U.S. Department of Energy Hydrogen Storage Cost Analysis

Final Public Report

Prepared for:
U.S. Department of Energy

Date: March 11, 2013

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TIAX Reference No. D0268

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Acknowledgments

The authors gratefully acknowledge the guidance and support of Grace Ordaz, Katie Randolph, Scott McWhorter, and Ned Stetson of the U.S. Department of Energy, the members of the Hydrogen Storage Systems Analysis Working Group, and the members of the Hydrogen Storage Technical Team.

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Executive Summary

The overall objective of this project is to conduct cost analyses and estimate costs for on- and off-board hydrogen storage technologies under development by the U.S. Department of Energy (DOE) on a consistent, independent basis. This can help guide DOE and stakeholders toward the most-promising research, development and commercialization pathways for hydrogen-fueled vehicles.

A specific focus of the project is to estimate hydrogen storage system cost in high-volume production scenarios relative to the following DOE target that was in place when this cost analysis was initiated:

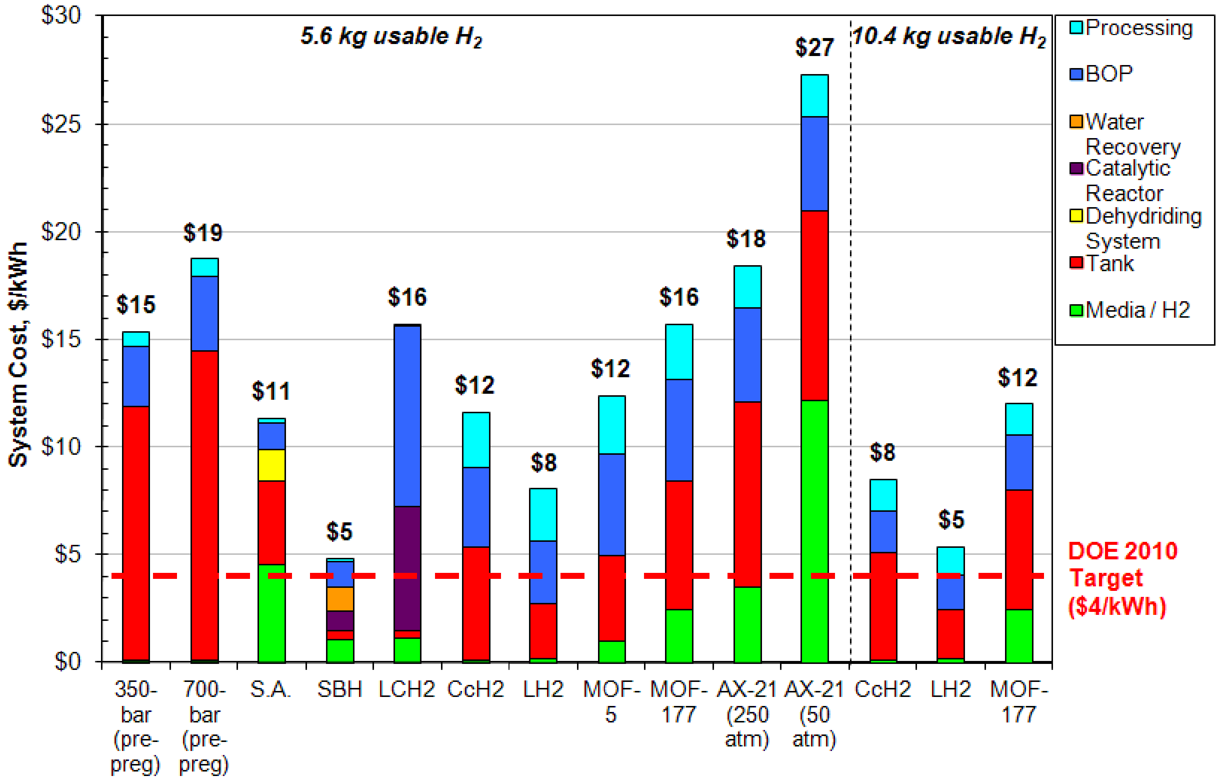
DOE Storage System Cost Target

Cost Metric	Units	2010 Target
Storage System Cost	$/kWh	4

This report and its results reflect work conducted by TIAX between 2004 and 2012, including recent refinements and updates. The report provides a system-level evaluation of costs and performance for four broad categories of on-board hydrogen storage: (1) reversible on-board metal hydrides (e.g., magnesium hydride, sodium alanate); (2) regenerable off-board chemical hydrogen storage materials(e.g., hydrolysis of sodium borohydride, ammonia borane); (3) high surface area sorbents (e.g., carbon-based materials); and 4) advanced physical storage (e.g., 700-bar compressed, cryo-compressed and liquid hydrogen). Additionally, the off-board efficiency and processing costs of several hydrogen storage systems were evaluated and reported, including: (1) liquid carrier, (2) sodium borohydride, (3) ammonia borane, and (4) magnesium hydride.

TIAX applied a “bottom-up” costing methodology customized to analyze and quantify the processes used in the manufacture of hydrogen storage systems. This methodology, used in conjunction with DFMA® software and other tools, developed costs for all major tank components, balance-of-tank, tank assembly, and system assembly. Based on this methodology, the figure below shows the projected on-board high-volume factory costs of the various analyzed hydrogen storage systems, as designed.

Reductions in the key cost drivers may bring hydrogen storage system costs closer to this DOE target. In general, tank costs are the largest component of system cost, responsible for at least 30 percent of total system cost, in all but two of the 12 systems. Purchased BOP cost also drives system cost, accounting for 10 to 50 percent of total system cost across the various storage systems. Potential improvements in these cost drivers for all storage systems may come from new manufacturing processes and higher production volumes for BOP components. In addition, advances in the production of storage media may help drive down overall costs for the sodium alanate, SBH, LCH_2, MOF, and AX-21 systems.



Note: System cost estimates assume use of pre-preg carbon fiber, except where noted for the 350- and 700-bar compressed systems. Additional assumptions, technology maturity, and uncertainty level vary by system; systems may not be directly comparable.

