Hydrogen Storage System Cost Analysis: Summary of FY 2017 Activities Sponsorship and Acknowledgements

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Sponsorship and Acknowledgements

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Disclaimer

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Contents

1 Introduction

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. To chart the impact of FCTO supported projects, FCTO has established ultimate targets for H_2 storage cost ($8/kWh) and capacity (2.5 kWh/kg and 2.3 kWh/L). This cost assessment project supports the overall FCTO goals by identifying manufacturing and assembly techniques most likely to lead to the lowest system storage cost, and by estimating the cost impact of material and manufacturing improvements demonstrated under both FCTO supported projects as well as those reported in the open literature. Costs of hydrogen systems studied under this contract are forecast at multiple rates of annual manufacture to allow comparison with DOE cost targets. Cost breakdowns of the system are reported to identify high-cost components and manufacturing steps, which can be used to guide future research and development (R&D) decisions.

This report is prepared to provide a summary of Strategic Analysis Inc. activities in FY 2017 (October 1, 2016 – September 31, 2017) in support of Milestone 2 and the Year 1 year-end go/no go decision. The report is organized around systems analyzed to provide a holistic view of what was completed in FY 2017 and what remains to be investigated. After briefly discussing the cost analysis methodology and defining global assumptions in Section 2, the six systems analyzed in 2017 are discussed. These include

- A low volume 700 bar Type 4 H_2 storage system analysis based on available Toyota Mirai design parameters in Section 3
- A refinement of previously analyzed metal organic framework (MOF) material cost based on recently reported MOF-74 in Section 4
- A 500 bar cryo-compressed H_2 system cost analysis for fuel cell electric bus (FCEB) and fuel electric vehicle (FCEV) applications in Section 5
- An analysis of two Type 4 compressed natural gas (CNG) storage systems in support of the Department of Energy (DOE) sponsored Institute for Advanced Composites Manufacturing Innovation (IACMI) Section 6
- A design space evaluation to estimate potential cost savings for cold (100 K – 300 K) H_2 storage for Type 3 and Type 4 pressure vessels Section 7
- A reverse engineering analysis of a metal hydride storage system to identify metal hydride material cost targets and potential component cost reductions Section 8

This report represents a snapshot of the systems discussed in Sections 3 through 8, which are at various stages of completion. Finally, a short description of work planned for FY 2018 is described in Section 9.

2 Methodology

Strategic Analysis uses a Design for Manufacture and Assembly® (DFMA®) cost methodology approach to project the cost to manufacture hydrogen storage systems. DFMA® is an iterative, bottoms-up, process-based cost analysis methodology which projects material and manufacturing cost of the complete system by modeling specific manufacturing steps. 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). The cost for each manufacturing step includes the annual capital equipment repayment, tooling, utilities, and labor, expressed as a machine rate ($/min):

$$R = \frac{P_{Capital} + P_{Operations}}{T_{Operations}}$$

Equipment costs, C, are amortized over their useful life, T, to achieve a specified after tax discount rate according to:

$$P_{Capital} = f_{Installation} * \left[\frac{C * R_{Discount}}{1 - (1 + R_{Discount})^{T}} - \frac{R_{Tax}}{T}\right] / (1 - R_{Tax})$$

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 typically 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.

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

Throughout the analysis, cost is normalized on a $/kWh and in 2007 USD 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, and cost are adjusted to 2007USD using the Bureau of Labor Statistics Producer Price Index[1].

3 Low-Volume (<10k systems per year) 700 bar Type 4

Given the high interest in the Toyota Mirai H_2 fuel cell vehicle and available modeling data from Argonne on the pressure vessel performance, we modified our baseline 700 bar Type 4 hydrogen storage system to project a system cost for the Mirai at volumes consistent with current production as well as to moderate volumes to see the impact of economies of scale on system cost. The Toyota Mirai uses a two-tank configuration—a 2.8 and 1.7 aspect ratio front and rear Type 4 tank, respectively— to store approximately 5.0 kg of usable hydrogen at 700 bar [2]. Composite mass was estimated based on public reports from Toyota [2], [3] as modeled by ANL. Critical tanks design assumptions are summarized in Table 2. While Toyota reports that Mirai tanks use a higher tensile strength T-720 carbon fiber, T-700 was used in this analysis for two reasons. First, it provides a direct comparison with the DOE baseline [4].

Second, a reliable T-720 price is not available and the cost of T-720 reported in private communications suggests that the carbon fiber mass reduction for T-720 does not offset the higher cost of the fiber.

Table 2: Summary of Mirai cost model assumptions.

Parameter	Front Tank	Rear Tank	Basis
Internal Volume (L)	60	60	SAE Paper
Length/Diameter (L/D)	2.8	1.7	SAE Paper
Available H_2 (kg)	5.0	5.0	ANL Model Result
Composite Mass (kg)	39.9	45.2	ANL Model Result
Carbon Fiber Volume Fraction (%)	60	60	Model Assumption
Carbon Fiber	T-700S	T-700S	Model Assumption
Resin	Epoxy	Epoxy	Model Assumption

The baseline model covers production rates of 20k to 500k systems per year; however, shipments of the Toyota Mirai were approximately 3,000 in 2016. Some minor modifications to the model were required to tailor the model for production rates below 10k systems per year. The manufacturing steps are identical for both the baseline system and the Mirai, Table 3 summarizes changes to the manufacturing steps used for low-volume production and the top machine utilization for each step. While the machine utilization is quite low for some processing steps, the cost of the system is not significantly impacted. Indeed, the cost of all manufacturing excluding fiber winding accounts for only 10% of the system cost at 3k systems per year as shown in the cost breakdown in Figure 1.

