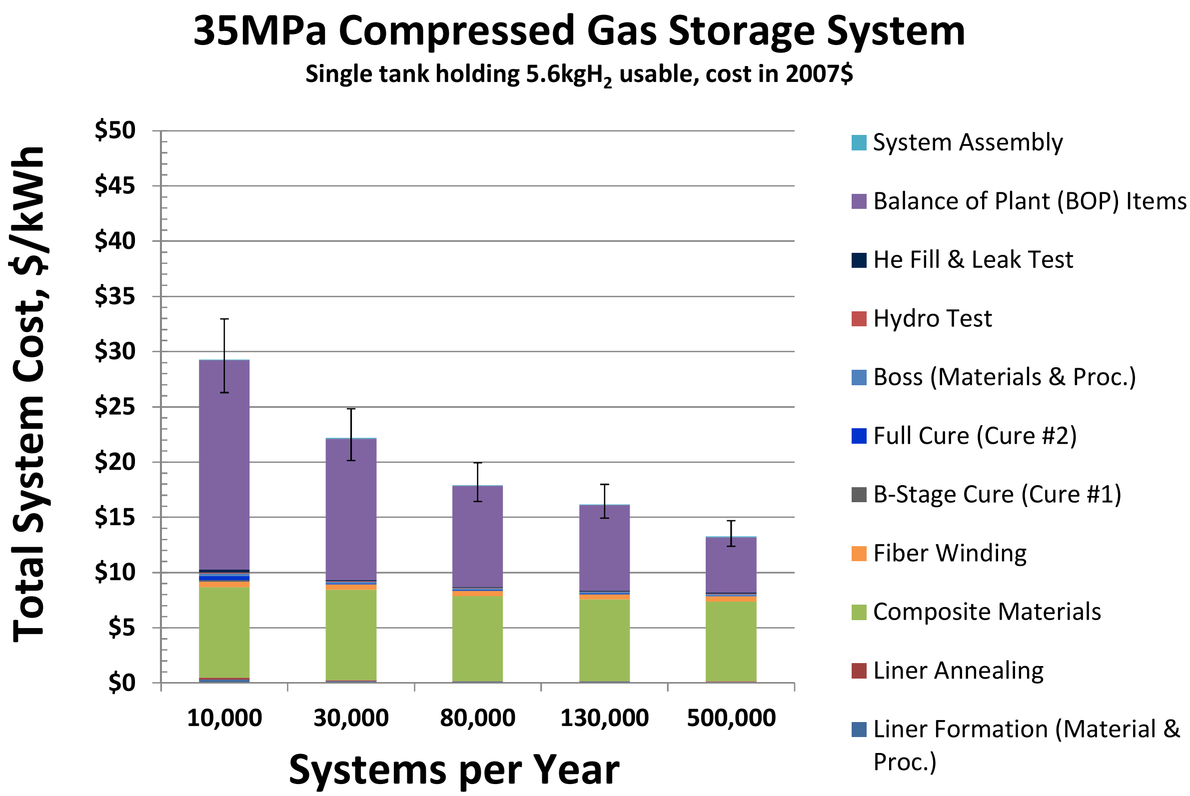

Figure 3: Cost breakdown for modeled Type IV 350 bar H_2 storage systems at multiple production volumes.

2.2.3 Type IV 700 bar H_2 Pressure Vessel Analysis

Strategic Analysis worked with the Department of Energy to prepare data records describing the status of Type IV 700 bar H_2 storage systems[1], [2]. The following sections describe the progression of modeled cost status from the 2013 model through the end of the contract. In this report, the first documentation of the provisional 2016 status is presented.

2.2.3.1 2013 and 2015 Baseline Reports

In 2013, a 700 bar type IV H_2 storage system storing 5.6 kg of usable H_2 was projected to cost $16.76/kWh ($2007) at a manufacturing rate of 500,000 systems per year[1]. SA tracked and modeled a series of improvements in tank design, which by 2015 led to a projected cost $14.75/kWh for an equivalent system. These improvements along with single-variable sensitivity cost changes included:

- Material changes
  - Replacement of the higher density epoxy resin with a lower-cost, lower-density resin identified by PNNL (-$0.59/kWh).

    - Use of a lower-cost carbon fiber made from a polyacrylonitrile with methyl acrylate co-monomer precursor based on a high volume textile fiber process developed by ORNL (-$1.73/kWh).
- Design changes
    - Further integration of the BOP components (-$1.34/kWh).
    - Removal of a design feature based on pre-fabricated carbon fiber strips (doilies). Use of doilies had previously led to lower composite mass but was removed on the advice of manufacturers (+$1.36/kWh).
    - Addition of an explicit accounting for manufacturing variations. This change led to increased composite mass to meet safety factors but is more representative of industry practice (+$0.42/kWh).

Note that the single-variable sensitivity cost changes listed above represent the difference between the 2013 system cost ($16.76/kWh) and the system where each of the individual material or design changes was made in isolation. The cumulative effect of all changes is $2.01/kWh vs. the sum of the individual changes, $1.88/kWh, for this reason.

A comparison of key system parameters between 2013 and 2015 are presented in Table 4.

Table 4: Comparison of key cost and processing assumptions used in 2013 and 2015 for bulk 700 bar Type IV compressed hydrogen storage system.

Key Cost Assumptions[a]	Units	2013 Values	2015 Values	Notes
System Production Volume	#/year	500,000	500,000	
Carbon Fiber Mass	kg	62.2	72.0	
Resin Mass	kg	28.8	25.0	
Resin Type		Epoxy	Vinyl Ester	
Fiber Volume Fraction	%	60	64.7	Due to low density resin
Carbon Fiber	$/kg	28.67	23.43	Low-cost precursor fiber
Resin for Carbon Fiber	$/kg	7.09	4.52	Low-cost resin
High Density Polyethylene (HDPE) (Liner)	$/kg	1.77	1.77	
Aluminum (Boss)	$/kg	4.75	4.10	Footnote b
Blow Molding Capital Cost	$	592,916	591,940	Footnote c
Wet Winding Capital Cost	$	343,719	343,154	Footnote c
Average Fiber Laydown Rate	m/min	26	26	
Curing Oven Capital Cost	$/ft	2,008	2,008	
B-Stage Dwell Time	hrs	2.5	2.5	
Full Cure Dwell Time	hrs	8	8	
Helium Pressure Test Rig Capital Cost	$	1,671,267	1,673,747	Footnote c

[a] All costs are reported in 2007$.

[b] The aluminum base year price was adjusted from 2007$ to 2012$.

[c] Small differences in capital equipment costs between 2013 and 2015 are due to updates to the CPI reported by the U.S. Department of Labor. For example, the Blow Molding Capital Cost in both 2013 and 2015 is based on the same quoted cost of $690,000 in 2012. The difference of 0.2% reflects updates to the price index made between the 2013 and 2015 analyses.

2.2.3.2 Provisional 2016 Baseline Cost

Since completing the 2015 status assessment, two further improvements were identified that have reduced the projected system cost: a switch to aluminum for selected BOP components, and incorporation of Toyota design and manufacturing improvements.

Based on input from suppliers and OEMs, the material for the integrated regulator body and in-tank valve body were switched from 316L stainless steel to aluminum. This resulted in a system cost reduction from $14.75/kWh to $14.57/kWh due to lower material costs for aluminum and lower machining costs due to aluminum being a softer material that takes less time to form.

Additionally, Toyota reported tank designs used within their Mirai fuel cell vehicle that enable reduced carbon fiber composite usage[3],[4]. The Toyota improvements are based on:

- an alternate liner geometry that eliminates high-angle helical winding
- an alternate winding scheme
- a smaller diameter boss with a longer flange
- replacing T-700 CF with higher modulus T-720 CF

ANL modeled the Toyota design changes within ABAQUS and applied them to the 2015 H_2 tank design. Those modeling results were then used as inputs to SA's cost model to understand the impact of the Toyota composite reductions. To separate the impact of the Toyota design changes from the impact of the higher strength T-720, an analysis of the cost tradeoffs was conducted comparing the Toyota design with the design used in the 2015 baseline with the lower cost and density vinyl ester resin used in the 2015 baseline[2]. The results of this analysis, presented in Table 5, demonstrate that the greatest cost reduction is achieved using the Toyota design with the vinyl ester resin. These results support claims by Toyota that their alternative tank design reduces the total composite mass, and extends those results to show a modest reduction in system cost of 3.2% from the 2015 design ($14.57/kWh vs. $14.07/kWh). System cost breakdowns corresponding with the Toyota design and lower density resin are shown in Figure 4 for two production volumes (500,000 and 10,000 systems per year. Finally, a complete bill of materials for the provisional 2016 system is shown in

Table 1.

Table 5: Comparison of Type IV 700 bar H_2 storage system costs at 500k systems/year for a single 147 L tank configuration with 5.6 kg usable H_2 and length to diameter ratio of 3.

Winding Pattern	Resin	CF Volume Fraction [%]	Composite Mass [kg]	Tank Cost [$/kWh]	BOP & Assembly [$/kWh]	Total Cost [$/kWh]	Cost Change [%]
2015 Baseline	Epoxy	60	106.6	12.06	3.53	15.59	0.0
Toyota	Epoxy	60	99.9	11.33	3.53	14.86	4.7
2015 Baseline	Vinyl Ester	64.7	97.0	11.04	3.53	14.57	6.5
Toyota	Vinyl Ester	64.7	92.3	10.54	3.53	14.07	9.7

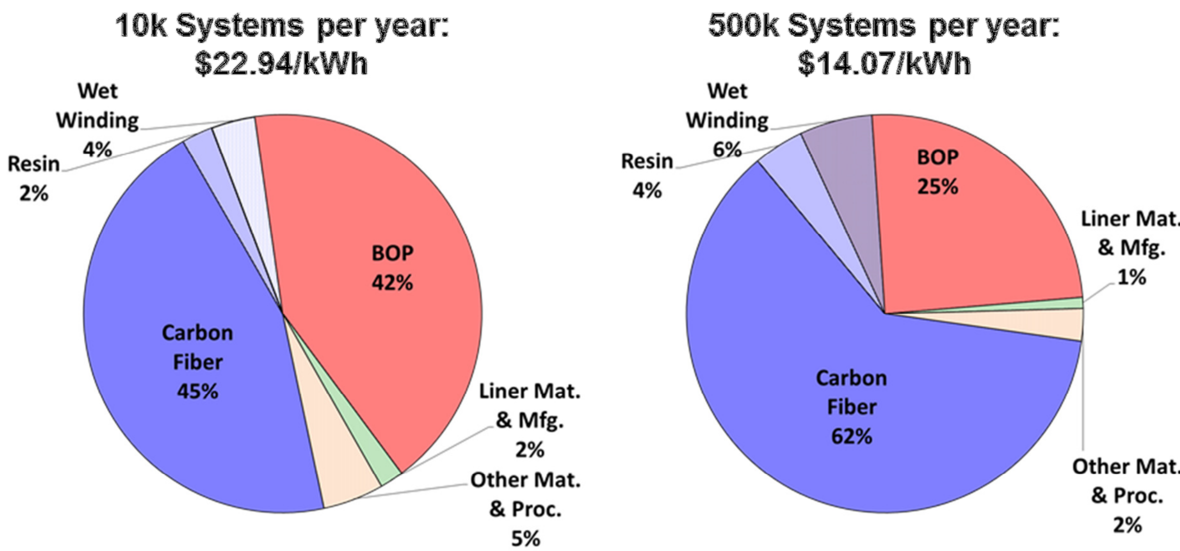

Figure 4: Cost breakdown for type IV 700 bar H_2 single tank storage systems with 5.6 kg usable H_2 and aspect ratio of 3.

Table 6: Bill of materials for the Provisional 2016 type IV 700 bar system cost status.

		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	$8.59	$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	$9.90
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	$0.08	$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

2.2.4 Compressed H_2 Component and Process Analyses

Analyses were conducted to validate our cost models for balance of plant components, and to investigate materials cost (pre-preg, carbon and glass fiber, and dicyclopentadiene resin) and processes (winding speed tradeoffs and vacuum infusion resin transfer) for compressed storage systems. While the balance of plant components were ultimately incorporated into the baseline storage system cost models, the other analyses were primarily used to understand avenues of cost reduction.

2.2.4.1 Balance of Plant

As shown in Figure 4, balance of plant components account for almost 50% of the system cost at low volume (10,000 systems/year) and around 25% at high volume (500,000 systems/year). To better understand and enumerate these costs, the low and high pressure (LP and HP, respectively) fittings were investigated as well as strategies to integrate functionality into the valve and regulator.

2.2.4.1.1 Low and High Pressure Fittings

Two main types of fittings, metal-on-metal cone/thread sealing fittings (eg. Swagelok or EV Metal fittings), and O-ring face seal fittings (eg. Parker Hannifin Seal-Lok™ fittings) were considered. Based on quotes received for high pressure fittings manufacturers, two issues became apparent. First, the range of quoted fitting costs was unacceptably high. More importantly, suppliers were unable to provide quotes for quantities greater than 50,000 parts, while demand is expected to be approximately 3 million fittings per year to supply 500,000 H_2 storage systems per year. Furthermore, some distributers provided quotes that were constant at all purchase quantities and thus did not reflect the expected economies of scale for very large purchase quantities. This was attributed to suppliers being unable or unwilling to project the sales price at purchase quantities that are well outside their typical volume.