Summary of On-Board Hydrogen Storage System Costs

Abbreviations

AB	Ammonia Borane
AC	Activated Carbon
ANL	Argonne National Laboratory
APCI	Air Products and Chemicals, Inc.
BDC	Terephthalic acid
BOM	Bill of materials
BOP	Balance of plant
BTB	Tribenzoate
CcH2	Cryo-compressed hydrogen
CF	Carbon fiber
CH_2	Compressed hydrogen
CoEs	Centers of Excellence
DFMA®	Boothroyd-Dewhurst Design for Manufacturing & Assembly (software)
DOE	U.S. Department of Energy
FCV	Fuel cell vehicle
G&A	General & Administration
gge	Gasoline gallon equivalent
GHG	Greenhouse gas
GJ	Gigajoule
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (model)
H2A	Hydrogen Analysis (model)
HDPE	High-density polyethylene
HDSAM	Hydrogen Delivery Scenarios Analysis Model
HTF	Heat transfer fluid
HX	Heat exchanger
ICEV	Internal combustion engine vehicle
kWh	Kilowatt-hour
L/D	Length/diameter
LCH_2	Liquid hydrogen carrier
LH_2	Liquid hydrogen
LHV	Lower heating value
LLNL	Lawrence Livermore National Laboratory
μ	Mean
MLVI	Multi-layer vacuum insulation
MLVSI	Multi-layer vacuum superinsulation
MOF	Metal-organic framework
MSRP	Manufacturer's suggested retail price
$NaAlH_4$	Sodium alanate
OEM	Original equipment manufacturer
PDF	Probability distribution function
PR	Progress ratio
Pre-preg	Pre-impregnated carbon fiber
QC	Quality control
R&D	Research and development

σ	Standard deviation
SBH	Sodium borohydride
SMR	Steam methane reforming
SS	Stainless steel
SSAWG	Hydrogen Storage System Analysis Working Group
TPD	Temperature-programmed desorption
USD	United States dollar
wt	Weight
WTT	Well-to-tank
WTW	Well-to-wheels

1 Objectives

The overall objective for this project is to evaluate and analyze various on- and off-board hydrogen storage technologies on a consistent, independent basis to help guide the U.S. Department of Energy (DOE) and stakeholders toward promising research, development and commercialization pathways for hydrogen-fueled vehicles. Specific objectives include:

- Work with relevant stakeholders, including the Centers of Excellence (CoEs), Argonne National Laboratory (ANL), the Hydrogen Storage Systems Analysis Working Group (SSAWG), and the Hydrogen Storage Technical Team, to compare different on- and off-board hydrogen storage approaches in terms of lifecycle costs, energy efficiency and environmental impact;
- Identify and compare other performance factors and parameters that could impede or limit successful commercialization (e.g., on-board hydrogen storage system weight and/or volume);
- Examine the effects of system-level cost and performance trade offs for different storage approaches; and
- Estimate storage system cost at high-volume production relative to the DOE target at the time of project commencement (Table 1).

Table 1. DOE Storage System Cost Target

Cost Metric	Units	2010 Target
Storage System Cost	\$/kWh	4

This report summarizes the cost analyses performed for twelve on-board and off-board hydrogen storage systems. The results reflect work conducted by TIAX between 2004 and 2012. Where possible and as directed by DOE, we refined and updated the analyses during this period as new information became available or alternate assumptions were adopted; not all aspects of all analyses were revisited. As a result, this compilation of analysis outcomes may show small differences in inputs, assumptions, and results among the storage systems.

2 Background

DOE is funding the development of hydrogen storage technologies. By evaluating the various hydrogen storage technologies on a consistent basis, the independent analysis provided in this report will help to identify areas requiring further improvement and R&D efforts. Without a consistent and complete comparison of the various technology options, erroneous investment and commercialization decisions could be made, resulting in wasted effort and risk to the development of hydrogen and fuel cell technologies.

TIAX has conducted system-level evaluations of costs for four broad categories of on-board hydrogen storage technologies. In addition, we are working with relevant groups to evaluate the well-to-wheels (WTW) cost, primary energy use, and environmental impact of each storage system. Evaluations are based on developers' on-going research, input from DOE and key stakeholders, in-house experience, and input from material experts. Coordination with ANL through DOE's Hydrogen SSAWG continued to avoid duplication and ensure consistency. The four categories of storage are: (1) reversible on-board metal hydrides (e.g., magnesium hydride, sodium alanate); (2) regenerable off-board chemical hydrogen storage materials (e.g., hydrolysis of sodium borohydride, ammonia borane); (3) high surface area sorbents (e.g., carbon-based materials); and (4) advanced physical storage (e.g., 700-bar compressed, cryo-compressed and liquid hydrogen).

This project uses a multi-faceted approach to minimize uncertainty in cost analyses. System-level conceptual designs are developed based on input from developers and analysts (e.g., ANL, CoEs, SSAWG) and available system designs as appropriate for each on-board storage system and required fueling infrastructure. System models and cost models are used to develop preliminary performance and cost results. We use in-house activities- and product-based cost models to determine high-volume manufactured cost projections for the on-board storage system, and Hydrogen Analysis (H2A)-based discounted cash flow models [1] to estimate hydrogen selling prices based on the required off-board hydrogen infrastructure. Subsequently, these results are vetted with developers and key stakeholders and refined based on their feedback. This iterative process helps DOE and its grant recipients to better focus their efforts on the most promising technology options.