Table 3: Summary of changes to baseline model process steps for low-volume 700 bar Type 4 storage system

Process Step	Process	Change for Mirai/Low-volume	Machine utilization at 20k/year
Shoulder Foam	Injection Molding	No change	12%
Liner Forming	Blow mold	No change	20%
Liner Annealing	Batch oven	Reduced QC stations from 10 to 3	100%
Fiber Winding	Wet-Winding	No change	99%
Beta Cure	Batch oven	Batch process vs. continuous	43%
Full Cure	Batch oven	Batch process vs. continuous	60%
Proofing	Hydro burst test	No change	79%
Leak Test	He fill	No change	78%
Balance of System	--	Curve fit to baseline components	--
Tank boss	--	Curve fit to baseline components	--

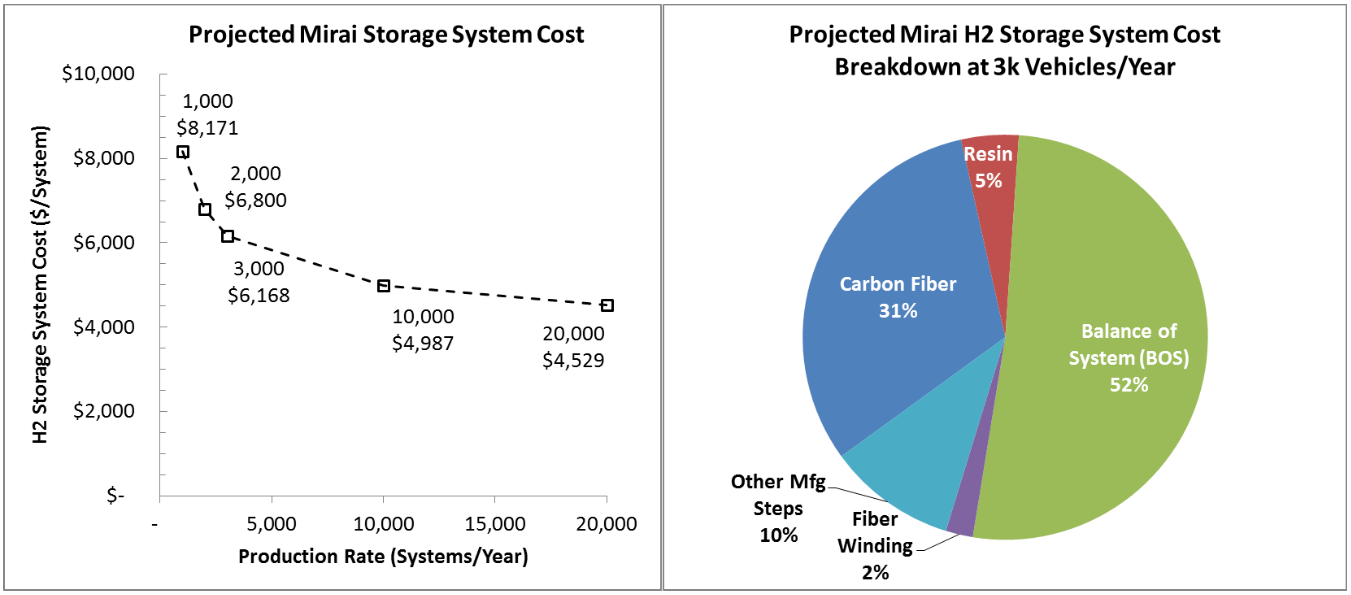


Figure 1: Projected system cost (left) and cost breakdown at 3k vehicles per year (right) for the Toyota Mirai

4 Sorbents

Based on work conducted by SA, Ford, and LBNL in previous DOE/ARPA-e contracts, SA published a paper in January 2017 comparing the cost of Metal Organic Framework (MOF) materials manufactured by traditional thermo-solvent methods, liquid assisted grinding (LAG), and aqueous solution synthesis [5]. Metal organic frameworks are typically synthesized in the lab as a precipitation reaction between a metal salt (eg. MCl_2; M = Mn, Fe, Co, Ni) and an organic linker (e.g. H_4(m-dobdc)) in organic solvents such as methanol and dimethylformamide (DMF). Aqueous synthesis [6], [7] and LAG [8] are modifications of the precipitation reaction. The key finding from this analysis was that solvent costs dominate for traditional thermo-solvent synthesis method leading to MOF costs >$50/kg MOF and that dramatic reduction in production costs for alternative synthesis methods using little or no organic solvents (LAG and aqueous synthesis) lead to MOF costs approaching the ARPA-e target of <$10/kg MOF.

Lawrence Berkeley National Lab (LBNL) recently reported improvement for H_2 adsorption on MOF-74 using an alternative, reportedly lower cost, m-dobdc linker as a substitute for p-dobdc [9]. The published MOF analysis relied on linker costs derived from a learning curve estimate based on an analogous linker, thus a comparison of linkers with subtle material input differences was not possible. To address this short-coming, a bottoms-up cost model was developed to project linker costs.

Linker costs were estimated from scaled up synthesis methods described in the literature for p-dobdc [10] and for m-dobdc [11]. Figure 2 shows the projected costs of p-dobdc (black) and m-dobdc (red), and the materials cost contribution for each isomer (dashed lines). Materials account for ~90% of the linker cost for both isomers, with the m-dobdc projected to cost ~50% of p-dobdc. Material cost contributions are further broken down in Figure 3 which shows that hydroquinone and potassium format contribute ~90% of the materials cost for p-dobdc while resorcinol contributes 96% of the materials cost of m-dobdc.