To gain insight into the costs of fittings and to understand how economies of scale would affect the cost of fittings at high volume, a DFMA® cost analysis was conducted on two representative hydrogen fittings based on Parker Hannifin Seal-Lok™ type fittings:

1. 4 F57OLO-SS H2U 990549 high pressure (HP) fittings, rated up to 12kpsi
2. 4-6 F57OLO-SS H2U for low pressure (LP) fittings, rated up to 400psi

The LP fittings are physically larger[1] than the HP fittings but have simpler sealing designs with lower tolerances. The total fitting cost for both HP and LP fittings at 500k sys/yr was projected to be approximately $12 per fitting with the greater material of the LP fittings offsetting the complex sealing of the HP fitting. In both cases, the fitting body and individual testing costs were the cost drivers. A comparison between vendor quotes and modeled low pressure fitting prices is shown in Figure 5. These results show that the general shape of the price curve follows 'Quote 2' and puts the lack of volume discount provided in 'Quote 1' into context of the price curve for 'Quote 2'.

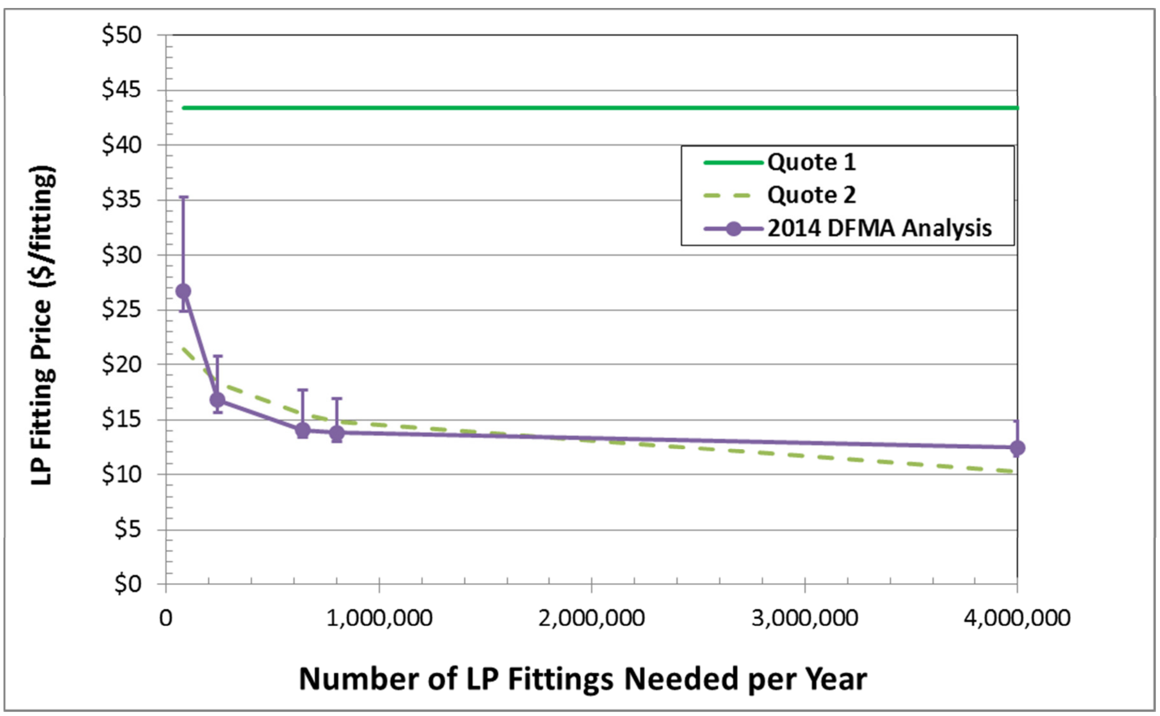

Figure 5: Comparison of LP fitting quoted prices with estimated cost.

[1] The LP fittings are sized for 20 gauge 0.5 inch tubing whereas the HP fittings are sized for 16 gauge 0.25 inch tubing. The size increase at LP is to manage the expected pressure drop from high velocity flow at low pressure.

2.2.4.1.2 In-Tank Solenoid Valve

In consultation with the U.S. DRIVE Hydrogen Storage Tech Team, SA developed a conceptual design of an in-tank pressure gas solenoid valve to reduce the total number of fittings and connections between balance of plant components on the high pressure side. Additional functionality was added to an integrated valve body, including a temperature activated pressure relief device (TPRD), excess flow valve, particle filter, port provision, a valve for manual override (to allow manual tank depressurization), and a temperature sensor. A schematic of the conceptual integrated valve is shown in Figure 6. The design and sizing used for the H_2 integrated valve DFMA® are loosely based on Quantum Technology's in-tank valve.

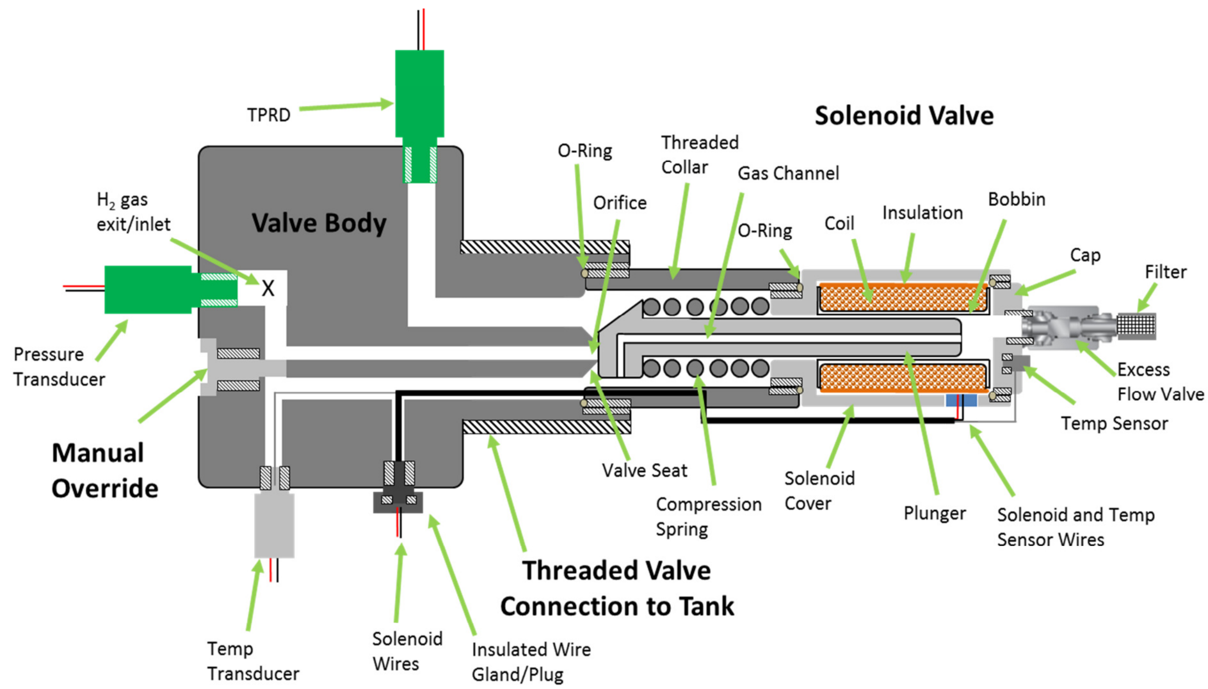

Figure 6: Conceptual design of integrated in-tank valve for 700 bar H_2 pressure vessels.

The integrated valve cost model was validated against both H_2 valves and CNG valves. The H_2 valve validation consisted of comparing modeled costs with an auto manufacturer's proprietary cost estimates at 10 k and 100 k per year. While the cost match was judged reasonable, the proprietary nature of the pricing data and lack of high-volume actual production prevented an in-depth validation. In contrast, CNG integrated valves have a similar design, are currently produced in relatively high quantities, and therefore provide an excellent opportunity to calibrate the cost estimation procedure. Consequently, the integrated valve model was adapted to represent a CNG valve and a full DFMA® analysis was completed to understand and compare to quotations of existing units at low production rates (10,000 systems per year). The CNG integrated valve design concept used by SA as the basis for the DFMA® cost analysis is based on an internal flow concept detailed in a GFI patent[5] and uses valve dimensions similar to the

OMB Saleri Lyra CV valve (one of the most widely used integrated valves and used on Quantum Technologies, 3M, and Hexagon Lincoln CNG tanks). Price quotations were provided by OMB and Tomasetto and are shown along with the results of the DFMA® cost analysis in Figure 7. The production volume corresponding to the Tomasetto price quotes is unknown but is estimated to be between 1,000 and 4,000 units/year. Markup was added to the DFMA® cost results (10-20% depending on production volume) to allow direct comparison to the price quotations. At 17k units/year, the DFMA® cost of a CNG integrated valve with markup aligns well with price projections for the currently produced Lyra CV CNG integrated valve ($130/valve).

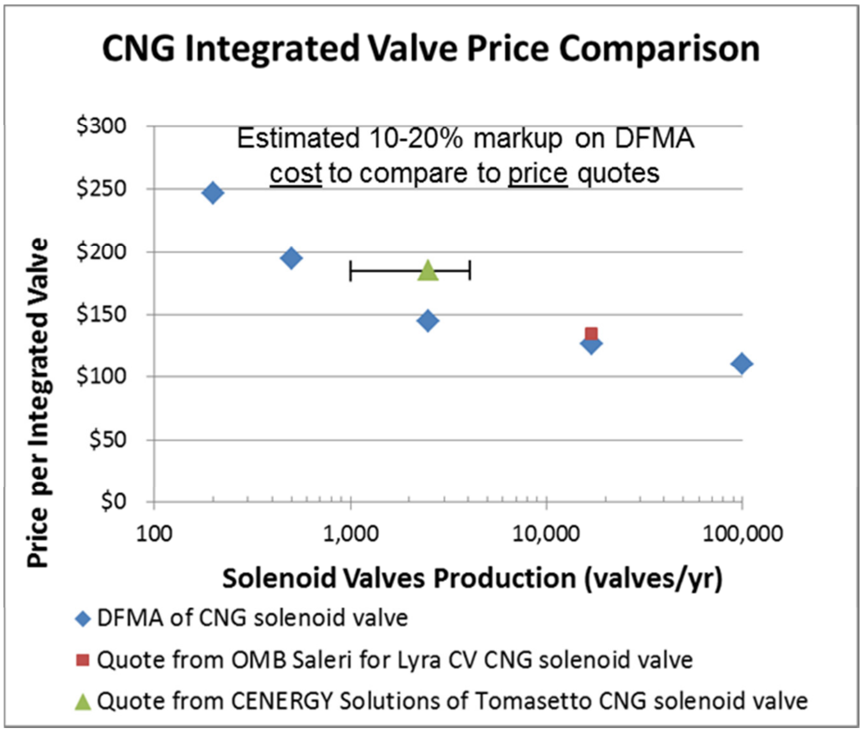

Figure 7: Graph showing price quotations compared to DFMA analysis of CNG integrated tank valves.

While the functionality of H_2 and CNG valves is similar, there are multiple component differences which were modified in the model in order to validate the H_2 valve using quotes for CNG valves. General differences between H_2 and CNG valves as projected for automotive application include:

- Operating pressure for CNG valves is typically 3,600psi while the pressure for H_2 valves is 10kpsi.
- The solenoid valve is internal to the H_2 tank and external to CNG tank.
- The temperature transducer and filter are included on the H_2 valve, but are not included on the CNG valve.

- At the time of the validation, H_2 valves were typically made of stainless steel while CNG valves were often composed of aluminum or brass.
- The typical neck opening is 2 inches in diameter on a CNG tank and 1.5 inches on a (higher pressure) H_2 tank.

As shown in **Error! Reference source not found.**, cost agreement between vendor quotes and the DFMA cost analysis for integrated tanks was in good agreement.

2.2.4.1.3 Integrated Pressure Regulator Block

A conceptualized integrated regulator block was also analyzed as a means of reducing BOP costs by reducing the total number of fittings and integrating low pressure components. A cross section of the integrated block is shown in Figure 8. The integrated pressure regulator block is forged from stainless steel[2], then machined with tight tolerances to allow proper fitting connections to the pressure regulator, pressure relief device, automatic shutoff valve, defuel receptacle, manual defuel valve, and the pressure transducer. By combining the components into one unit, the integrated pressure regulator reduced the projected cost by $77/system or $0.41/kWh at 500,000 systems per year.

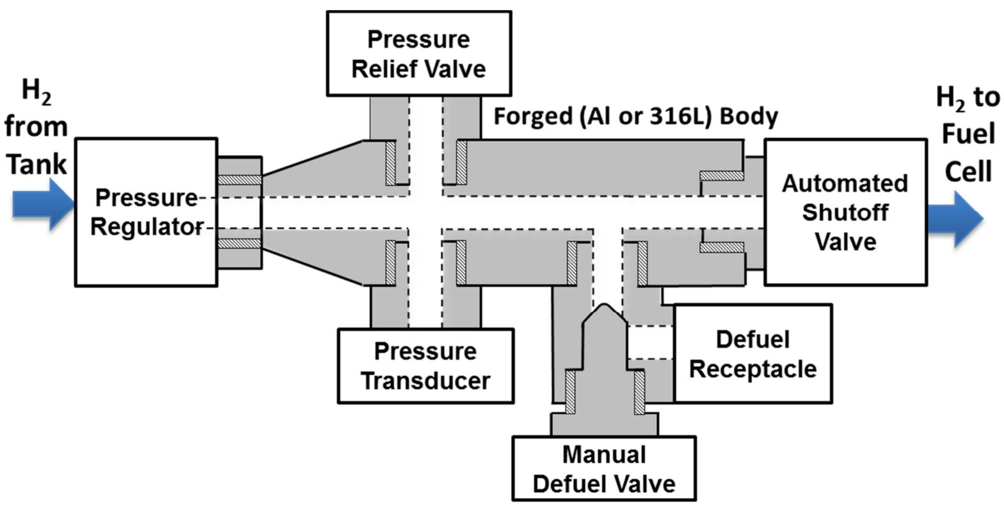

Figure 8: Conceptual integrated regulator schematic combining six low-pressure components.