3 Cost Model Methodology and Key Assumptions

TIAX applied a proprietary, technology-costing methodology that has been customized to analyze and quantify the processes used in the manufacture of hydrogen storage tanks and balance of plant (BOP) components. The bottom-up, activities-based cost model is used in conjunction with the conventional Boothroyd-Dewhurst Design for Manufacturing & Assembly (DFMA®) software. The model was used to develop costs for all major tank components, balance-of-tank, tank assembly, and system assembly. DFMA® concurrent costing software was used to develop bottom-up costs for other BOP components. On-board bottom-up cost analysis (Figure 1) refers to the methodology of developing an estimate of a system's manufacturing cost based on:

- Technology assessment – seek developer input, conduct literature and patent review
- Cost model development – define manufacturing process unit operations; specify equipment; obtain cost of raw materials and capital equipment; define labor rates, building cost, utilities' cost, tooling cost, and cost of operating & non-operating capital with appropriate financial assumptions
  - Fixed operating costs include tooling & fixtures amortization, equipment maintenance, indirect labor, and cost of operating capital
  - Fixed non-operating costs include equipment & building depreciation, cost of non-operating capital
  - Variable costs include manufactured materials, purchased materials, direct labor (fabrication & assembly), indirect materials, and utilities
- Model refinement – seek developer and stakeholder feedback, perform single-variable sensitivity and multi-variable Monte Carlo analyses

Figure 2 shows the off-board assessment methodology, which makes use of existing models to calculate the cost and performance for each technology on a consistent basis.

TIAX contacted developers and vendors and performed a literature and patent search to explicate the component parts, specifications, material type and manufacturing process. Subsequently, we documented the bill of materials (BOM) based on ANL system performance modeling (Figure 3), determined material costs at the assumed production volume, developed process flow charts (Figures 4 and 5) and storage system schematics (Figure 6), and identified appropriate manufacturing equipment. We also performed single-variable and multi-variable (Monte Carlo) sensitivity analyses to identify the major cost drivers and the impact of material price and process assumptions on the high-volume hydrogen storage system cost results. Finally, we solicited developer and stakeholder feedback on the key performance assumptions, process parameters, and material cost assumptions; and we calibrated the cost model using this feedback. A brief discussion of the key performance, process, and cost assumptions is presented below.