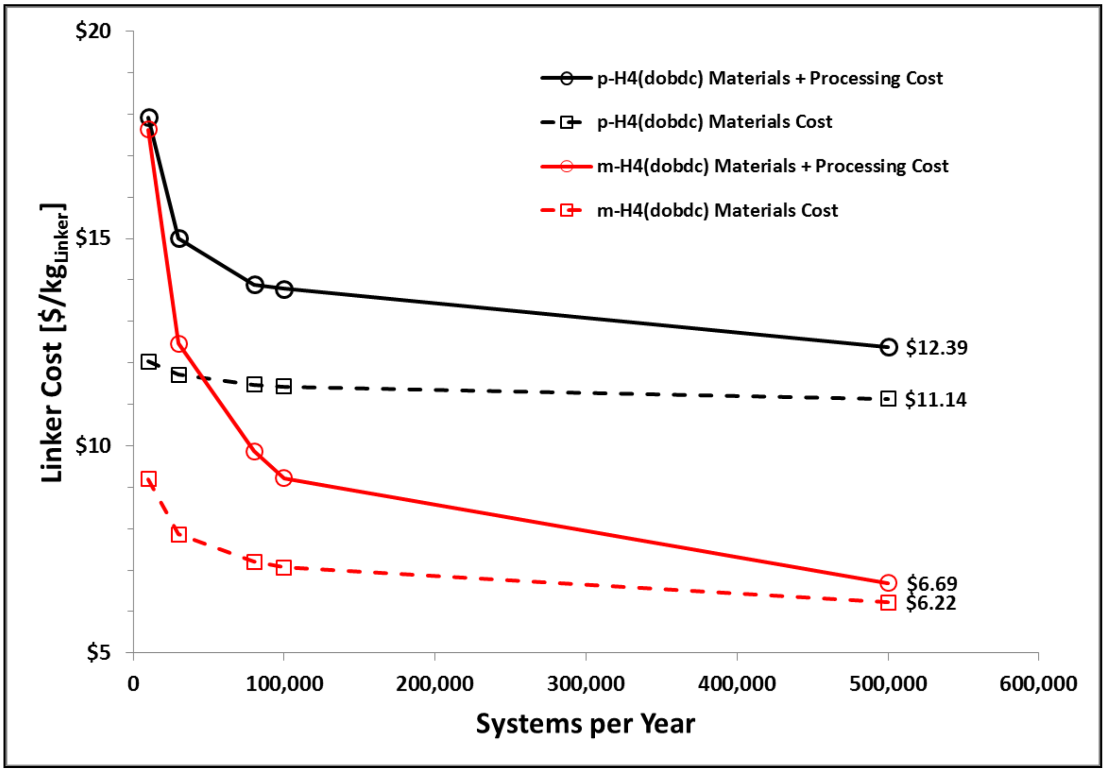
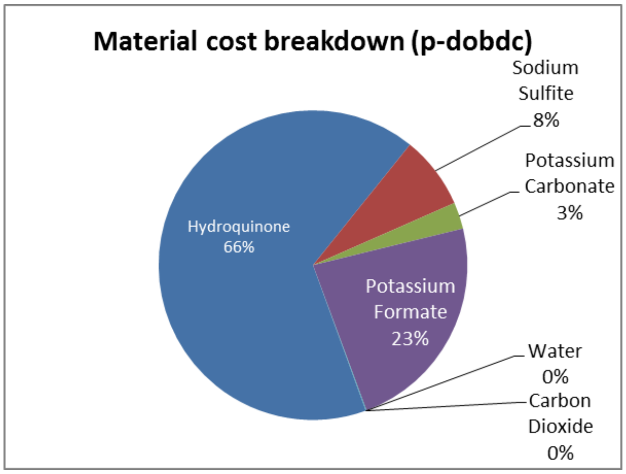


Figure 2: Comparison of p-dobdc (black) and m-dobdc (red) linker costs. Solid lines show the total linker cost, while the dashed lines show just the raw materials costs. Costs are shown with respect to annual sorbent systems per year assuming 44.44 kg of linker



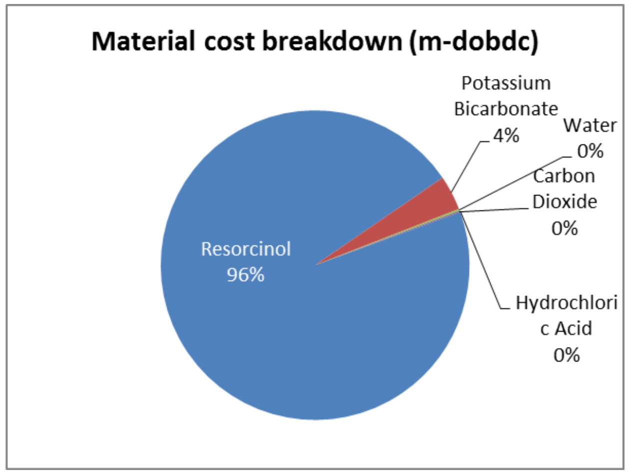


Figure 3: Material cost contributions for p-dobdc and m-dobdc.

With the updated linker cost estimates completed, MOF-74 manufacturing costs were updated. Costs were also extended to 500,000 systems per year (25,000 tonnes/year MOF-74 production) from 50,000 systems studied previously. In addition, three methods of MOF production were investigated based on past analysis [5]. While MOF-74 investigated in the lab was prepared by solvothermal synthesis [9], this method is expensive at industrial scale due to the high cost of the organic solvents DMF and methanol as previously discussed [5]. A comparison of MOF-74 costs with both linkers (p-dobdc and m-dobdc) prepared by solvothermal synthesis, aqueous synthesis, and liquid assisted grinding is presented in Figure 4. Unsurprisingly, MOF-74 (m-dobdc) is less expensive than MOF-74 (p-dobdc) due to the lower cost linker for all three production methods studied. This analysis further suggests that MOF-74 [Mg(m-dobdc)] can achieve the ARPA-e goal of <$10/kgMOF when prepared by liquid assisted grinding.

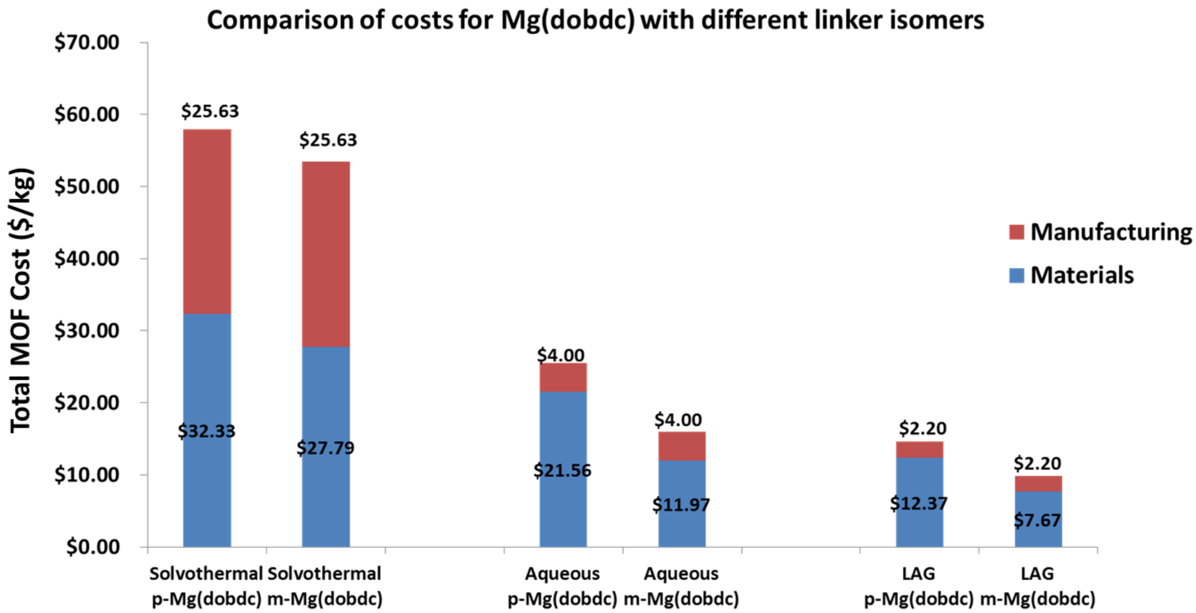


Figure 4: Costs to manufacture MOF-74 with p-dobdc and m-dobdc linkers for solvothermal synthesis, aqueous synthesis, and liquid assisted grinding for 500,000 systems per year assuming 50 kg MOF to store 5.6 kg of usable H_2.