2.2.4.1.4 Balance of Plant Summary

A summary bill of materials for Type IV 700 bar H_2 storage systems single and two tank configurations is shown in Table 7.

[2] In the initial analysis which is described in this section, the pressure regulator block was formed from stainless steel; however, the block was re-analyzed in 2016 using aluminum as described in 2.2.3.2 Provisional 2016 Baseline Cost.

Table 7: Bill of materials for type IV 700 bar H_2 storage systems balance of plant at multiple production volumes and for single and two tank configurations.

		Config. 1: One 5.6kgH2 Tank (outside L/D=3)					Config. 3: Two 2.8kgH2 Tank (outside L/D=3)				
Type-IV Tank		Annual Manufacturing Rate					Annual Manufacturing Rate				
		10,000	30,000	80,000	100,000	500,000	10,000	30,000	80,000	100,000	500,000
BOP											
Integrated In-Tank Valve	**Per Tank**	**$310**	**$237**	**$198**	**$190**	**$148**	**$619**	**$474**	**$396**	**$381**	**$295**
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
Integrated Pressure Regulator	Per System	**$862**	**$604**	**$488**	**$455**	**$317**	**$862**	**$604**	**$488**	**$455**	**$317**
Integrated Pressure Regulator Block	Per System	$33	$10	$12	$11	$8	$33	$10	$12	$11	$8
Check Valve (1)	Per System	$44	$29	$21	$19	$11	$44	$29	$21	$19	$11
Fuel Tank Controller (1)	Per System	$138	$117	$101	$97	$76	$138	$117	$101	$97	$76
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
High Pressure Transducer (1)	Per System	$94	$60	$41	$37	$20	$94	$60	$41	$37	$20
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	**$633**	**$424**	**$312**	**$290**	**$186**	**$854**	**$571**	**$417**	**$387**	**$245**
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

2.2.4.2 Pre-Preg and Winding Speed Tradeoff Analysis

Compressed pressure vessel costs are modeled in the baseline system as using a wet winding methodology, a process for fully wetting the carbon fiber with resin just prior to tank winding. Wet winding is, by far, the most common industry winding technique and traditionally leads to the lowest cost. However, pre-impregnated (pre-preg) composite is used by some tank manufacturers due to pre-preg being cleaner (no resin dripping), having less resin wastage, tighter fiber-to-resin ratio control, and ability to wind tanks faster. The cost difference between wet winding and pre-preg results from the above differences plus imposition of an additional markup to the pre-preg supplier (i.e. profit/business expenses for the pre-preg supplier who coats the carbon fiber and partially cures the resin). A trade-off between pre-preg markup, lower resin wastage, and faster winding speed was studied.

The cost of winding is relatively small. Figure 9 shows the manufacturing cost of winding a single 5.6 L 700 bar pressure vessel at several winding speeds. Cost of manufacturing is shown on the left axis while the contribution of manufacturing cost to the total system cost is shown on the right axis. In the baseline analysis, 26 m/min is used as an average winding speed for wet wound tanks with a cost of ~$0.80/kWh. Average winding speeds of 40 m/min to 90 m/min have been reported privately to SA. At the upper end of winding speed, system cost can be reduced by around $0.60/kWh or about 4% of system cost.

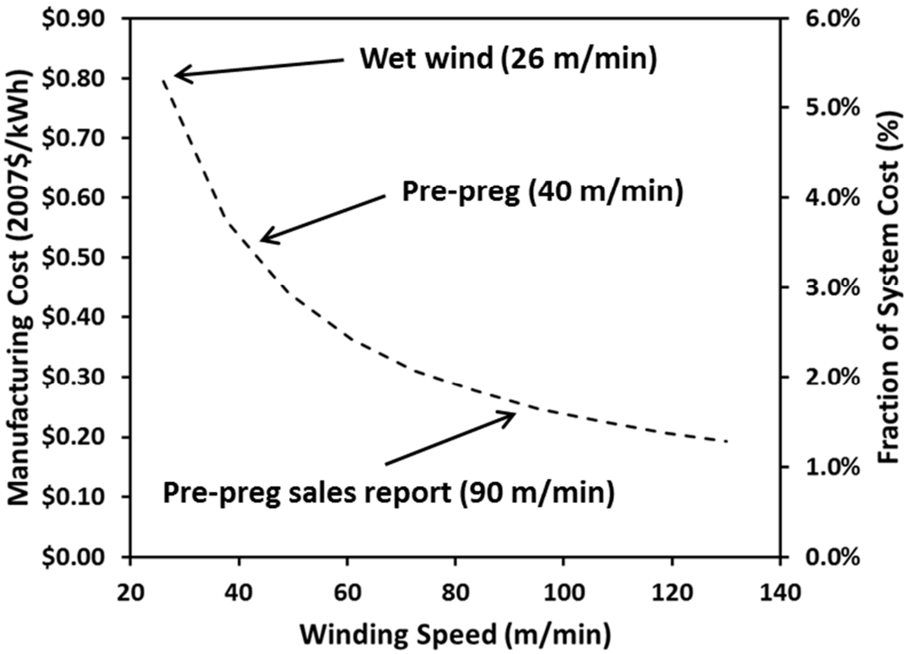

Figure 9: Impact of winding speed on cost

To better understand the cost tradeoffs between faster winding speed and higher price for pre-preg, a parametric analysis was conducted. (A parametric analysis is necessary as neither the pre-preg winding speed nor the markup is known with certainty: each is only characterized by a probable range in values.) Compared to wet-winding, and in addition to faster winding speeds, pre-preg is expected to achieve lower resin wastage and may achieve a lower manufacturing coefficient of variation ($COV_{manufacturing}$) due to more uniform wetting of the carbon fiber. Lower $COV_{manufacturing}$ leads to lighter tanks and lower cost[1].

To understand these tradeoffs, we analyzed the cost of materials and manufacturing for pre-preg and compared them at multiple markup rates against the cost of wet winding. The cost of materials and manufacturing for pre-preg at multiple markups is shown in Figure 10. The red line marks the cost of wet winding materials and manufacturing (at 26 m/min). Where the gray dashed lines cross the red line is where the cost of pre-preg is expected to be at cost parity with wet winding for a given markup. Markup values ranging from 8%-20% have been reported to SA privately. At a representative 8% markup, the average winding speed would need to be around 50 m/min to reach cost parity with wet winding. Higher speed or lower markup would result in a net cost savings. It is noted that even if use of pre-preg results in cost parity, it may still be desirable due to its other advantageous attributes (tighter $COV_{manufacturing}$, less mess, less smell, lower capital investment due to a faster winding speed).

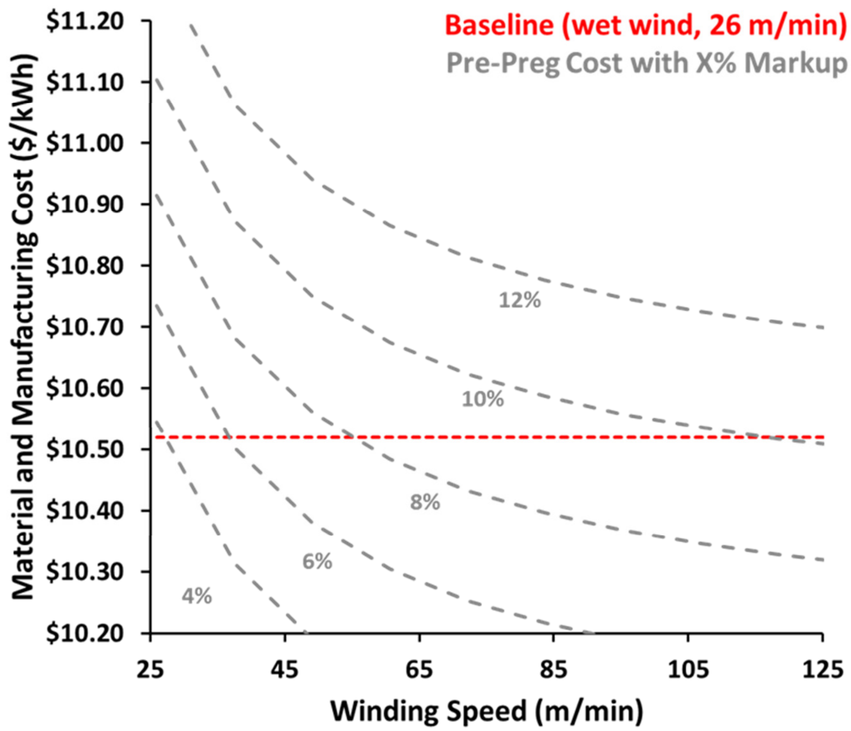

Figure 10: Comparison of material and manufacturing costs as a function of winding speed for pre-preg at multiple markups. Gray dashed lines are cost curves for pre-preg at the indicated markup (e.g. the upper curve has a 12% markup applied; the next curve has a 10% markup, etc.). The red dashed line marks the cost for wet winding at 26 m/min. The analysis is based on a 1.6% $COV_{manufacturing}$ for pre-preg and 3.3% $COV_{manufacturing}$ for wet winding.

2.2.4.3 Carbon Fiber Cost Analysis

Carbon fiber represents the single highest cost component of composite overwrapped pressure vessels (COPV). For example, Figure 4 shows that carbon fiber is 62% of the total system cost at 500,000 systems per year annual production. To better understand the cost drivers for carbon fiber manufacture and to independently examine processing assumptions in existing analyses[6], [7], SA spoke with members of the carbon fiber supply chain (manufacturers and processing equipment suppliers). A preliminary cost model was created, updating processing assumptions from Das et al[7] and Kline and Company[6]. A process flow diagram summarizing key cost model assumptions and results in shown in Figure 11. Using SA's standard modeling approach and inputs (see

Table 1), the cost of carbon fiber produced at 25,000 MT per year is estimated at $27.22/kg. This cost is slightly lower that ORNL's projection of $30.25/kg (due to SA's use of updated capital equipment and energy requirements) but is slightly higher than Kline's projection of $26.51/kg.

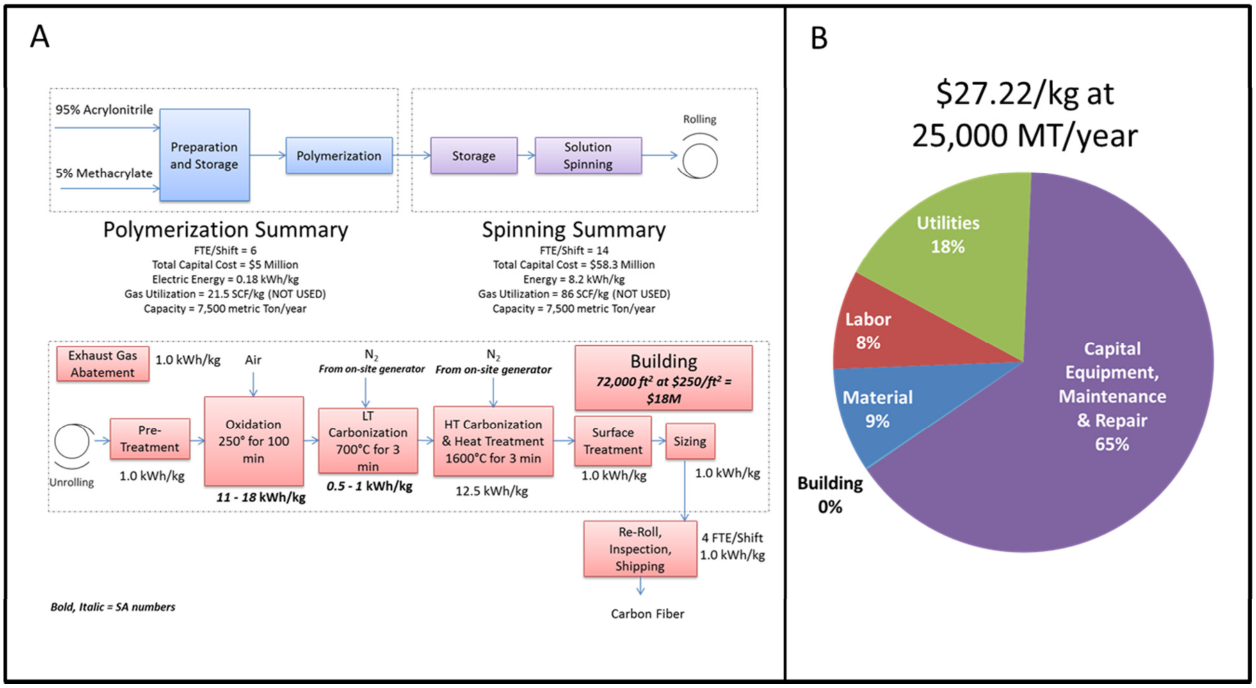

Figure 11: A. Process flow diagram and B. cost breakdown for carbon fiber manufacture.