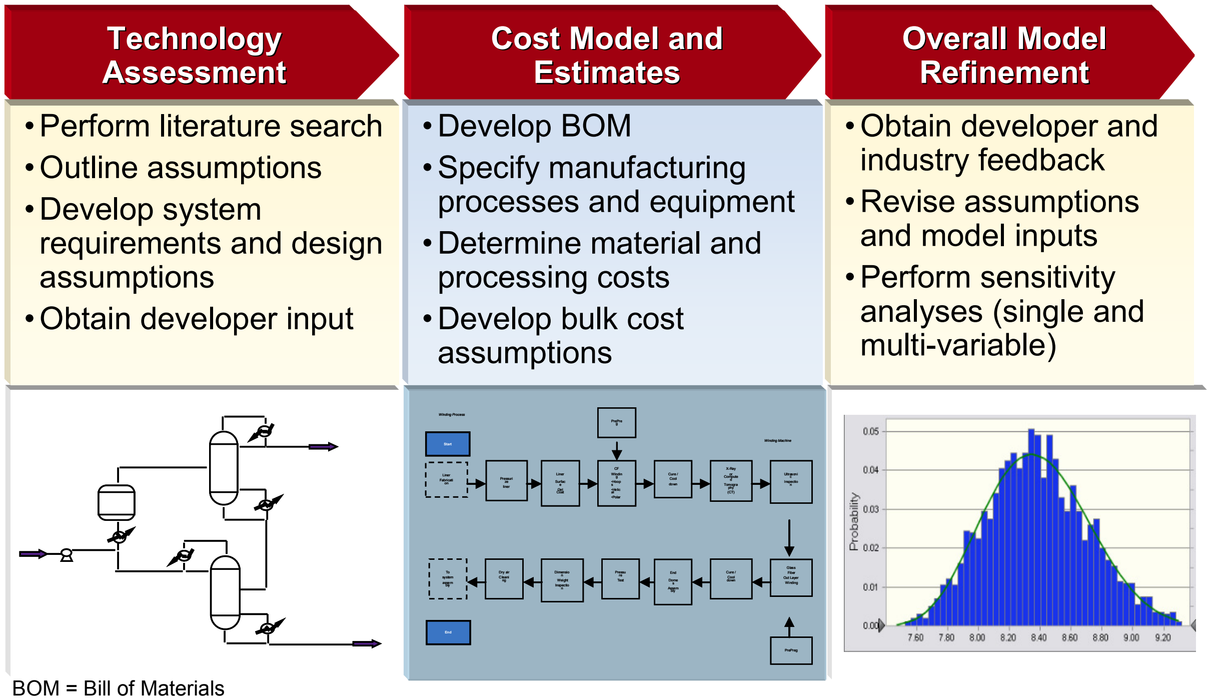


Figure 1. On-Board Bottom-Up Cost Modeling Methodology

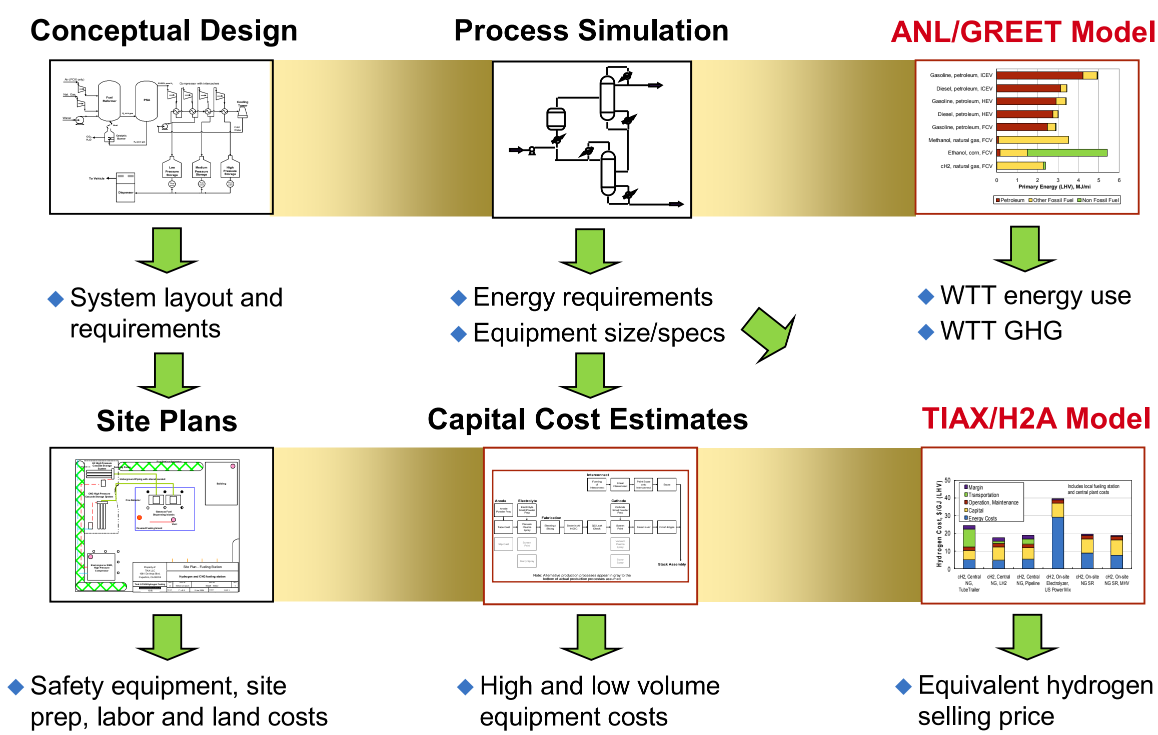


Figure 2. Off-Board Cost Modeling Methodology

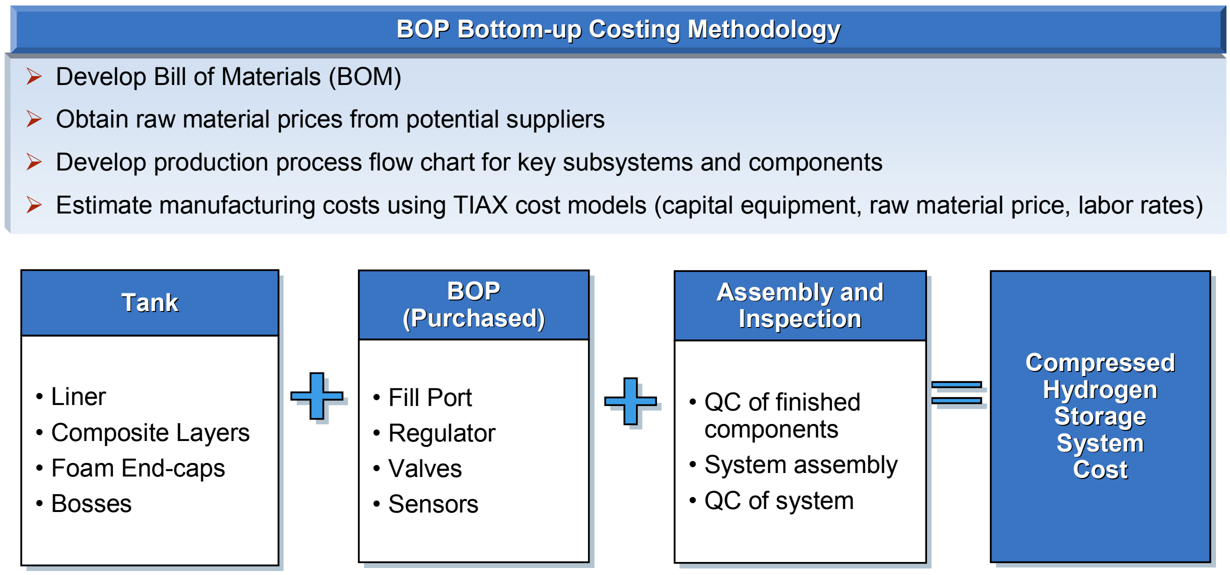


Figure 3. BOP Bottom-Up Costing Methodology

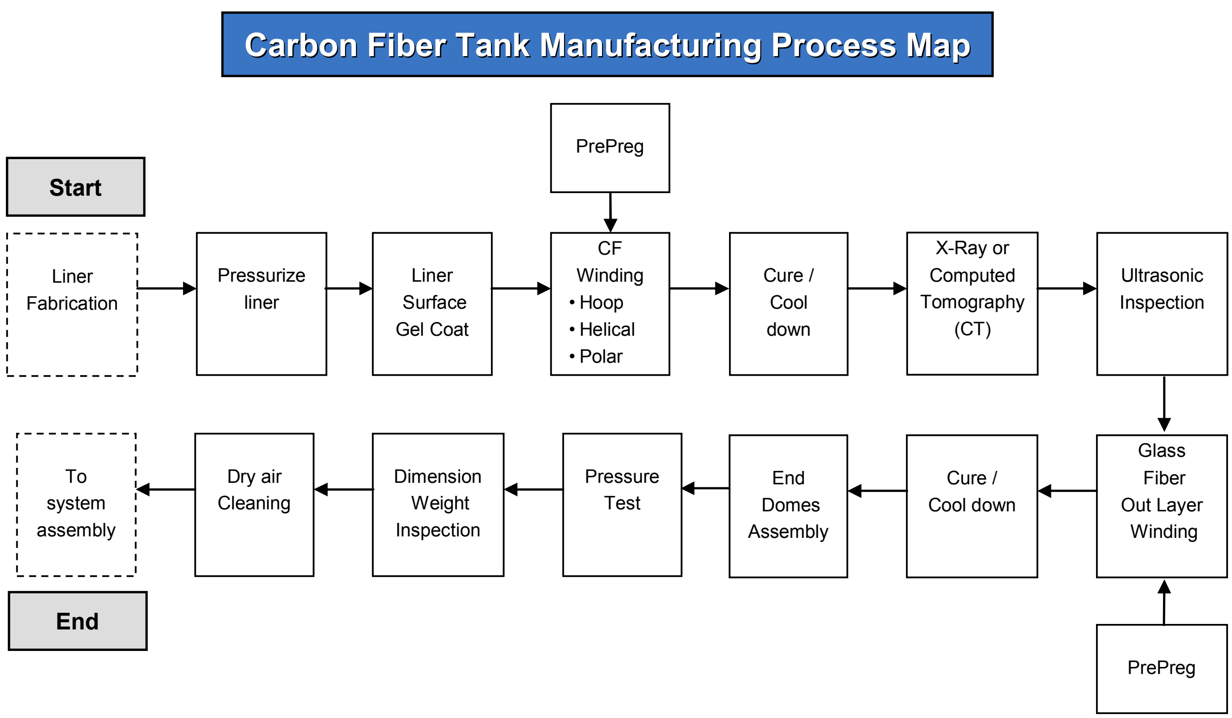


Figure 4. Carbon Fiber Tank Manufacturing Process Flow Chart