Two sorbent storage systems developed by the Hydrogen Storage Engineering Center of Excellence [12] have been investigated in the past [13]: a system based on compacted discs of MOF-5 sorbents between cooling plates (MATI) and a system based on loose powder MOF-5 sorbent with hexagonal heat transfer plates (Hexcell). The next step for this analysis is to revisit the previous sorbent system cost models, update process assumptions as appropriate, and update linker material costs. In addition to updating the model with improved cost assumptions, LBNL anticipates publishing updated MOF-74 hydrogen adsorption isotherms at both liquid nitrogen (77 K) and ambient (300 K) temperatures. The system will be sized to account for the new isotherms so that it is specific to MOF-74. To complete this analysis, PNNL will model the system size and MOF-74 mass required to store 5.6 kg usable H_2. We have obtained recently published [9] low pressure data (up to 1.2 bar) for MOF-74 (p-dobdc, 77 K) from LBNL. LBNL will share the high pressure and temperature data with us once the paper has been accepted for publication (estimated to be submitted around September 2017).

5 Cryo-Compressed

Cyro-compressed hydrogen (CcH_2) storage systems for both light-duty vehicle (5.6 kg H_2) and bus (40 kg H_2) were analyzed this year. Cryo-compressed systems are characterized by H_2 storage at cryogenic temperatures (typically 70-200K) and elevated pressure (typically 100-500bar). The benefits of CcH_2 storage include higher effective storage density of H_2 (and reduce system size) without incurring the energy and cost of a full H_2 liquefaction, and a long driving range after a full boil off event. Cryo-compressed storage system designs for both bus and LDV examined by this project are based on analysis by ANL, the main properties of which are summarized in Table 4.

A manufacturing process flow used for both bus and light duty vehicle applications is shown in Figure 5. Capital equipment and process parameters for wet winding, beta cure, full cure, auto-frettage & burst test, and tank drying are the same as for the Type 4 baseline model. Capital costs and process parameters for the liner and containment vessel formation are taken from Ahluwalia et al [14]. The capital cost for orbital wrapping was estimated to be $1.2M vs. $200k estimated by Ahluwalia. SA spoke with several cryogenic component manufacturers and insulation suppliers who declined to discuss insulation wrapping speed or capital cost because it is considered a trade secret. A patent describing orbital wrapping for insulation and wrapping system design was used to estimate winding speeds [15], while the capital cost is an estimate. Finally, the vacuum processing step capital cost and processing parameters is similar to Ahluwalia et al, but was arrived at using online equipment prices and pump speeds (with an estimated low conductance to account for the tortuous path from the insulation). It is worth noting that vacuum pump-down time in the lab can take as long as 1 week, which could have a substantial impact on cost if similar times are required in production systems.

Table 4: Common system definition for 40 kg bus and 5.6 kg LDV CcH_2 storage systems

Design Parameter	Base Case Value	Basis/Comment
Rated Storage Pressure	500 bar	ANL modeling assumption
Burst Pressure	1,125 bar	2.25 safety factor per SAE J2579
Minimum (Empty) Pressure	5 bar	Minimum delivery pressure to fuel cell system
Storage Temperature Range	93-123 K	Refueling schedule and pump efficiency
Liner Thickness	2 mm	ANL modeling assumption
Carbon Fiber Type	T700S	ANL modeling assumption
Resin	Epoxy	ANL modeling assumption
Total Allowable Heat Leak	10 W	ANL assumption
Insulation Thickness	7 mm	K_{eff} = 5E-5 W/m-K; $\Delta Q_{insulation} \leq 3W$
Insulation Vacuum Pressure (design)	10^{-3} Torr	LLNL feedback (ANL assumes 10^{-5} Torr)
Liner Material	316L	ANL modeling assumption
Vacuum Gap	8.4 mm	1.2 x insulation thickness

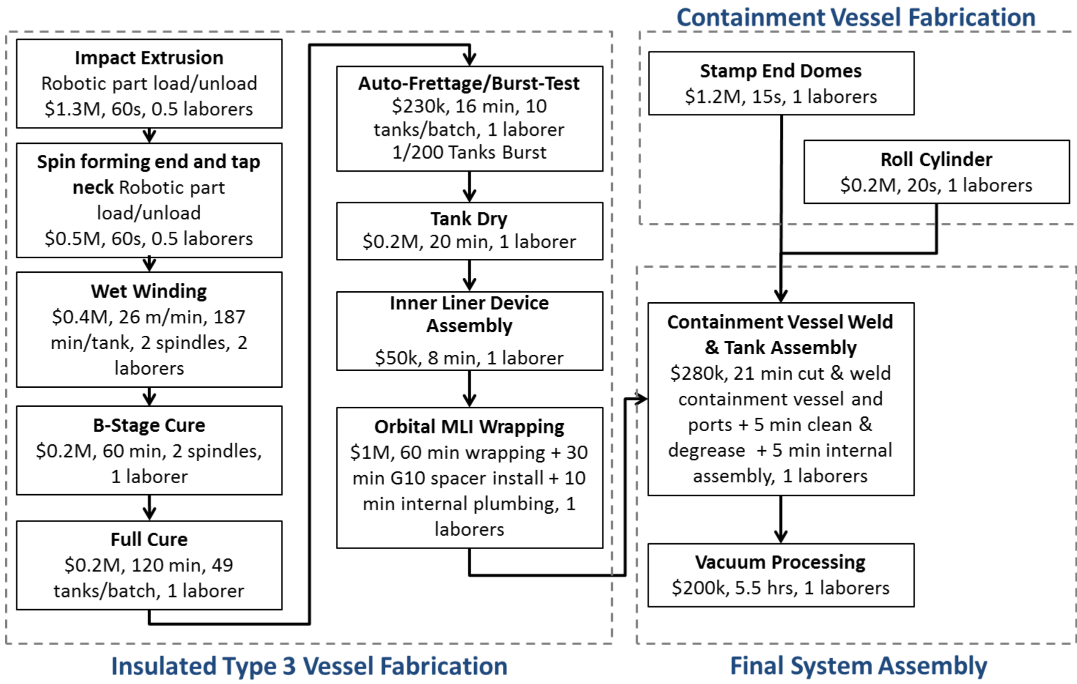


Figure 5: Cryo-compressed storage system manufacturing process flow.