2.2.4.4 Preliminary High Strength Glass Fiber Cost Analysis

Glass fiber is being considered as a lower cost alternative structural material to carbon fiber for COPVs[8]. While typical E-glass has tensile strength and modulus around half that of comparable T-700 carbon fiber, efforts are under way to develop new formulations with improved mechanical properties that could replace carbon fiber. A preliminary cost analysis of structural E-glass fibers was performed based on process parameter, electricity and natural gas consumptions, and capital equipment cost reported in Ross et al[9] and Masanet et al[10] to gain an understanding of the cost to manufacture glass fiber. A process flow diagram of the modeled processing steps is shown in Figure 12.

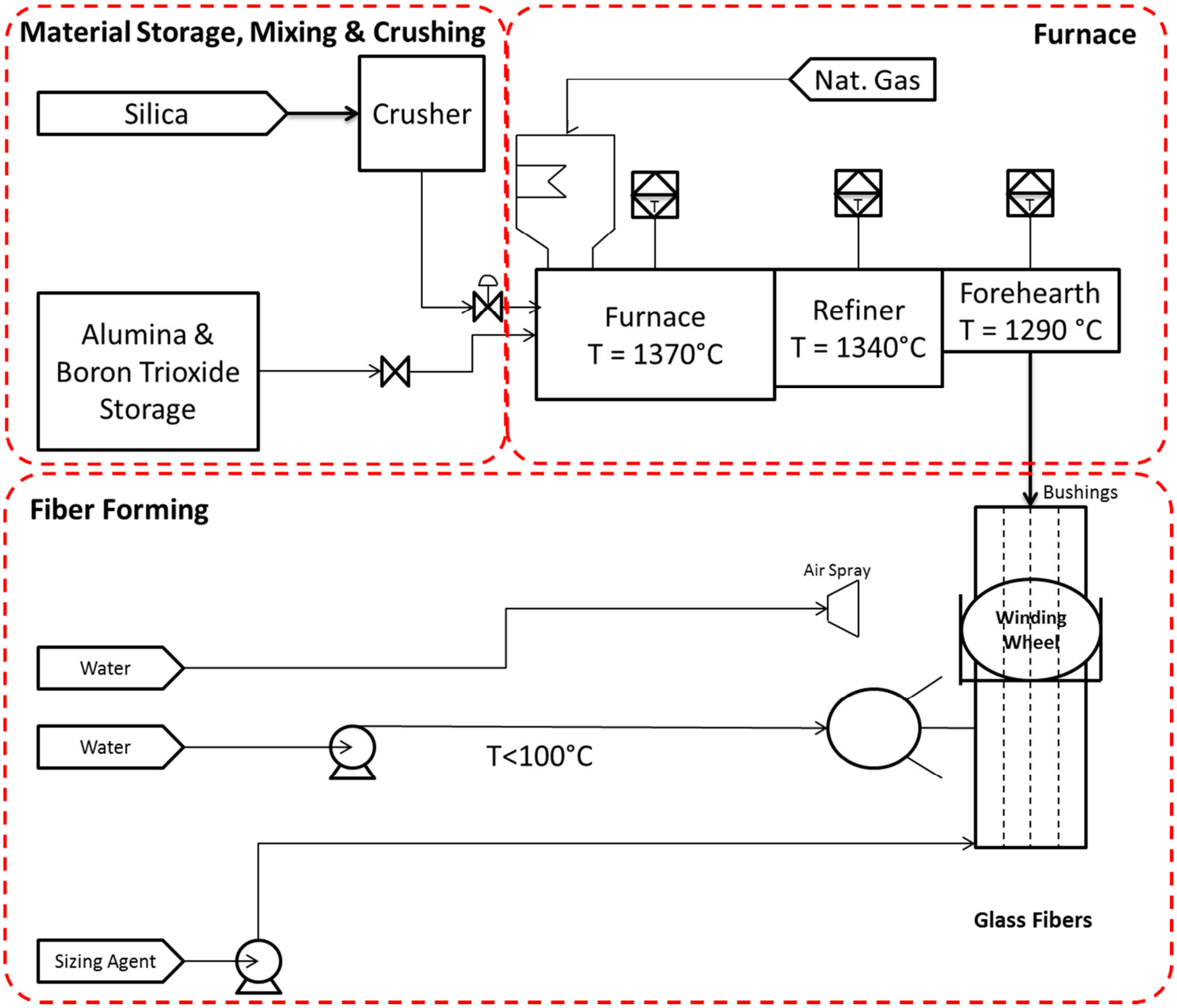

Figure 12 - PFD for E-glass fiber manufacturing

The techno-economic analysis compared the cost of manufacturing at rates ranging from 1,000 metric tons (MT) per year to 50,000 MT per year. A cost breakdown for the glass fiber and a material cost breakdown are shown in Figure 13. Material costs account for 65% of the total cost with alumina accounting for about half the materials cost. The furnace operation is the largest processing expense due largely to the energy and capital equipment costs.

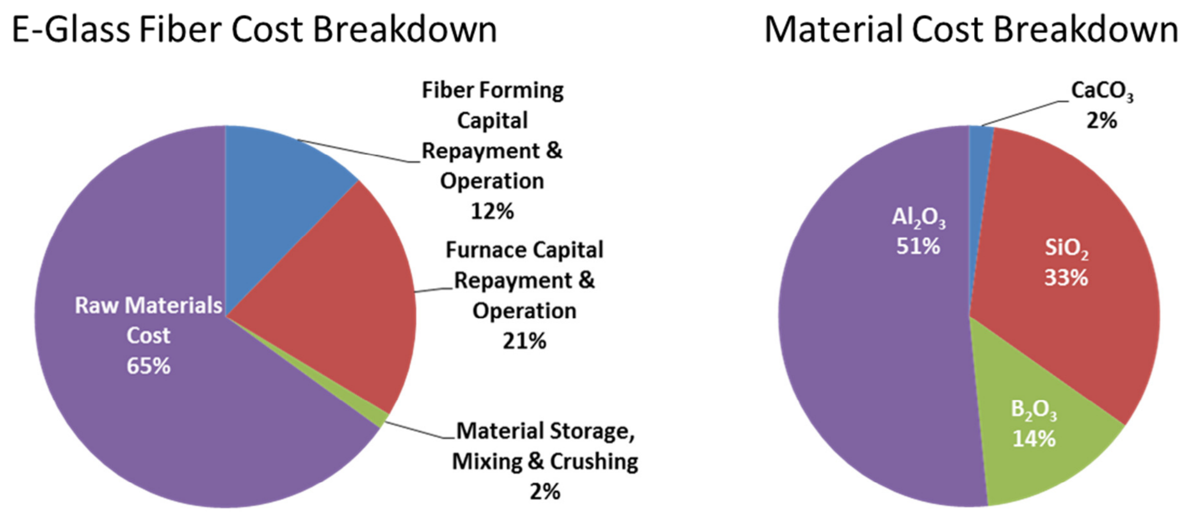

Figure 13: Cost breakdown for E-glass fiber manufacture at 50,000 MT per year production volume.

These preliminary model results represent generalized glass fiber manufacture for a commodity material. Specific formulations and processing conditions for structural fibers are proprietary and may result in higher manufacturing costs, and high strength glass fiber for COPVs will likely be produced at lower volumes than are assumed in this preliminary model. While E-glass is expected to cost less per kg than carbon fiber, the combination of lower modulus/tensile strength and higher statutory safety factors (3.5 for glass fiber COPV vs. 2.25 for carbon fiber COPV) will result in heavier tanks and may offset cost savings that result from lower cost materials. Further testing and validation of glass fiber will need to be completed and codes and standards will need to be modified before glass fiber can be considered a viable alternative to carbon fiber.

2.2.4.5 Parametric Vacuum Resin Infusion Cost Analysis

Vacuum infusion of the resin may improve the strength of the carbon fiber composite by reducing void space within the composite matrix. This is the approach Materia Inc. is taking under a DOE supported program to reduce tank cost by reducing the total amount of composite[11]. A manufacturing process flow shown in Figure 14 was developed based on the processes described in [11] and discussions with Brian Edgecombe of Materia Inc. Vacuum infiltration/infusion replaces the wet winding step shown in Figure 1 with a dry fiber winding step followed by vacuum infiltration to impregnate the fiber with resin.

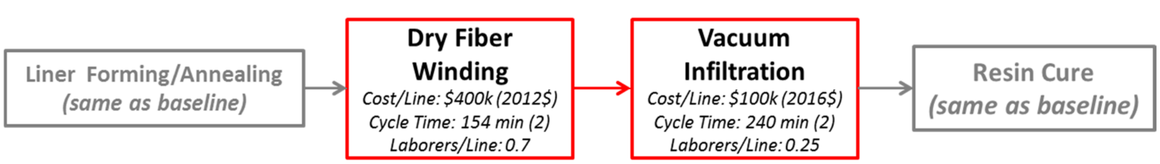

Figure 14: Manufacturing process flow for vacuum infusion.

Preliminary assumptions for the process include:

- Winding Assumptions
    - Capital cost, power, labor modeled using wet winding assumptions.
    - Winding speed was assumed to be 40 m/min analogous to current estimate of pre-preg winding speed.
- Infiltration Assumptions
    - Capital cost is assumed to be $100k (2016$).
    - Reusable clamshell infiltration station assumed for high volume production.
    - Infiltration time assumed to be 4 hours based on Materia experience.
    - One laborer operating 4 infiltration stations.
    - 2 tanks per station.
    - Resin cost assumed to be $13.5/kg in 2016$ (with Materia indicating a potential range of $9-$18/kg).
- Curing the resin is assumed to be identical to current vinyl ester curing conditions.

At the time of this report, Materia did not have full tank burst test results to share with SA to support the project objective of reducing the composite mass by 30%. Consequently, a sensitivity study was conducted around key parameters such as composite reduction and resin price to understand the cost impact of the Materia process and materials. Figure 15 presents a summary Tornado chart of these results. If there is no composite mass reduction for the Materia process, the cost of the composite material, winding, and resin application at 500k systems/year would be $12.03/kWh compared to $10.52/kWh for the baseline system. The higher cost is due largely to the higher resin cost: $13.5/kg for dicyclopentadiene with Grubb's catalyst compared to $4.52/kg for vinyl ester. (Approximately the same resin mass is needed for both.) The additional processing cost associated with the vacuum infiltration process itself also contributes an additional $0.51/kWh. In order to offset these additional costs and reach cost parity with wet winding, a 14% composite mass reduction would need to be realized. If Materia meets the 30% composite mass reduction project objective, these results project a system cost savings of $1.79/kWh.

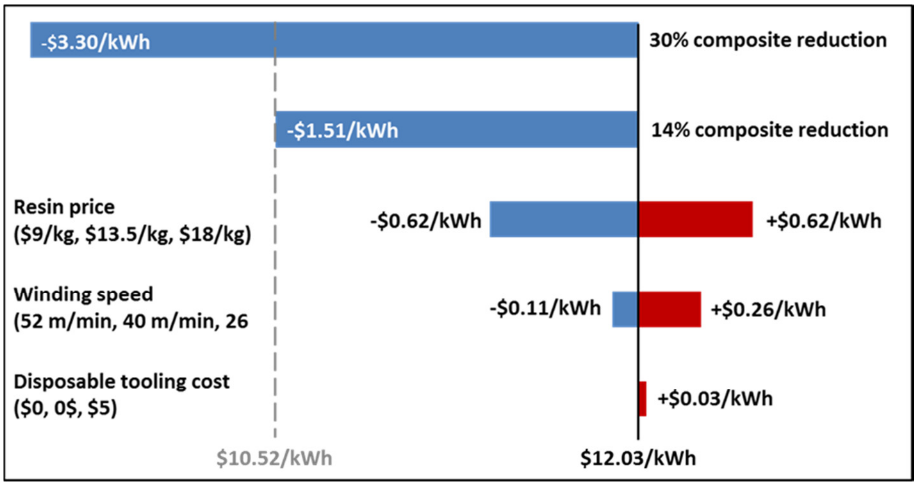

Figure 15: Single variable sensitivity analysis of the Materia vacuum infiltration process for a single 147 L tank with 5.6 kg usable H_2 produced at 500,000 systems per year.

2.3 Materials-Based Storage Cost Analysis

2.3.1 Sorbent System Cost Analysis

Two gas containment strategies for storing hydrogen on metal-organic framework (MOF) sorbents were developed by the Hydrogen Storage Engineering Center of Excellence (HSECoE). The two designs, HexCel and modular adsorption tank insert (MATI), represent different approaches to thermal management during fueling and de-fueling. A DFMA® cost analysis was conducted for both the Hexcel and MATI systems, with both sized to storage 5.6kg of usable H_2.

2.3.1.1 HexCell System

The HexCell system is based on work performed at Savannah River National Lab (SRNL) with minor changes to SRNL's design to lower costs and simplify operation of the system for large scale commercial usage, and to include additional safety features assumed to be required on this type of system. The changes made to the SRNL design include:

- Type 1 welded aluminum tank.
- Separated liquid nitrogen (LN_2) ports from H_2 isolation valve (to reduce the complexity of the valve for high volume manufacturing).
- Eliminated H_2 check valve after isolation valve (isolation valve includes a solenoid valve that essentially serves the same functionality as the check valve).
- Added a fuel tank controller.
- Added Manual Defuel Valve and Receptacle.
- Added Automated Shut-off Valve (Fail Close).
- Added thermal pressure relief device (T-PRD) after the second pressure regulator.