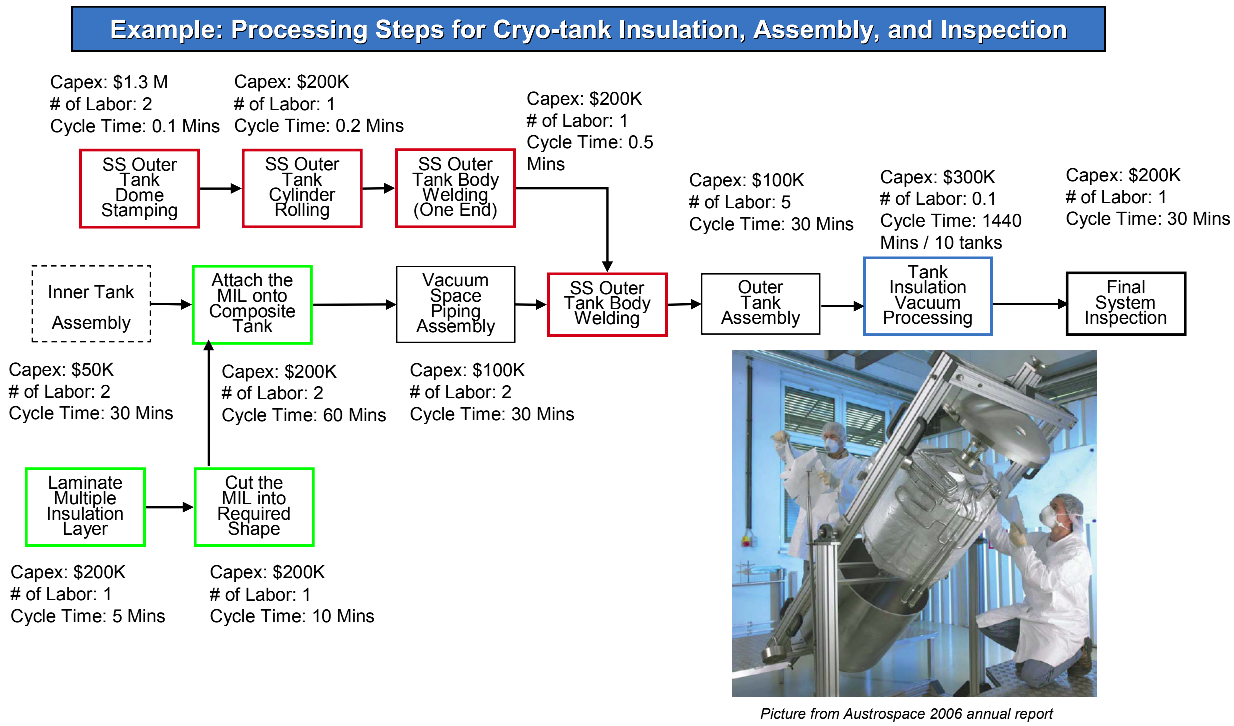
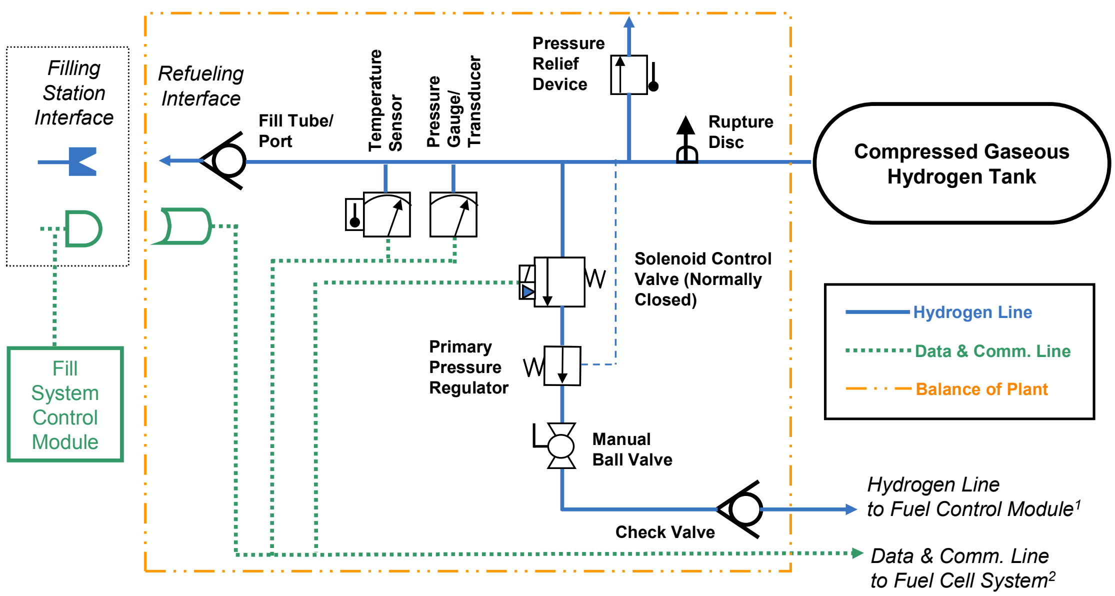


Figure 5. Detailed Processing Steps Flow Chart



[1] Schematic based on the requirements defined in the draft European regulation "Hydrogen Vehicles: On-Board Storage Systems" and US Patent 6,041,762.
[2] Secondary Pressure Regulator located in Fuel Control Module of the Fuel Cell System.