Key differences between light duty vehicle (LDV) and Bus CcH_2 storage systems are summarized in Table 5. Cost was computed based on DFMA cost estimation of the manufacturing process described in Figure 5 with ranges estimated using Monte Carlo uncertainty analysis. As shown in Figure 7, BOS makes up more than 40% of the system cost for both buses and LDVs at annual production rates of 5,000 and 500,000 systems, respectively. Four components—integrated valve, integrated regulator, fittings, and external heat exchanger—contribute ~80% of the BOS cost. Initial feedback from developers suggested components for cryogenic service could cost as much as double the ambient temperature components; however, based on a low volume vendor quote for solenoid valves, using the lower projected cost for 700 bar ambient temperature solenoid valve can't be ruled out.

Table 5: Comparison of key system parameters for LDV and bus onboard CcH_2 storage systems and current range of projected system cost.

	Bus	Light-Duty Vehicle
Usable H_2	40 kg	5.6 kg
Internal Volume (per tank)	169.1 L	97.2 L
Number of Tanks	4	1
Composite Mass (per tank)	64.2	34.5
Annual Production Rates Analyzed	200-5,000	10,000-500,000
System Cost (High)	\$13.66/kWh (@5k/year)	\$16.01/kWh (@500k/year)
System Cost (Low)	\$9.75/kWh (@5k/year)	\$12.12/kWh (@500k/year)

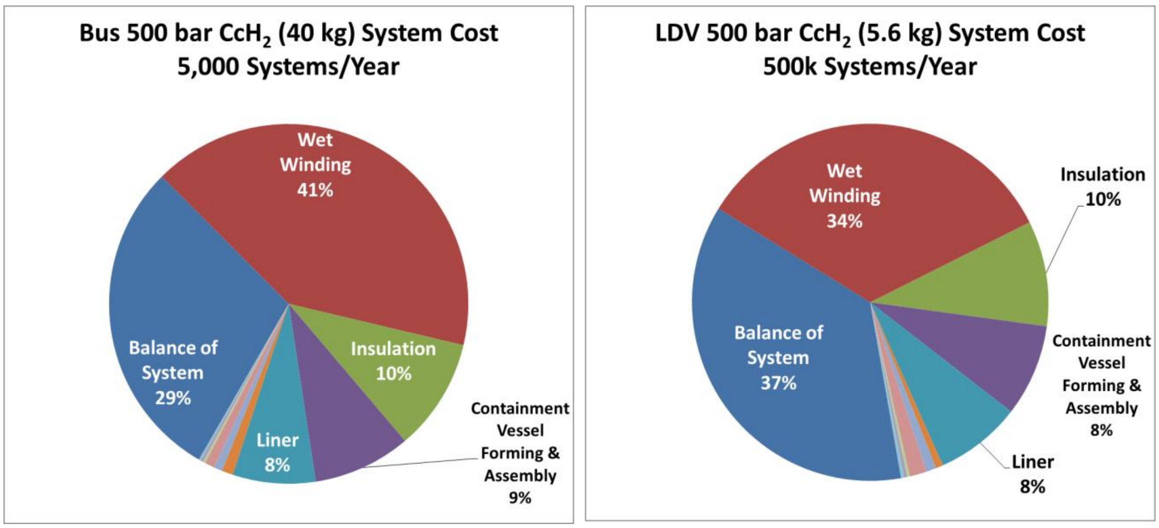


Figure 6: CcH_2 system cost breakdown for bus (left) and LDV (right)

The CcH_2 analysis is mostly complete, but would benefit from small refinements. Finally, a joint publication between Strategic Analysis and Argonne updating CcH_2 system cost and performance is in the early drafting stage.