The system stores 5.6 kg usable H_2 in an insulated 165L dual wall, welded internal aluminum storage vessel (35cm diam. x 165cm length). The storage vessel contains a honeycomb HexCell heat transfer element packed with 32 kg of metal organic framework (MOF) adsorbent. The containment vessel (170cm by 44cm) is cooled by liquid nitrogen (LN_2) during the adsorption stage and is electrically heated to release H_2 via a heating element inserted down the axial length of the vessel. The total vessel mass without H_2 is estimated to be 96 kg.

The isolation valve on the containment vessel includes multiple ports for fueling and defueling in addition to temperature and pressure transducers and a T-PRD. When hydrogen is required by the fuel cell, a downstream pressure regulator controls the amount sent to the fuel cell. The first pressure regulator ensures that lower pressure H_2 (~10 bar) enters the heat exchanger (to heat up the H_2 before entering the fuel cell). The second pressure regulator is for stepping down the H_2 pressure (to ~5 bar) after the heat exchanger, before entering the fuel cell. The assumption of 5 bar H_2 will need to be re-evaluated in future analyses since this pressure is below the H_2 ejector inlet requirement for the fuel cell system. A few safety components are needed in case of over-pressurization or if manual defueling is required.

During the re-fueling process, hydrogen enters the onboard system through the refueling receptacle, check valve, and filter to remove impurities prior to being stored in the containment vessel. Upon refueling, the temperature within the containment vessel is lowered to adsorb the hydrogen molecules within the MOF powder. The internal tank contains the MOF and HexCell heat exchanger. LN_2 is flowed between the inner and outer tanks to remove the heat of adsorption released upon hydrogen uptake of the MOF powder. The LN_2 is assumed to be supplied by an off-board system and is required only during refueling. Cost of the LN_2 system is not included in the present system cost projections. When the MOF is fully charged with hydrogen, the containment vessel is at a pressure of 100 bar and a temperature of 77K.

During vehicle operation, hydrogen is removed from the MOF tanks by opening the gas port and allowing the high pressure hydrogen to flow to the lower pressure downstream portion of the vehicle fuel system. To maintain tank pressure, a resistive heater is used to heat the MOF bed inside the Hexcell. The control scheme is based on temperature and pressure readings within the tank and allows prediction of the amount of fuel remaining within the tank. A schematic of the system is shown in Figure 16 and a bill of materials is presented in Table 8.

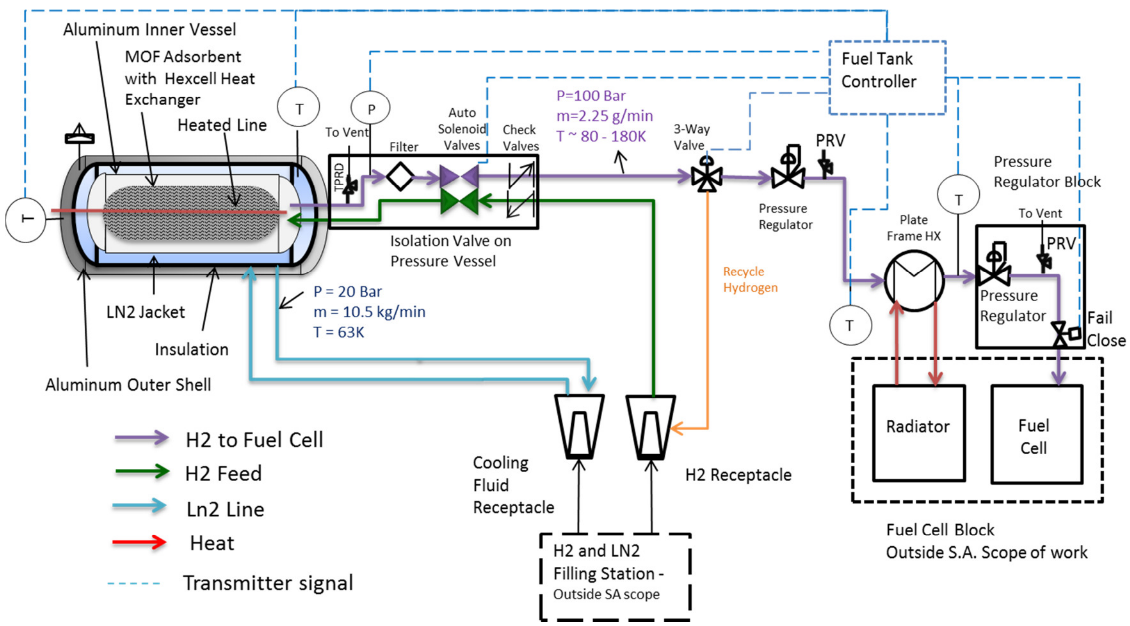

Figure 16: HexCell system schematic.

System operation during normal vehicle usage follows the following logic:

- The pressure within the tank will decrease as the temperature is held constant and hydrogen is withdrawn from the tank: just enough electrical power is sent to the heater inside the heat exchanger to maintain temperature as pressure decreases.
- Once the vessel pressure reaches a minimum threshold (approximately 25 bar), the resistive heater increases the temperature inside the vessel to flow additional hydrogen while maintaining vessel pressure.
- This tank heating continues until the internal tank temperature reaches a maximum threshold (approximately 160 to 180K), at which point temperature is maintained but pressure begins to drop. Pressure declines until pressure reaches the minimum delivery pressure (approximately 5 bar) and maximum temperature (approximately 180K). At that point, system is no longer able to supply hydrogen at the appropriate rate and temperature, and the tank may be considered “empty”.

Table 8: HexCell Bill of Materials.

			Total Cost (2014 $/system)				
	Name	Quantity	*10,000*	*30,000*	*80,000*	*100,000*	*500,000*
	H2 Fill receptacle	1	*$231.69*	*$146.85*	*$97.74*	*$89.10*	*$45.68*
	Cooling Fill Receptacle	1	*$231.69*	*$146.85*	*$97.74*	*$89.10*	*$45.68*
	Filter	1	*$27.39*	*$17.36*	*$11.55*	*$10.53*	*$5.40*
	T-PRD	3	*$363.32*	*$230.29*	*$153.28*	*$139.72*	*$71.64*
	Temperature Transducer	1	*$15.06*	*$58.11*	*$38.68*	*$35.26*	*$18.08*
	Pressure Transducer	1	*$110.58*	*$70.09*	*$46.65*	*$42.52*	*$21.80*
Containment Vessel							
Type	**Welded Inner Vessel**		$3,007.46	$2,441.97	$2,236.19	$2,206.66	$2,133.70
	Outer Vessel	1	*$720.48*	*$455.25*	*$372.36*	*$362.41*	*$352.29*
	Inner Vessel	1	*$853.62*	*$705.27*	*$657.78*	*$652.09*	*$646.29*
	HexCel	1	*$50.40*	*$43.18*	*$40.92*	*$40.65*	*$41.09*
	MOF Bed Material	1	$972.13	$873.11	$816.43	$804.95	$753.36
	CryoInsulation (10 mm)	1	*$112.25*	*$110.35*	*$108.66*	*$108.27*	*$105.49*
	Internal Supports for inner vessel	8	*$2.45*	*$2.45*	*$2.45*	*$2.45*	*$2.45*
	Internal Heating Element	1	*$44.37*	*$43.62*	*$42.95*	*$42.80*	*$41.70*
	Tank Assembly	----	*$66.74*	*$66.12*	*$65.57*	*$65.61*	*$65.54*
	10% Containment Vessel Cost Contingency	----	*$185.03*	*$142.62*	*$129.07*	*$127.43*	*$125.49*
	Auto Solenoid Isolation Valve	1	*$172.80*	*$139.34*	*$116.81*	*$116.99*	*$99.16*
	Pressure regulator	2	*$1,263.74*	*$801.00*	*$533.14*	*$485.98*	*$249.18*
	3-way valve/switch	2	*$98.79*	*$81.04*	*$69.35*	*$71.92*	*$64.42*
	Check Valve	1	*$47.39*	*$30.04*	*$19.99*	*$18.22*	*$9.34*
	Radiator Heat Exchanger	1	$190.33	$92.45	$89.56	$72.71	$68.10
	Automated Shut off Valve	1	*$126.37*	*$80.10*	*$53.31*	*$48.60*	*$24.92*
	Manual Defuel Equipment (manual valve and receptacle)	1	*$105.31*	*$66.75*	*$44.43*	*$40.50*	*$20.77*
	Fuel Tank Controller	1	*$166.40*	*$140.81*	*$121.31*	*$117.26*	*$91.81*
	Couplings		$114.66	$79.01	$70.90	$69.15	$63.77
	H2 and LN2 Lines (external to containment vessel)	1	$25.92	$23.74	$21.80	$21.36	$18.17
	TOTALS =		$6,298.89	$4,645.80	$3,822.44	$3,675.59	$3,051.65

2.3.1.2 MATI System

The MATI system includes many of the same components as the HexCell system; however, the form of the MOF absorbent and the internal heat transfer manifold are different. Within the MATI system, the MOF absorbent is in the form of "pucks" created by compressing MOF powder in a stamping press to 5cm thick by 40 cm diameter with a density of 6.5 gMOF/cm^3.Cooling discs are placed on either side of the pucks for heat transfer. The cooling discs are two-part assemblies. The bottom plate is stamped from stainless steel sheet and is then electrochemically etched to create a serpentine flow field on one surface. The top part is a flat stainless steel plate (the lid) that is welded to the bottom plate to form a heat transfer plate with enclosed cooling channel. The LN_2 coolant and H_2 fuel share gas lines in the storage vessel. This design carries some risk that residual nitrogen will accumulate in the fuel cell stack resulting in reduced performance. Consequently a possible refueling scenario to mitigate this risk of dilution was devised. During vehicle refueling, LN_2 flows through the MATI discs to remove heat generated by hydrogen adsorption. After LN_2 stops flowing, nitrogen gas from the refueling station is pushed through the line to purge LN_2 from the onboard system. The nitrogen gas flow is followed by a hydrogen gas purge. Afterwards, the refueling receptacle is disengaged from the vehicle and the vehicle is ready to resume normal operation without risk of gaseous or liquid nitrogen dilution or obstruction. A full schematic with necessary onboard hardware to manage the LN_2 (including an additional check valve, an automatic metering valve, and a 3-way valve shown in orange) is shown in Figure 17 along with a bill of materials in Table 9.

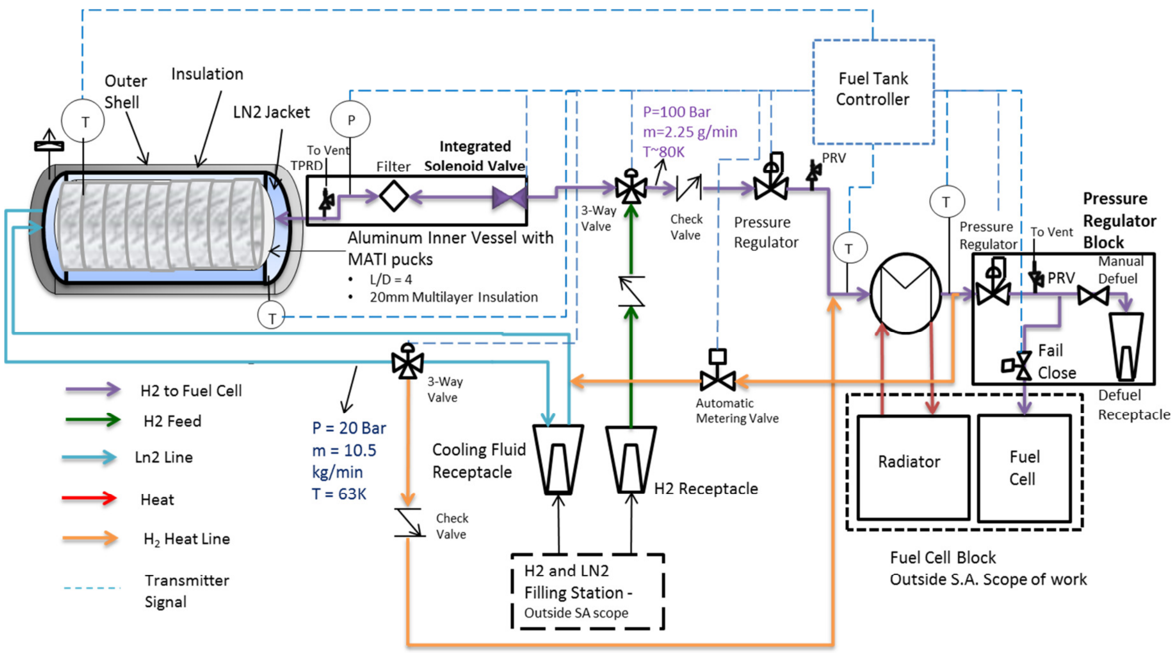

Figure 17: Updated MATI system diagram showing alternative heating configuration and integration of components.

The MATI storage vessel with 5.6 kg available H_2 is slightly smaller and lighter than the HexCell vessel (106L internal volume and 61 kg). However, the MATI storage vessel requires 41 kg MOF vs 32 kg for the HexCell system, so the MATI vessel weighs 102 kg vs 96 kg for the HexCell.