Figure 6. Compressed Hydrogen Storage System Schematic

Performance Parameters

Tank designs and key performance assumptions were developed by ANL based on storage performance data and modeling. TIAX used sensitivity analyses to capture the impact of variation in key performance assumptions, such as tank safety factor, composite tensile strength, and translation efficiency.

Carbon Fiber Price

The cost of carbon fiber (CF) is a major driver in the manufacturing costs and commercial pricing of high-pressure hydrogen storage systems. To maintain a common basis of comparison with previous cost analyses, TIAX chose a base case carbon fiber price of $13/lb ($29/kg) based on discussions with Toray in 2007 regarding the price of T700S fiber at high volumes. Carbon fiber is already mass produced at high volume for the aerospace and other industries, so it is not expected to become significantly less expensive in the near term. However, there are DOE programs that are assessing ways to significantly reduce carbon fiber costs [2]. We used sensitivity analyses to capture the impact of the uncertainty in carbon fiber prices, using $10/lb at the low end and $16/lb at the high end.

We assumed the hydrogen storage system manufacturer purchases pre-impregnated ("pre-preg") carbon fiber composite at a price that is 1.27 (pre-preg/fiber ratio) times the raw carbon fiber material [3]. The use of the pre-preg material corresponds to a dry resin winding process. An alternative approach would be to assume a wet resin winding process that would allow the purchase of raw carbon fiber material and resin separately, instead of buying pre-preg tow fiber, where the fiber and resin are already combined. For all systems, we chose a pre-preg winding process based on the assumption that this process results in greater product throughput and reduced environmental pollutants and/or hazards (e.g., volatile organic compounds, ozone depleting chemicals, and greenhouse gases [GHGs]) compared to a wet winding process. According to Du Vall [3], greater throughput is typically achieved because pre-preg tow allows for more precise control of resin content, yielding less variability in the cured part mechanical properties and ensuring a more consistent, repeatable, and controllable material compared to wet winding. In addition, wet winding delivery speeds are limited due to the time required to achieve good fiber/resin wet out. The downside of the pre-preg material is that raw material costs may be higher than for wet winding.

It might be possible to reduce the overall manufactured cost of the CF composite layer of the tank − perhaps closer to the cost per pound of the CF itself ($13/lb), or even lower (since the resin is less expensive per pound) − if the wet winding process is proven to be more effective. In particular, increasing wet winding throughputs could lower costs. However, the detailed evaluation that is required to explore these cost trade-offs is beyond the scope of work of this project. Instead, we address the potential for significantly lower CF composite costs in the sensitivity analysis at 500,000 units per year (Section 4.1.2).

BOP Cost Projections

BOP costs were estimated using the Delphi method with validation from top-down and bottom-up estimates described below.

- Delphi method: projections solicited from industry experts, including suppliers, tank developers, and end users. The issue of automotive-scale production is being considered by end users (e.g., automotive original equipment manufacturers [OEMs]) and, to some extent, tank developers. End-user or developer estimates are optimistic or based on reasonable targets in some cases and pessimistic in other cases by not taking into account the process or technology changes required for automotive-scale production. A reasonable base case cost for each component is selected by using our judgment of the projections and results from the top-down and bottom-up estimations.
- Top-down: high-volume discounts applied to low-volume vendor quotes using progress ratios (PRs)
  - Provides a consistent way to discount low-volume quotes
  - Attempts to take into account process or technology developments that would be required for automotive-scale production
  - Requires an understanding of base costs, production volumes, and markups
- Bottom-up: cost modeling using DFMA® software
  - Calculates component costs using material, machining, and assembly costs, plus an assumed 15 percent markup for component supplier overhead and profit
  - May not be done at the level of detail necessary for estimating the true high-volume cost of the component

Vertically Integrated Process vs. Outsourcing of Tank Components

In reporting the "Factory Cost" or "Manufactured Cost" of the hydrogen storage system, we have assumed a vertically integrated tank manufacturing process; i.e., the automotive OEM or car company makes all the tank components in-house, so that intermediate supply chain markups are not included for individual tank components. The major tank costs (liner, CF layer, and tank assembly) are bottom-up estimated, and reported with no added supplier markup. In reality, the manufacturing process would be a combination of horizontally and vertically integrated, with variable markups.

Markup of BOP Components

In our model, some major BOP costs (e.g., fill tube/port, pressure regulator, and pressure relief valve) are also bottom-up estimated (similar to the major tank costs). Since we assume that the automotive OEM buys all the BOP components/subsystems from suppliers, and assembles the overall system in-house, we assume a uniform supplier-to-automotive OEM markup of 15 percent for all major BOP components. Raw materials and some BOP hardware are purchased and implicitly include a supplier markup that is not quantified but assumed to include:

- Profit
- Sales (transportation) and marketing
- Research and development (R&D)

- General and administration (G&A) (human resources, accounting, purchasing, legal, and contracting), retirement, health
- Warranty
- Taxes

Based on discussions with industry, automotive Tier 1 suppliers would most likely not have any sales and/or marketing expenses since they often obtain guaranteed five-year supply contracts with OEMs. Also, the warranty and R&D costs are increasingly being shared by the supplier and the OEM. Previously, OEMs covered warranty costs themselves; now suppliers support their own warranties. Furthermore, OEMs share in some R&D costs. The OEMs usually negotiate five percent per year cost reduction for five years with the supplier, further squeezing the supplier's margin. Therefore, profit margins for Tier 1 suppliers are typically only in the single-digits (perhaps five to eight percent), and a supplier that can negotiate 15 percent markup is doing very well. We address these markup uncertainties and other BOP component cost uncertainties in the sensitivity analyses.[1]

Tank QC and System QC

At a high-production volume of 500,000 units per year, we have assumed that the hydrogen storage system production process is mature and that all quality issues are "learned out". We have included rudimentary tank and system Quality Control (QC) such as leak tests and visual and ultrasonic inspections.