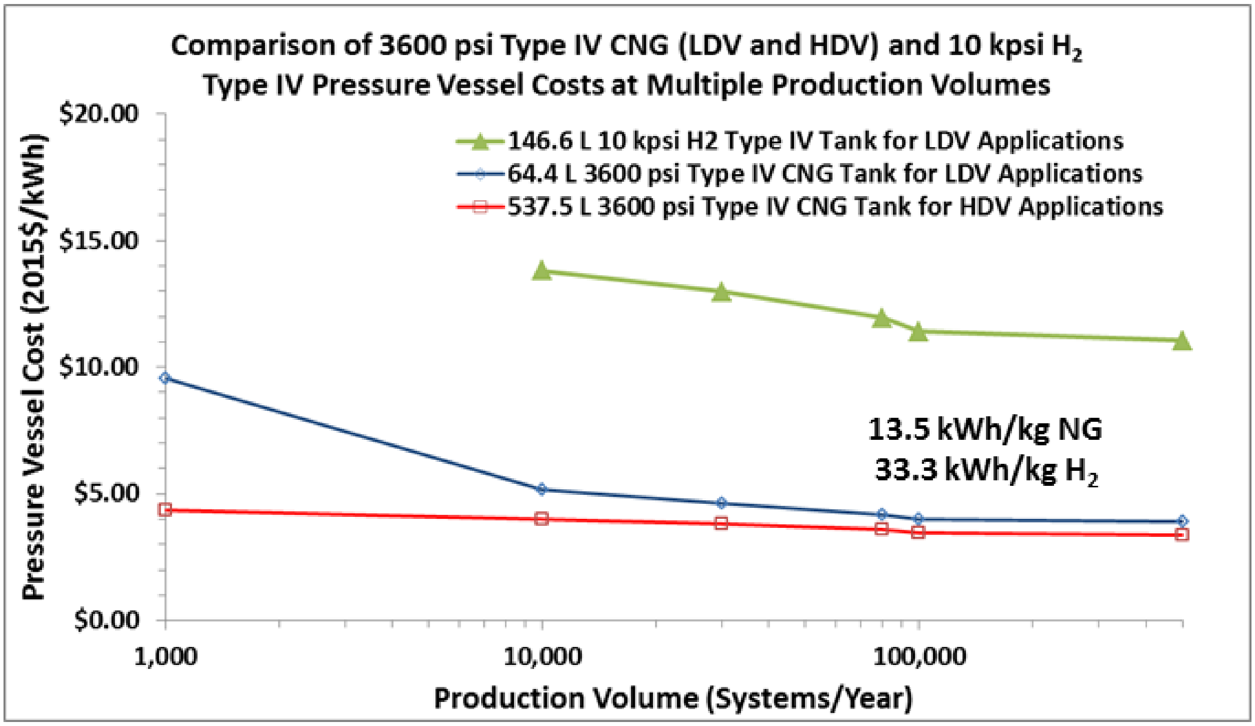
6 Type 4 CNG baseline analysis

In support of the Institute for Advanced Manufacturing Composites Innovation (IACMI), our 700 bar Type 4 hydrogen storage system model was adapted to provide a cost estimate of two commercially available compressed natural gas (CNG) pressure vessels. In consultation with DOE, two Hexagon TUFFSHELL tanks—a 64.4 L light-duty vehicle tanks and a 537.5 heavy duty tank—were selected as model systems. A summary of system parameters used in the model is provided in Table 6. The total composite mass for the CNG tanks was estimated from a derived performance factor for 700 bar tanks modeled by Argonne National Lab and calibrated to Hexagon tanks that were burst tested at Pacific Northwest National Lab [4]. The modeled tank mass (boss, liner, and composite) was within ±5% of the masses reported to us privately by Hexagon, so we are confident that our model adequately represents realistic composite mass for mass produced Hexagon tanks.

Table 6: Comparison of available TUFFSHELL system parameters and modeled hydrogen system parameters

	units	TUFFSHELL LDV[1]	CNG Model LDV	TUFFSHELL HDV[2]	CNG Model HDV	Hydrogen (ref [4])
Fill Pressure	MPa	24.8	24.8	24.8	24.8	70.0
Water Volume	L	**64.4**	**64.4**	**537.5**	**537.5**	146.6
Performance Factor	In	--	**1.04E+06**	--	**1.04E+06**	**1.04E+06**
Carbon Fiber Volume Fraction	%	--	60.0	--	60.0	60.0
Composite Mass	kg	--	**16.3**	--	**135.9**	102.0
External Diameter	cm	33	31.8	53.3	52.8	
External Length	cm	109.2	100.4	304.8	286.9	--
Boss Stem Length	cm	--	2.5	--	2.5	--
Internal Diameter	cm	--	29.6	--	49.6	39.1
Internal Length	cm	--	106.7	--	302.3	129.3
Total Mass of Fuel (@ Fill Pressure)	kg	--	10.3	--	86.1	5.76
Mass of Usable Fuel (@ Empty Pressure)	kg	--	9.5	--	79.0	5.6

CNG system costs are compared with hydrogen storage system on a volume basis ($/L water volume) and on an energy basis ($/kWh) in Figure 7. A breakdown of embodied energy is shown in Figure 8.



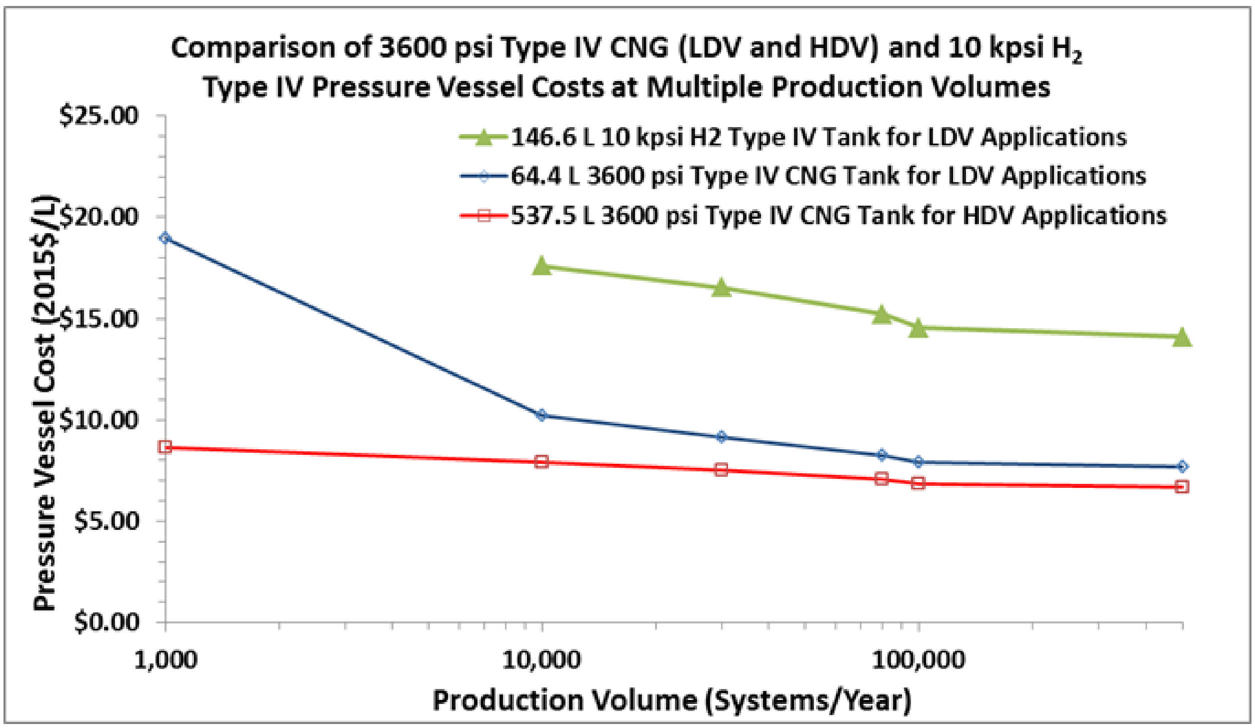
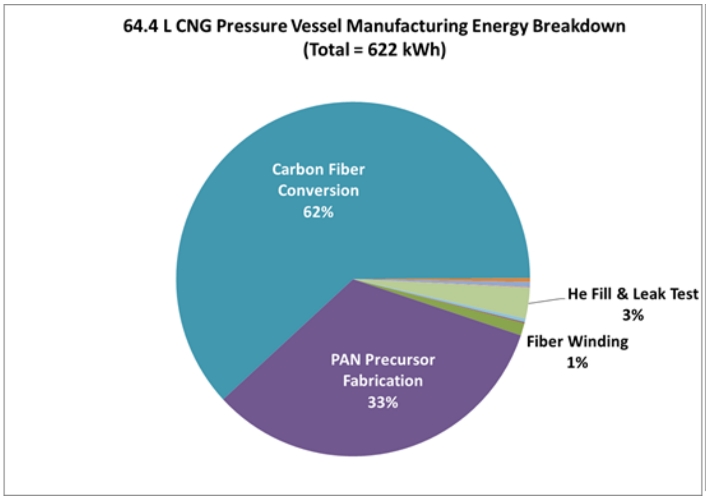


Figure 7: Comparison of CNG and hydrogen storage system cost. Top figure shows cost normalized to kWh (lower heating value). Bottom figure shows cost normalized to internal volume (L).