Table 9: MATI Bill of Materials.

Name	Quantity	*10,000*	*30,000*	*80,000*	*100,000*	*500,000*
H2 Fill receptacle	1	*$203*	*$129*	*$86*	*$78*	*$40*
Cooling Fill Receptacle	1	*$203*	*$129*	*$86*	*$78*	*$40*
Filter	1	*$24*	*$15*	*$10*	*$9*	*$5*
T-PRD	1	*$106*	*$67*	*$45*	*$41*	*$21*
PRV	2	*$194*	*$123*	*$82*	*$74*	*$38*
Temperature Transducer	4	*$53*	*$33*	*$22*	*$20*	*$10*
Pressure Transducer	1	*$97*	*$61*	*$41*	*$37*	*$19*
Welded Inner Vessel (AL)		$2,175	$1,624	$1,464	$1,435	$1,367
Outer Vessel	1	*$324*	*$174*	*$127*	*$122*	*$116*
Inner Vessel	1	*$447*	*$304*	*$259*	*$254*	*$249*
MOF Compressed into Pucks		*$37*	*$27*	*$26*	*$25*	*$23*
MOF Bed Material	1	$488	$406	$392	$379	$346
LN_2 Channel (corrugated Al)		$166	$127	$115	$114	$112
CryoInsulation (10 mm)	1	*$189*	*$186*	*$183*	*$183*	*$178*
Internal Supports for inner vessel	8	*$4*	*$4*	*$4*	*$4*	*$4*
Getter		*$20*	*$20*	*$20*	*$20*	*$20*
Burst Disc		*$7*	*$7*	*$7*	*$7*	*$7*
MATI (Internal Cooling Disc)	11	*$120*	*$78*	*$65*	*$65*	*$59*
MATI Disc Leak Testing	----	*$6*	*$5*	*$5*	*$5*	*$5*
Tank Assembly	----	*$128*	*$128*	*$127*	*$127*	*$126*
Tank Testing	----	*$94*	*$51*	*$38*	*$37*	*$32*
Containment Vessel Cost Contingency		*$145*	*$106*	*$94*	*$93*	*$90*
Integrated Solenoid Valve	1	*$175*	*$141*	*$118*	*$118*	*$100*
Pressure regulator	2	*$1,106*	*$701*	*$467*	*$425*	*$218*
Pressure Regulator Block Body	1	*$50*	*$32*	*$23*	*$22*	*$18*
3-way valve/switch	2	*$100*	*$82*	*$70*	*$73*	*$65*
Check Valves	3	*$124*	*$79*	*$52*	*$48*	*$25*
Radiator Heat Exchanger	1	$141	$78	$79	$62	$55
Manual Defuel Valve and Receptacle	1	$92	$58	$39	$35	$18
Automated Shut off Valve	1	*$111*	*$70*	*$47*	*$43*	*$22*
Automatic Metering Valve	1	*$111*	*$70*	*$47*	*$43*	*$22*
Fuel Tank Controller	1	*$146*	*$123*	*$106*	*$103*	*$80*
Couplings		$334	$250	$221	$216	$195
External H2 and LN2 Lines	1	$26	$24	$22	$21	$18
Mounting Frame/Brackets		$58	$36	$24	$22	$11
BOP Assembly	1	$92	$92	$92	$92	$92
System Testing	----	$58	$26	$22	$24	$15
Total		$5,777	$4,044	$3,263	$3,119	$2,495

2.3.2 Reversible Metal Hydride—Alane

A preliminary cost analysis was conducted of a reversible aluminum hydride (alane) storage system concept developed and previously analyzed by the HSECoE[12], [13]. The system shown schematically in Figure 18 is based on the system design developed by the HSECoE and has the following key features:

- A volume displacement tank to hold the hydrogenated fuel slurry.
- A modified plug-flow reactor to liberate H_2 from alane.
- Gas-liquid separator to remove H_2 from the slurry.
- Gas and liquid radiators for thermal management.

Bottoms up DFMA® analysis was conducted for the recuperator, reactor, gas-liquid separator, drain vessel, volume displacement tank, and ballast tank shown in Figure 18. A bill of materials is presented in

Table 10. SA's estimate of the system cost is more than double the cost reported in [13], $9434/system vs $4133/system. The largest single discrepancy is in the cost of alane. HSCoE used a low volume price quote for alane with a learning curve to estimate a cost at high volume. In contrast, SA used price estimates from a DOE supported project investigating alternative alane production methods[14]. Further investigation into alane costs is recommended for future analyses since it has such a large impact on overall system cost. Finally, these results should not be viewed as final but are included in this document to be a complete report of analyses

conducted under the contract.

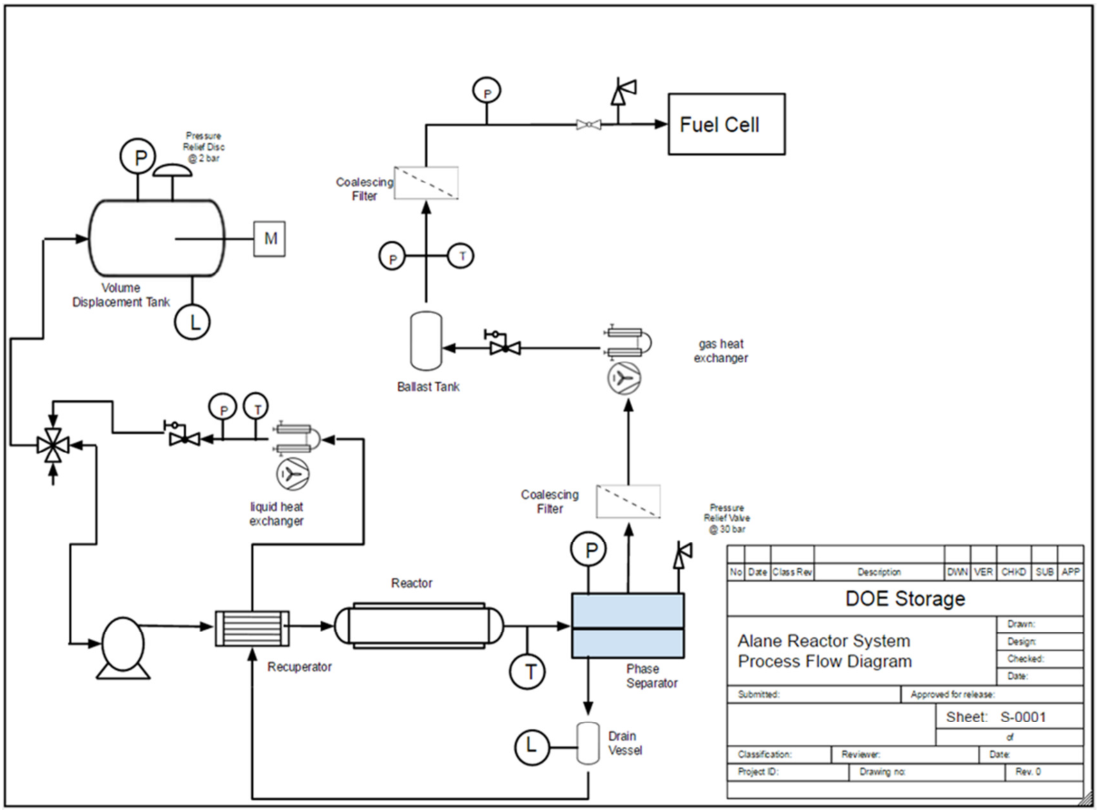

Figure 18: Alane storage system design.

Table 10: Alane storage system bill of materials.

	Manufacturing Rate				
	10,000	**30,000**	**80,000**	**130,000**	**500,000**
Volume Displacement Tank System	**$962**	**$897**	**$851**	**$829**	**$777**
Volume Displacement Tank	*$302*	*$302*	*$302*	*$302*	*$302*
Stirrer 1	*$18*	*$8*	*$7*	*$7*	*$7*
Stirrer 2	*$18*	*$17*	*$14*	*$12*	*$9*
Rupture Disc	*$154*	*$154*	*$154*	*$153*	*$153*
Level Indicator	*$281*	*$248*	*$222*	*$210*	*$181*
Pressure Indicator	*$188*	*$168*	*$151*	*$144*	*$125*
Feed Loop	**$1,154**	**$903**	**$738**	**$665**	**$564**
H2 Feed Port	*$166*	*$141*	*$121*	*$112*	*$92*
Slurry Feed Port	*$166*	*$141*	*$121*	*$112*	*$92*
Slurry Control Valve	*$188*	*$159*	*$146*	*$136*	*$131*
Feed Pump (P-1)	*$629*	*$459*	*$346*	*$301*	*$205*
Recuperator	*$5*	*$4*	*$4*	*$4*	*$4*
Reactor	*$53*	*$50*	*$47*	*$45*	*$41*
Agitator	*$5*	*$5*	*$5*	*$4*	*$3*
Reactor Thermocouple	*$43*	*$40*	*$39*	*$37*	*$37*
Return Loop	**$820**	**$721**	**$662**	**$633**	**$579**
Gas Liquid Separator	*$126*	*$114*	*$110*	*$109*	*$108*
Drained Vessel	*$56*	*$55*	*$54*	*$54*	*$54*
Coalescing Filter	*$58*	*$58*	*$58*	*$58*	*$58*

Level Indicator	*$281*	*$248*	*$222*	*$210*	*$181*
Pressure Relief Valve	*$112*	*$79*	*$67*	*$58*	*$54*
Pressure Indicator	*$188*	*$168*	*$151*	*$144*	*$125*
Balance of Plant	**$2,612**	**$2,179**	**$2,042**	**$1,964**	**$1,851**
Liquid Radiator	*$30*	*$25*	*$21*	*$19*	*$15*
Gas Radiator	*$67*	*$61*	*$56*	*$54*	*$48*
Thermocouple	*$43*	*$40*	*$39*	*$37*	*$37*
Ballast Tank	*$218*	*$43*	*$30*	*$26*	*$26*
Particulate Filter	*$58*	*$58*	*$58*	*$58*	*$58*
H2 Pressure Control Valve	*$991*	*$944*	*$904*	*$885*	*$834*
Pressure relief Disc	*$268*	*$128*	*$90*	*$65*	*$56*
Pressure Indicator	*$188*	*$168*	*$151*	*$144*	*$125*
Back Pressure Regulator	*$133*	*$127*	*$122*	*$119*	*$112*
Stainless Steel Tubing - Lines	*$618*	*$587*	*$571*	*$556*	*$540*
Materials	**$26,391**	**$17,076**	**$11,585**	**$9,549**	**$5,663**
Alane	*$26,095*	*$16,779*	*$11,289*	*$9,253*	*$5,367*
Silicon Oil	*$296*	*$296*	*$296*	*$296*	*$296*
Total System Cost	**$31,941**	**$21,777**	**$15,878**	**$13,639**	**$9,434**
System Cost ($/kWh)	**$171**	**$117**	**$85**	**$73**	**$51**

2.3.3 Hawaii Hydrogen Carriers

A preliminary analysis of a prototype storage system based on metal hydride H_2 storage for material handling applications [15] was performed. A system diagram (based on current prototype systems) and manufacturing process flows were developed. Based on this preliminary analysis, it was recommended that the storage system be redesigned for manufacturing ease by addressing the system manifold.

2.3.4 Spent Fuel Recycle Cost Analysis

To better understand the costs associated with regenerating spent hydride fuels (e.g. alane and ammonium borane), a bottoms-up analysis of alane and ammonium borane (NH_3BH_3) recycle costs was conducted.

2.3.4.1 Alane Recycle Cost Analysis

The alane recycle process is based on hydrogenation of the aluminum dimethylethylamine (DMEA) adduct as analyzed by ANL for performance[16]. Overviews of the processing steps from spent fuel to regeneration are presented in Figure 19 and Figure 20.

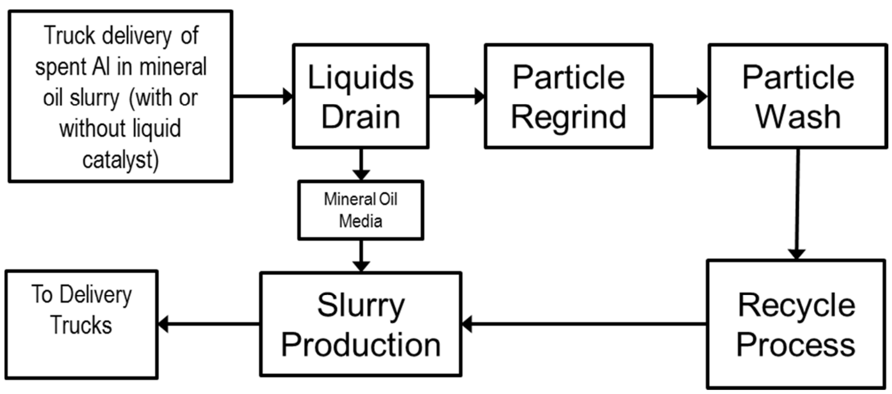

Figure 19: Pre-processing steps for alane recycle.