Process Yield, Material Scrap and Reject Rate

Based on experience from similar manufacturing processes at high volumes, the cost models include assumptions about Process Yield (i.e., the percentage of acceptable parts out of the total parts that are produced); Material Scrap Rate (i.e., the recyclable left-over material out of the total materials used in the process); and Reject Rate (i.e., the percentage of unacceptable parts out of the total parts produced). An appropriate material scrap credit is applied to the left-over material; however, the material recycling process is not included within the bounds of our analysis. We address uncertainties in these assumptions in the sensitivity analyses.

Other Technical Issues

One goal of this assessment is to identify the major cost contributions to the overall hydrogen storage system cost. Within the scope for a project of this type, the system chosen for assessment is not intended to address all technical issues facing developers today. For example, the added vehicle controls required to operate the storage system and hydrogen leak detection sensors are not included. These BOP components are not expected to make a significant contribution now; however, if the cost of the tank and major BOP components decrease, the balance of system may represent a larger share of the system cost in the future.

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[1] The supplier markup does not include the markup for the hydrogen storage system manufacturer (e.g., automotive OEM) that sells the final assembled system.

A summary of key general assumptions for the analyses presented in this report is shown in Table 2.

Table 2. Summary of General Analysis Assumptions

Included in Analysis	
BOP cost methodology	Projected based on Delphi method (projections solicited from industry experts, including suppliers, tank developers, and end users)
Top-down cost analysis	High-volume discounts applied to low-volume vendor quotes using progress ratios
Base case BOP costs	Identified for each component using TIAX's judgment of projections and results from top-down and bottom-up estimations
BOP markup	A uniform supplier-to-automotive OEM markup of 15 percent assumed for all major BOP components
Tank and system quality control (QC)	Rudimentary tank and system QC (e.g., leak tests and visual and ultrasonic inspections) assumed to be included in tank costs
Process yield	Specific yield assumed for each process step in cost model
Material scrap rate	Specific rate assumed for each process step in cost model
Reject rate	Specific rate assumed for each process step in cost model
Cost basis	All costs given in 2005 U.S. dollars (USD)
DOE hydrogen storage system cost target	All references refer to the $4 per kWh target in place at analysis initiation
Not Included in Analysis	
Intermediate supplier markup	Excluded from analysis for individual tank components (assume that automotive OEM or car company makes all tank components, e.g., liner, CF layer, and tank assembly, in-house)
Vehicle controls	Excluded from analysis (assume part of vehicle, not storage, system)
Hydrogen leak detection sensors	Excluded from analysis (assume part of vehicle, not storage, system)

4 Results

Note: The "DOE 2010 target" referenced in the following results is the storage system cost target in place when this analysis was initiated. The date of completion for each analysis is listed for each section. As described in the previous section, all storage systems assume the use of pre-preg carbon fiber.

4.1 On-Board Analysis

4.1.1 Compressed Hydrogen Storage (December 23, 2011)

The cost of compressed hydrogen storage was assessed and compared to the DOE 2010 target for automotive applications. Using high-volume manufacturing assumptions (500,000 units per year), costs were determined for on-board tanks capable of storing 5.6 kg of usable hydrogen at design pressures of 350 bar (approximately 5,000 psi) and 700 bar (approximately 10,000 psi). The off-board and cost of delivering compressed hydrogen was determined for hydrogen produced by central steam methane reforming (SMR). The compressed tank schematic is shown in Figure 7. As shown, the compressed hydrogen storage tank consists of an inner liner, around which a carbon fiber layer is wound, a protective glass fiber layer, and protective foam endcaps. The system schematic (Figure 8) and bill of materials for compressed systems were generated through discussions with ANL and tank developers. The design assumptions for the on-board compressed hydrogen storage system are presented in Table 3, with the cost projections for major BOP components and raw materials shown in Tables 13 and 14.

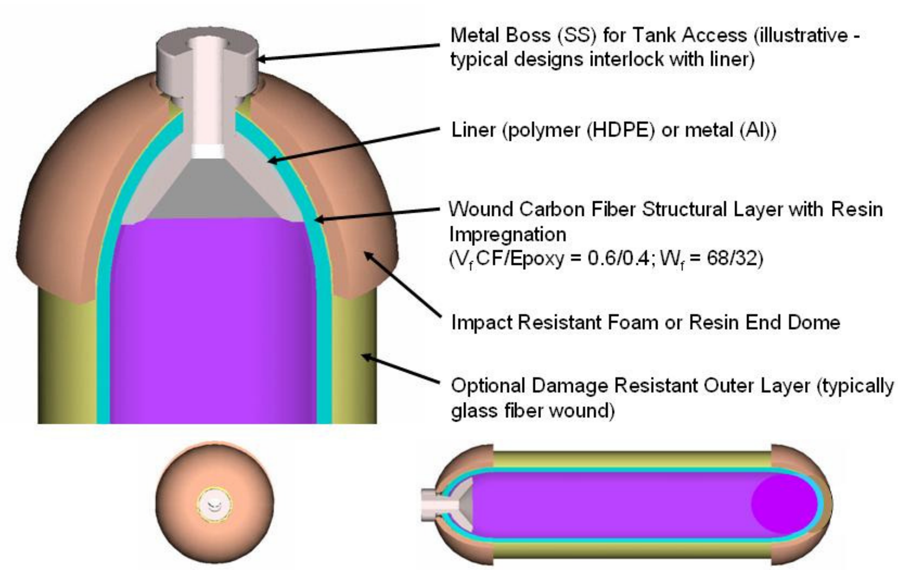
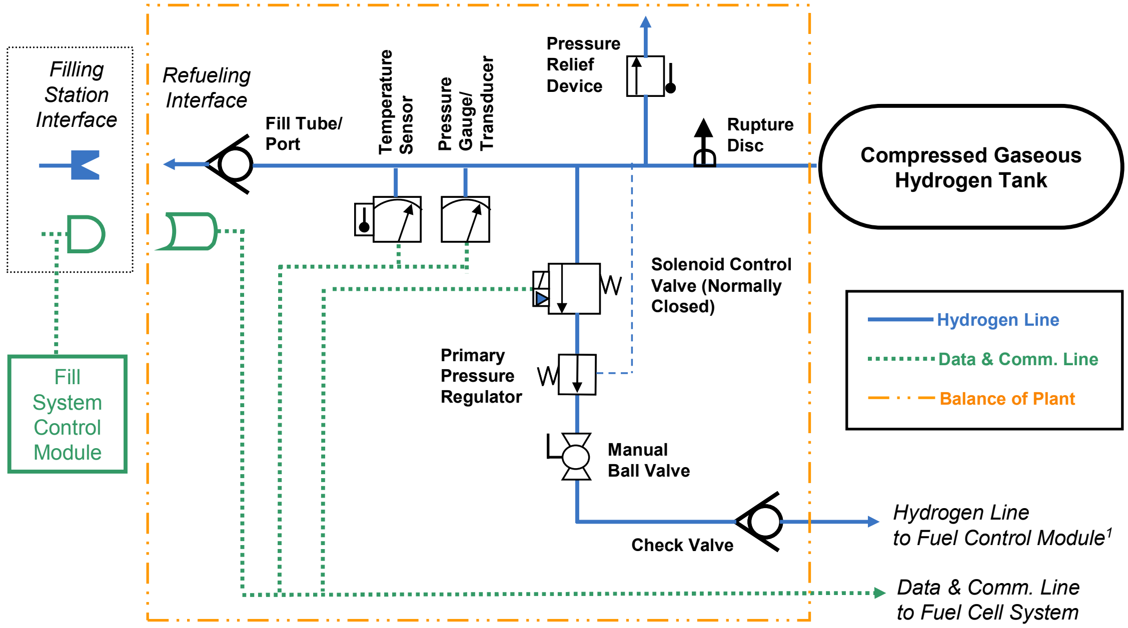