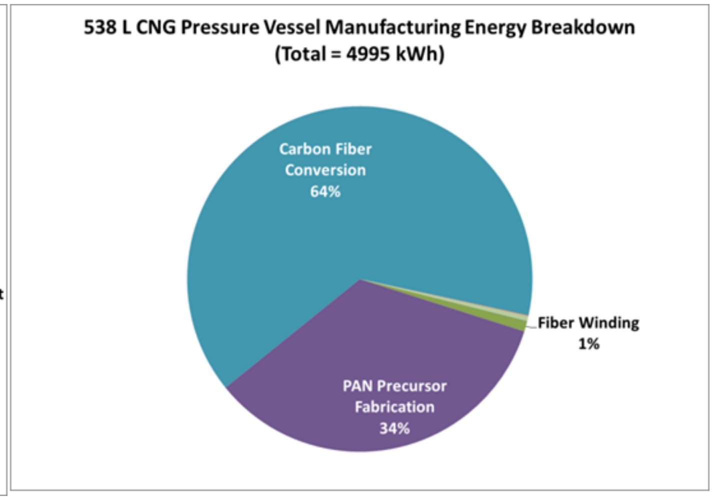


Figure 8: Breakdown of CNG storage system embodied energy.

The modeled tanks were well within ±5% Hexagon masses when accounting for the modeled components; however, there is a wide range of tank masses within the industry. The CNG composite masses tanks developed under a test program to reduce tank mass (particularly the high-cost composite). Production tanks are likely to be heavier reflecting winding patterns and engineering safety factor differences between different companies. In addition, protective fiberglass and a gel coat are typically applied but were excluded from the analysis since these are optional. Despite these potentially confounding factors, the modeled tank represents the state-of-the-art and is therefore a reasonable standard to measure programmatic progress against.

Future analyses will be conducted as directed by DOE. The next analysis will be of a thermoplastic carbon fiber tape and advanced composite placement being developed by DuPont and Steelhead Composites. Preliminary meetings were held to discuss data transfer.

7 Cold compressed H_2 Storage

Finally, a computational survey of cold- and cryo-compressed H_2 storage systems was conducted to explore the cost impact of various temperature and pressure storage combinations. This work was inspired partly by work from ANL and PNNL on cold-compressed gas storage. Composite mass can be estimated by a performance factor which relates composite mass, internal volume, and pressure

$$PF = \frac{V * P * SF}{m},$$

Where PF has units of in, volume is in in^3, pressure is in psi, m is in lbs., and the minimum allowable safety factor is 2.25. An expression for the tank liner volume was developed to compute liner material required for a given internal volume, liner thickness, aspect ratio (ratio of length to diameter), and dome eccentricity assuming a simplified cylinder with spheroid end domes shown in Figure 9 and given by

$$r = \sqrt[3]{\frac{V}{2\pi\left[AR - \frac{ar}{3}\right]}}$$

Where AR = L/D, and ar = L_{dome}/D (typically assumed to be 0.2). The liner material volume was calculated by rearranging the above expression for V and taking the difference between V(r) and V(r+t) where t is the liner thickness. Incidentally, a similar expression can be derived to compute the tank surface area for insulation from the same input parameters

$$S = 2\pi r^2\left[(1 + AR - 2e) + \frac{1-e^2}{e}\tanh^{-1} e\right]$$

The eccentricity, e, is $1\text{-}ar^2$.

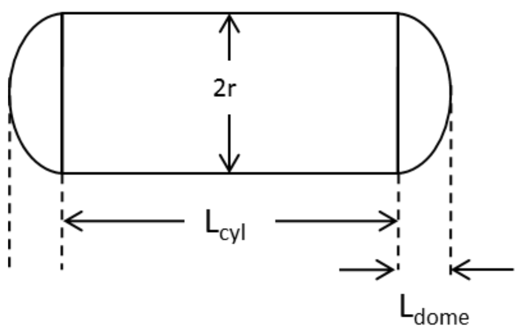


Figure 9: Schematic of simplified tank geometry.

The total tank cost is then the sum of the liner, composite, curing, where each is calculated according to the method described in Section 2 Methodology which includes materials and manufacturing at a given production rate, R. The above expressions for composite mass, wet-winding cost, liner material volume, and blow molding cost were combined with a hydrogen state function developed by Lemmon and co-workers at NIST [16] to relate the tank cost to H_2 temperature and pressure, $f_{tank\ cost}(T, P, PF, AR, ar, t, R)$, in a Python script.

The code was used to estimate the potential savings for the inner pressure vessel neglecting insulation and outer containment vessel on a range of pressures and temperatures. Figure 10 is a contour plot of

$$f(T = 300K, P = 700bar) - f(T, P)$$

based on a performance factor (PF) of 1E6 inches, an aspect ratio (AR) of 3, ratio of L_{dome} to D (ar) of 0.2, liner thickness (t) of 0.078 inches (0.2 cm), and production rate (R) at 500k per year. Below 200 K the liner type switches from polymer (HDPE) to 316L stainless steel to account for the HDPE glass transition temperature (~190 K).