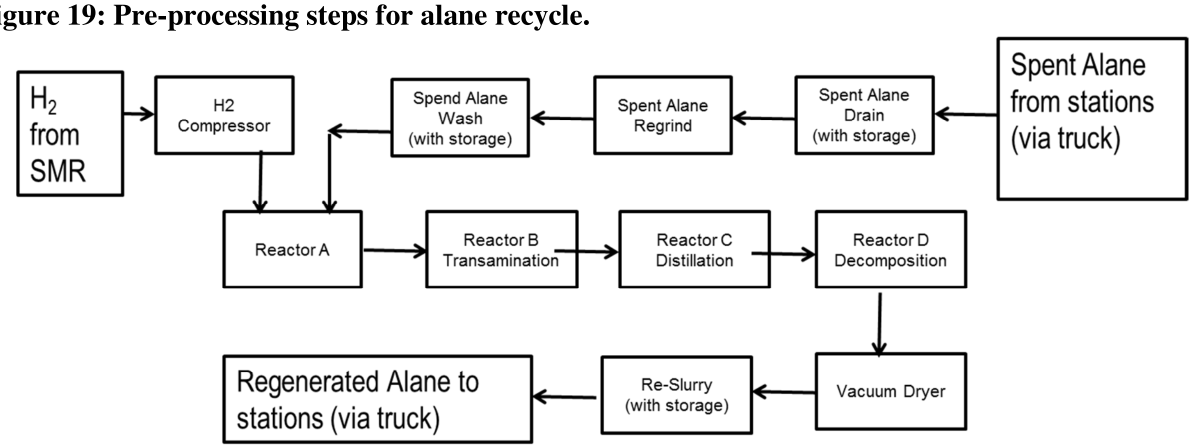

Figure 20: Simplified process flow diagram for batch regeneration of alane using dimethylethylamine based on analysis in [16].

Alane regeneration in Figure 20 was modeled as four main reaction blocks:

- The pretreated, spent aluminum adduct is formed with DMEA according to $C_4H_{11}N$ + Al + 1.5 $H_2 \rightarrow AlH_3 \cdot C_4H_{11}N$ in diethyl ether in reactor 'A'. Process assumptions are summarized in Table 11.
- Transamination reaction occurs in reactor 'B' according to $AlH_3 \cdot C_4H_{11}N + N(C_2H_5)_3 \rightarrow AlH_3 \cdot N(C_2H_5)_3 + C_4H_{11}N$ in diethylether. Process assumptions for this step are summarized in Table 12.
- Distillation to separate the alane adducts occurs in Reactor 'C' according to the process flow assumptions summarized in Table 13.
- A decomposition reaction occurs in reactor 'D' according to $AlH_3 \cdot N(C_2H_5)_3$ + $AlH_3 \cdot C_4H_{11}N \rightarrow AlH_3 + N(C_2H_5)_3 + AlH_3 \cdot C_4H_{11}N$. Process assumptions for this step area described in

The total capital investment for regeneration was estimated at $153M which leads to a recycle cost of ~$4/kg$H_2$. This does not include the cost of H_2, just the cost of recycling the alane.

Table 11: Process assumptions for reactor A.

Demonstrated	Cost Modeling Assumption
300ml Parr Reactor	15.2 m^3 Batch Reactor
Stirred reactor with H_2 in headspace	Stirred, H_2 bubbled from bottom, collected at top, recycled to bottom bubbler, cooling coils on outside and within vessel.
25 °C, 65-75 bar	25C, 20 bar
10-12 hours for ~90% reaction completion (including several hour induction period where no reaction occurs, presumably while surface oxides are being broken down)	4 hours to 80% reaction. Induction period assumed to be zero due to aluminum pre-treatment (washing, rinsing, acid reduction if needed)
Ti catalyzed Aluminum (similar to TiAl3) Lifetime of Ti not known. All Ti appears to stay with Al.	All Ti stays with Al and is ignored in all subsequent calculations. Ti does not decompose; no Ti replacement.
Ratio of Et_2O to DMEA typically 1:1 molar	Ratio of Et_2O to DMEA 0.25:1 molar
Ratio of Al to DMEA typically 1:1 molar	Ratio of Al to DMEA 1:1 molar

Table 12: Process assumptions the transamination reaction, reactor 'B'.

Demonstrated	Cost Modeling Assumption
Vacuum chamber	Stirred, vacuum chamber with heating/cooling coils on outside and within vessel.
60-70C, 10 – 50 mbar	55C, 10 – 50 mbar
4.5 hours at 50C for 80-100% conversion Alternately: 4 hours at room temp at 80mbar (Lacina, et al, 2010) Alternately: 9 hours at 55C under ~1atm N2 sweep gas for "nearly complete" reaction (Lacina, et al, 2010)	4 hours to 80% reaction.

Table 13: Process assumptions for adduct distillation.

Demonstrated	Cost Modeling Assumption
300ml Parr Reactor	Large distillation column 4m diameter, 5:1 L/D,, based on twice volume of liquid flow, 15 trays per column
Vacuum chamber	Vacuum distillation with heating/cooling
60-70C, 10 – 50 mbar	55C, 10 – 50 mbar
NA	2 hours to 100% separation of Ether and DMEA

Table 14: Process assumptions for the decomposition reaction.

Demonstrated	Cost Modeling Assumption
300ml Parr Reactor	15.2 m^3 Batch Reactor
Vacuum chamber	Stirred, vacuum chamber with heating/cooling coils on outside and within vessel.
70C, 100 mbar drifting to 15 mbar	70C, 100 mbar drifting to 15 mbar
3 hours to: 70% AlH3 30% Al 0% TEA or TEAA	2 hours to: 95% AlH3 5% Al 0% TEA or TEAA

2.3.4.2 Ammonia Borane Recycle Cost Analysis

An extension of existing work [16], [17] analyzing ammonia borane recycle cost was conducted based on a one-pot process $BNH_{1.3} + NH_3 \rightarrow BH_3NH_3 + 1.175\ N_2$[18], [19] summarized in Figure 21. Neglecting the hydrazine cost, the cost to regenerate ammonia borane by this method is ~\$2/kgH_2; however, including market prices for hydrazine contributes as much as \$50/kgH_2. A one-pot preparation method for hydrazine from benzophenone was analyzed as an alternative, lower cost method for supplying hydrazine for ammonia borane recycle. A process flow for the benzophenone hydrazine synthesis is shown in Figure 22 and process assumptions are summarized in

Table 15.

The capital cost for the hydrazine processing plant was estimated to be \$345M based on the work of Linehan and co-workers[17] resulting in an ammonia borane recycle cost of ~\$10/kgH_2.

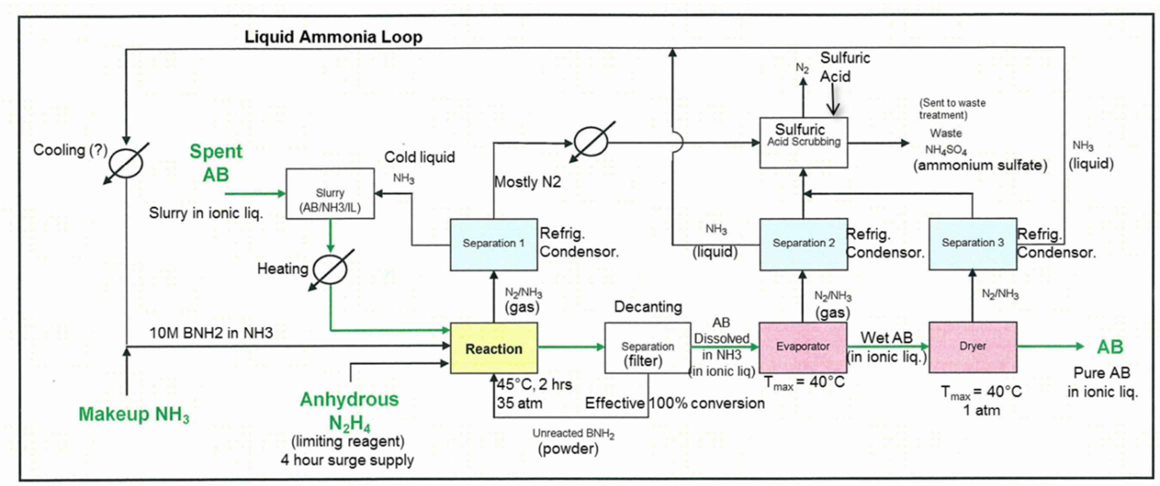

Figure 21: Block flow diagram for hydrazine-based ammonia borane recycle.

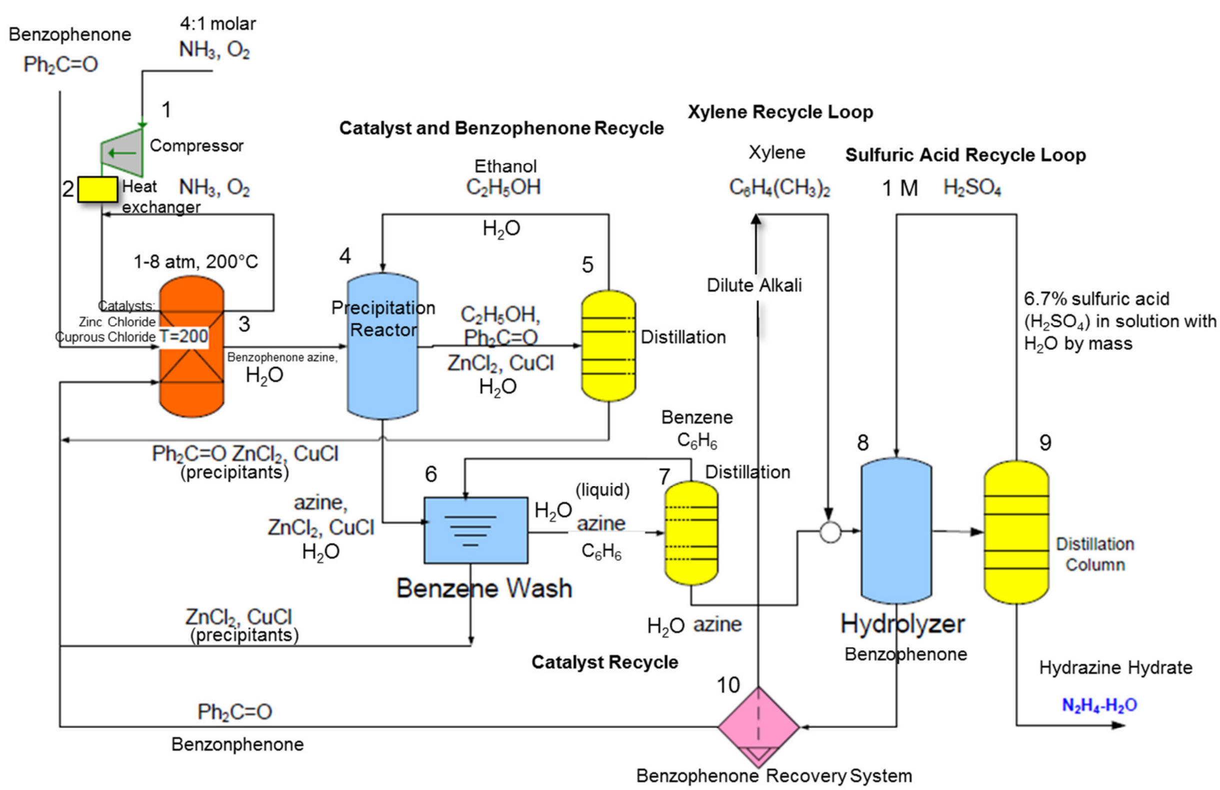

Figure 22: Process flow diagram for hydrazine synthesis from benzophenone.

Table 15: Hydrazine synthesis process assumptions.

Demonstrated	Cost Modeling Assumption
Main One-Pot reactor: 4 hours, 4 atm, 200C to 71% conversion powder catalyst 250ml reactor with ammonia/O_2 bubbler	Main reactor: 4 hours, 5 atm, 200C to 100% conversion ignore presence of catalyst 15.2m^3 reactor, with thermal control, mixers, bubblers
(Step #4) Precipitator Mass flow modeling from ANL. No other sizing data available.	Based on distillation column, 15 trays 4 hour residence time of liquids
(Step #5) Ethanol Distillation Mass flow modeling from ANL. No other sizing data available.	Based on distillation column, 15 trays 2 hour residence time of liquids
(Step # 6) Benzene Wash Mass flow modeling from ANL. No other sizing data available.	Based on Jacketed/Stirred reactor 2 hour residence time of liquids
(Step #7) Benzene Distillation Mass flow modeling from ANL. No other sizing data available.	Based on distillation column, 15 trays 2 hour residence time of liquids
(Step # 8) Hydrolyzer Mass flow modeling from ANL. No other sizing data available.	Based on Jacketed/Stirred reactor, 1 hour residence time of liquids
(Step # 9) Sulfuric Acid Distillation Mass flow modeling from ANL. No other sizing data available.	Based on distillation column, 15 trays 2 hour residence time of liquids

2.4 Electrochemical Hydrogen Compression

Past studies have shown that compression of H_2 to the required dispensing pressure (typically 875 bar for dispensing to 700 bar systems) can require substantial energy input and be a considerable capital expense. While mechanical compression systems (piston or diaphragm) are typically used for refueling station hydrogen compression, electrochemical compressors represent an intriguing alternate due to their potential for high efficiency and low cost. Since fuel cells and electrochemical compressors share many design attributes, and SA has conducted extensive fuel cell cost analysis in the past, SA was tasked to project the capital cost of electrochemical hydrogen compression.

Electrochemical hydrogen compression (EHC) is isentropic and thus has the potential to be more efficient than mechanical compression. At its core, EHC has the same components as a polymer electrolyte fuel cell system (PEMFC), an anode and cathode with precious metal catalyst, and a perfluorosulfonic acid electrolyte membrane. A DFMA® cost analysis was conducted based on

SA's interpretation of an existing Giner EHC design modified for high production rate. Details of the design concept are illustrated in Figure 23. Energy input requirements were based on experimental results and a simplified first principals performance model.

Several system sizes (H_2 pumping capacities varying between 250 and 1,000 kgH_2/day) were examined at two annual system production rates (500 and 5,000 systems/year). The systems consisted of multiple arrays of EHC stacks, manifolding, power inverters, mechanical compressors (as needed), and water management subsystems. EHC outlet pressure was varied to explore system cost sensitivity[3] with increasing level of compression, taking into account both the sealing requirements on the stack, changing rate of H_2 back diffusion, and the impact on water management.

In summary, the cost results show that normalized cost (i.e. system cost normalized by H_2 capacity):

- At 1kpsi outlet pressure:
  - o Varies between $211-$323/ (kgH_2/day) depending on system size and production rate
- At 15kpsi outlet pressure:
  - o Varies between $338-$471/(kgH_2/day) depending on system size and production rate.

Details of the cost breakdowns at two outlet pressures are presented in Table 16 and Table 17. Cost of compressed H_2 was found to be quite sensitive to the H_2 outlet pressures due to back diffusion of H_2 through the membrane. Additional work is needed to fully understand the cost tradeoffs and optimization of hybrid EHC-mechanical compression, and the impact of back diffusion.

[3] All EHC configurations are based on 1atm H_2 inlet pressure.

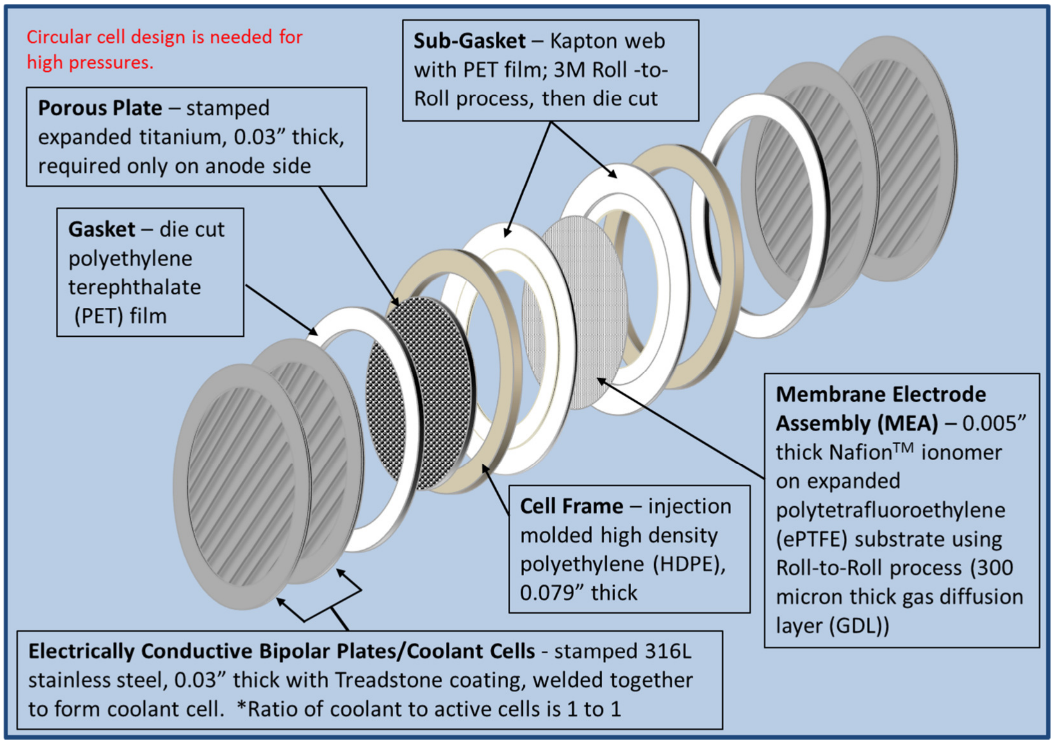

Figure 23: SA EHC cell design featuring individual components with the materials and manufacturing process used in the DFMA® model.

Table 16: EHC System cost breakdown for 1 kpsi outlet pressure.

Technology Type		PEM Electrochemical Hydrogen Compressor							
Annual Production Rate	systems/year	500				5,000			
kg Hydrogen/day	kg/day	250	500	750	1,000	250	500	750	1,000
Stacks per System	stacks/system	5	9	14	19	5	9	14	19
Electric Power Input to EHC Stacks	kW_{System}	63	125	188	250	63	125	188	250
System Total Electric Power (Input to System)	kW_{System}	89	178	267	356	89	178	267	356
Stack Outlet H2 Pressure	psi	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
EHC Subsystem Cost									
EHC Stacks	**$/kg/day**	$159.26	$136.99	$127.32	$122.43	$108.59	$99.79	$96.41	$94.04
Balance of Plant	**$/kg/day**	$163.62	$136.35	$124.91	$118.04	$159.15	$133.95	$123.39	$116.96
System Assembly & Testing	**$/kg/day**	$0.80	$0.40	$0.27	$0.20	$0.59	$0.29	$0.20	$0.15
Total EHC Subsystem Cost	**$/kg/day**	$323.68	$273.73	$252.50	$240.68	$268.33	$234.04	$219.99	$211.15
Total Annual Cost	**$/year**	$40,460,618	$68,433,230	$94,686,241	$120,338,074	$335,416,873	$585,087,540	$824,959,835	$1,055,725,041
Cost/m2 of Active Area	**$/m2**	$2,888.13	$2,438.99	$2,255.06	$2,139.94	$2,394.25	$2,085.28	$1,964.74	$1,877.37
Cost/System	**$/system**	$80,921.24	$136,866.46	$189,372.48	$240,676.15	$67,083.37	$117,017.51	$164,991.97	$211,145.01
Cost/kWgross	**$/kWgross**	$908.26	$768.10	$708.51	$675.34	$752.95	$656.70	$617.29	$592.47
System Energy Requirement	**kWh/kg**	8.55	8.55	8.55	8.55	8.55	8.55	8.55	8.55

Table 17: EHC System cost breakdown for 15 kpsi outlet pressure.

Technology Type		PEM Electrochemical Hydrogen Compressor							
Annual Production Rate	systems/year	500				5,000			
kg Hydrogen/day	kg/day	250	500	750	1,000	250	500	750	1,000
Stacks per System	stacks/system	11	21	32	43	11	21	32	43
Electric Power Input to EHC Stacks	kW_{System}	84	169	253	338	84	169	253	338
System Total Electric Power (Input to System)	kW_{System}	111	222	333	444	111	222	333	444
Stack Outlet H2 Pressure	psi	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000
EHC Subsystem Cost									
EHC Stacks	**$/kg/day**	$266.56	$240.33	$228.62	$222.57	$207.52	$195.06	$190.26	$187.25
Balance of Plant	**$/kg/day**	$203.94	$173.34	$159.91	$151.71	$199.54	$171.05	$158.51	$150.77
System Assembly & Testing	**$/kg/day**	$0.80	$0.40	$0.27	$0.20	$0.59	$0.29	$0.20	$0.15
Total EHC Subsystem Cost	**$/kg/day**	$471.30	$414.07	$388.80	$374.49	$407.64	$366.40	$348.96	$338.17
Total Annual Cost	**$/year**	$58,912,100	$103,517,108	$145,798,246	$187,244,326	$509,552,627	$916,002,536	$1,308,610,104	$1,690,830,108
Cost/m2 of Active Area	**$/m2**	$3,663.44	$3,218.59	$3,034.03	$2,919.06	$3,168.64	$2,848.07	$2,723.19	$2,635.93
Cost/System	**$/system**	$117,824.20	$207,034.22	$291,596.49	$374,488.65	$101,910.53	$183,200.51	$261,722.02	$338,166.02
Cost/kWgross	**$/kWgross**	$1,061.01	$932.17	$875.28	$843.07	$917.71	$824.86	$785.60	$761.30
System Energy Requirement	**kWh/kg**	10.66	10.66	10.66	10.66	10.66	10.66	10.66	10.66

3 Continuation of Project

The work described in this report will continue through a new contract beginning October 1, 2016. Future analyses will include updates to the Type IV 700 bar system, cryo-compressed storage, re-examination of metal organic framework systems with next generation MOFs, conformable tanks, and metal hydrides.

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5 Appendix: Project Publications and Presentations

1. "Hydrogen Storage Cost Analysis, Preliminary Results," Brian D. James, 2012 Annual Merit Review, 15 May 2012.
2. "Off-Board Recycle Analysis Status", Brian D. James, Whitney G. Colella, Strategic Analysis Inc., 6 September 2012. Internal status presentation to Recycle Analysis Working Group.
3. "Off-Board Recycle Analysis Status", Brian D. James, Whitney G. Colella, Strategic Analysis Inc., 18 September 2012. Status presentation to DOE Headquarters (Ned Stetson, Grace Ordaz, Channing Ahn).
4. "Alane and Ammonia Borane Off-Board Recycle Analysis Status", Brian D. James, Whitney G. Colella, Strategic Analysis Inc., 11 October 2012, Go-To-Meeting presentation to DOE and the Hydrogen Storage Engineering Center of Excellence (HSECoE).
5. "Pressure Vessel Cost Analysis", Brian D. James, Andrew B. Spisak, Strategic Analysis Inc., 14 November 2012, presentation to the Storage Systems Analysis Working Group (SSAWG) at USCAR facilities in Detroit MI.
6. "Pressure Vessel Cost Analysis", Brian D. James, Andrew B. Spisak, Strategic Analysis Inc., 15 November 2012, presentation to the Hydrogen Storage Tech Team at USCAR facilities in Detroit MI.
7. "Pressure Vessel Cost Analysis", Brian D. James, Andrew B. Spisak, Strategic Analysis Inc., 28 November 2012, presentation to the DOE Hydrogen Storage PI Meeting held at ARPA-E facilities in Washington DC.
8. James, B. D., Moton, J.M., Colella, W. G., "Hydrogen Storage Cost Analysis," U.S. DOE's 2013 Annual Merit Review and Peer Evaluation Meeting (AMR) for the Hydrogen and Fuel Cells Program, Arlington, VA, May 13–17, 2013, Project ID ST100.
9. James, B. D., Moton, J.M., Colella, W. G., "Advanced Hydrogen Compression Systems for Serving a Hydrogen Vehicle Refueling Infrastructure," American Society of Mechanical Engineers (ASME) 2013 7th International Conference on Energy. Sustainability, Minneapolis, MN, July 14-19th, 2013, ESFuelCell2013-18411.
10. James, B. D., Moton, J.M., Colella, W. G., "Electrochemical Hydrogen Compression (EHC) System Designs and Costs," ASME 2013 11th Fuel Cell Science, Engineering and Technology Conference, Minneapolis, MN, July 14-19th, 2013, ESFuelCell2013-18419.
11. Moton, J.M., James, B.D., Colella, W.G., James, B.D. "Design for Manufacturing and Assembly (DFMA) Analysis of Electrochemical Hydrogen Compression (EHC) Systems," Proceedings of the Fifth European Fuel Cell Technology & Applications Conference - Piero Lunghi Conference and Exhibition (EFC2013), Rome, Italy, Dec. 11th-13th, 2013 (EFC13-179).
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14. James, B.D., Moton, J.M., Colella, W.G., “Engineering Performance, Manufacturing Methods, and Capital Costs of Emerging Electrochemical Hydrogen Compression (EHC) Systems,” *2013 Fuel Cell Seminar*, STA44-2 High Temperature Fuel Cells, Paper Number 265, Greater Columbus Convention Center, Columbus, Ohio, October 21st-24th, 2013.
15. Colella, W. G., James, B. D., Moton, J. M., *Emerging Electrochemical Systems for Electricity, Heat, and Compressed Hydrogen,* Machine Group, Department of Industrial Engineering, University of Roma Tor Vergata (hosted by Professor Vincenzo Mulone), Rome, Italy, Dec. 18th, 2013.
16. James, B. D., Moton, J. M., Colella, W. G., *Electrochemical Hydrogen Compression (EHC) System Designs and Costs,* Presentation to U.S. DOE EERE FCT Program, delivered remotely from Arlington, VA, Oct. 16th, 2013.
17. James, B.D., Moton, J.M., Colella, W.G., “Engineering Performance, Manufacturing Methods, and Capital Costs of Emerging Electrochemical Hydrogen Compression (EHC) Systems,” *2013 Fuel Cell Seminar*, STA44-2 High Temperature Fuel Cells, Paper Number 265, Greater Columbus Convention Center, Columbus, Ohio, October 21st-24th, 2013.
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26. James, B.D., Moton, J.M., "Hydrogen Storage Cost Analysis-DRAFT" Annual Progress Report (APR), submitted to DOE, August 8th, 2014.
27. James, B.D., Moton, J.M., DeSantis, D.A., "Hydrogen Storage System Cost: Status and Technical Challenges," Presentation at the Hydrogen Storage Summit PI Workshop at the National Renewable Energy Laboratory (NREL), Golden, CO, January 29th, 2015.
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