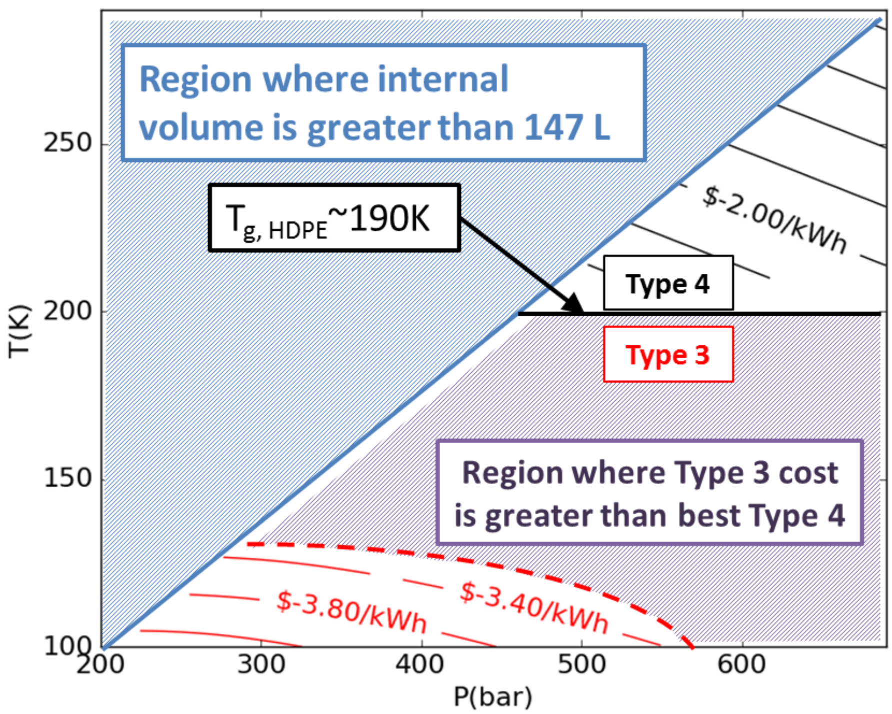


Figure 10: Potential cost savings for composite overwrapped pressure vessel with HDPE and 316L liners. Costs are reported as relative to ambient temperature 700 bar Type 4 pressure vessels. Contour lines show constant cost savings.

The analysis shown in Figure 10 shows that storage at 500 bar, 200 K has the potential to save around \$3/kWh compared to the baseline pressure vessel at 700 bar and 298 K when assessing only the inner pressure vessel cost. Insulation and an outer containment vessel are estimated to add ~\$0.50/kWh leading to an estimated potential \$2.50/kWh savings for the full pressure vessel (inner vessel plus insulation and containment shell) at 500k tanks per year. The model used to map out tank cost vs. storage temperature and pressure will be expanded to include (1) full system cost including insulation and thermal management components (e.g. in-tank heat exchangers for sorbent and metal hydride storage) and (2) delivery cost comparison with storage temperature and pressure.

8 Metal Hydride H_2 Reverse Engineering

The goal of this analysis is to extend a reverse engineering study by ANL of metal hydride thermodynamics. The ANL reverse engineering defined metal hydride thermodynamics (ΔS, ΔH) needed to achieve desirable charge and discharge the metal hydride at a set of temperatures and pressures relevant to LDV operation. The system diagram shown in Figure 11 is adapted from the ANL analysis [17]. The proposed system is based on a Type 4 pressure vessel capable of 350 bar and containing 51 kg of composite and is expected to be lower cost than the Type 4 reference tank while still meeting the reference tank volumetric capacity [4]. The dashed line defines what will be included in the storage system cost analysis, while the radiator and stack are included to show how the stack coolant is integrated into the ANL performance model. Two things are important to note. First, this is a hypothetical system. Second, even though there is much less carbon fiber predicted for the hybrid system, the composite and winding alone would contribute $7.15/kWh at 500,000 systems per year. The BOS is similar to the 700 bar $cH_{2,}$ so it is reasonable to expect it have a cost of up to $3.50/kWh, leading to a system cost >$10/kWh. Since one of the goals of the reverse engineering analysis is to identify upper bounds on metal hydride materials cost that can achieve system cost targets, additional work may be needed to identify a set of thermodynamic conditions which can reduce the design pressure of the tank.

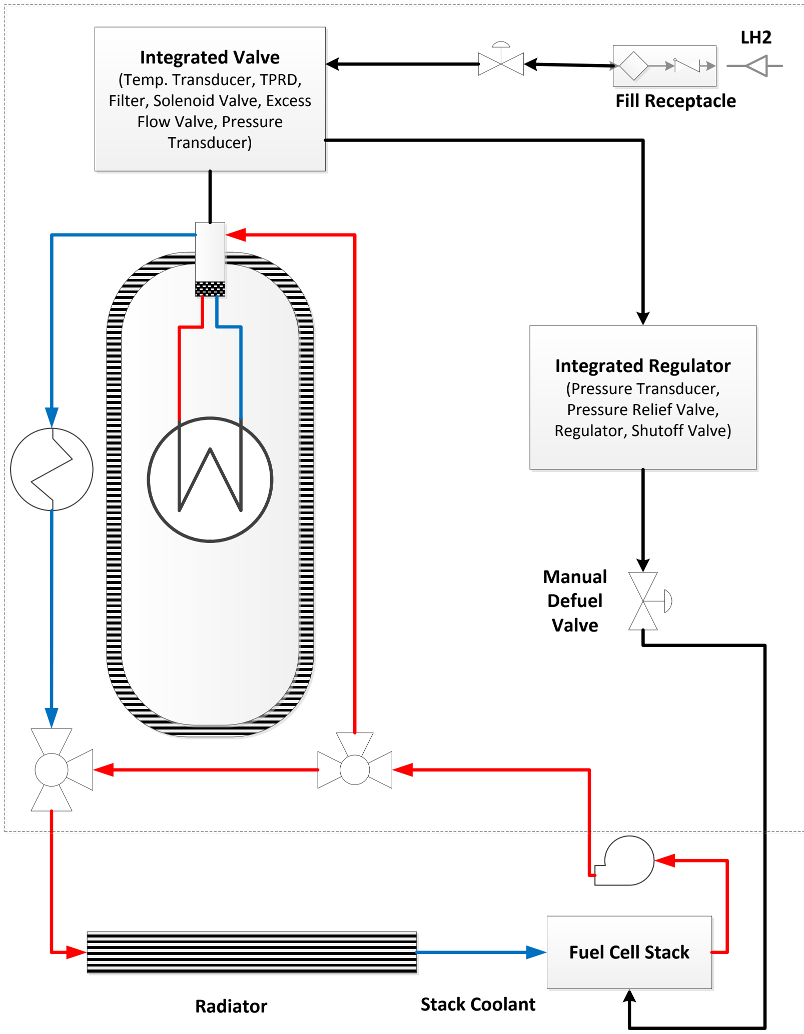


Figure 11: Proposed metal hydride system diagram.

A full system model will be developed based ANL's proposed model system to identify cost sensitivities and potential areas to reduce system cost and meet DOE targets.

9 Future Work

The analyses described in this report represent a summary of what was completed in the first year of a four year project. Pending a 'go' decision by DOE, work in FY 2018 will be continuation of the analyses described above. Highlights of anticipated FY 2018 work include

- An update to the 700 bar Type 4 DOE Record with changes to account for
  - Lower minimum tank pressure using a two-stage regulator

  - Lower assumed gas temperature (from 20°C to 15°C)
  - Lower composite mass based on analysis of reported Toyota Mirai winding pattern and boss design
  - Lower cost and weight for low-nickel alloys
- Updated peer reviewed article describing CcH_2 system cost and performance
- Updates to the sorbent system cost and design

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