Figure 7. Compressed Hydrogen Storage Tank Schematic



[1] Schematic based on the requirements defined in the draft European regulation "Hydrogen Vehicles: On-board Storage Systems" and US Patent 6,041,762.
[2] Secondary Pressure Regulator located in Fuel Control Module of the Fuel Cell System.

Figure 8. Compressed Hydrogen Storage System Schematic

Table 3. Compressed Hydrogen Storage System Design and Other Assumptions

Design Parameter	Base Case Value	Basis/Comment
Nominal pressure	350 and 700 bar	Design assumptions based on DOE and industry input
Number of tanks	Single and dual	Design assumptions based on DOE and industry input
Tank liner	Type III (Aluminum) Type IV (HDPE)	Design assumptions based on DOE and industry input
Maximum/ Filling Pressure	350-bar: 438 bar 700-bar: 875 bar	125% of nominal design pressure is assumed required for fast fills to prevent under-filling
"Empty" Pressure	20 bar	Discussions with Quantum, 2008
Usable H_2 storage capacity	5.6 kg	Design assumption based on drive-cycle modeling for 350 mile range assuming a mid-sized, hydrogen FCV
CF Weight	Type III, 1 tank, 350 bar: 48.6 kg Type III, 1 tank, 700 bar: 65.0 kg Type III, 2 tank, 350 bar: 24.4 kg Type III, 2 tank, 700 bar: 28.3 kg Type IV, 1 tank, 350 bar: 55.4 kg Type IV, 1 tank, 700 bar: 68.7 kg Type IV, 2 tank, 350 bar: 28.0 kg Type IV, 2 tank, 700 bar: 34.8 kg	Design assumptions from ANL
Tank size (water capacity)	350-bar: 258 L 700-bar: 149 L	Calculated based on Benedict-Webb-Rubin equation of state for 5.6 kg usable H_2 capacity and 20 bar "empty pressure" (6.0 and 5.8 kg total H_2 capacity for 350-bar and 700-bar tanks, respectively)
Safety factor	2.25	Industry standard criteria (e.g., ISO/TS 15869) applied to nominal storage pressure (i.e., 350 bar and 700 bar)
Length/Diameter Ratio	3.0	Discussions with Quantum, 2008; based on the outside of the CF wrapped tank
Carbon Fiber (CF) Type	Toray T700S	Discussions with Quantum and other developers, 2008
CF Composite Tensile Strength	2,550 MPa	Toray material data sheet for 60% fiber by volume
Adjustment for CF Quality	10%	Reduction in average tensile strength to account for variance in CF quality, based on discussion with Quantum and other developers, 2010
CF Translation Efficiency	350-bar: 82.5% 700-bar: 80.0%	Assumption based on data and discussions with Quantum, 2004-09
Tank Liner Thickness	7.4 mm Al (Type III) 5 mm HDPE (Type IV)	Discussions with Quantum, 2008; typical for Type III and Type IV tanks
Overwrap	1 mm glass fiber	Discussions with Quantum, 2008; common but not functionally required
Protective End Caps	10 mm foam	Discussions with Quantum, 2008; for impact protection

Table 4. Compressed Hydrogen Storage System Cost Projections for Major BOP Components

Purchased Component Cost Est. ($ per unit)	350-bar Base Case	700-bar Base Case	Comments/Basis
Pressure regulator	$160	$200	Industry feedback validated with discussion with Emerson Process Management/Tescom/Northeast Engineering (2009) and DFMA® cost modeling software
Solenoid Control valves (3)	$186	$233	Industry feedback validated with quotes and discussion with Pearse-Bertram for Circle Seal solenoid control valve (2009)
Fill tube/port	$50	$63	Industry feedback; quick connect capable of high pressures without leaks and accepting signals from the nozzle at the fueling station to open or close
Pressure transducer	$30	$38	Industry feedback validated with quotes and discussion with Taber Industries (2009)
Pressure gauge	$17	$17	Based on quotes from Emerson Process Management/ Tescom/ Northeast Engineering (2009)
Boss and plug (in tank)	$15	$19	Based on price estimate from tank developers (2009), validated with Al raw material price marked up for processing
Other BOP	$58	$68	Includes manual service vent valves (2), check valves (2), rupture disks (2), pipe assembly, bracket assembly, pressure relief devices (2), and gas temperature sensor.

Table 5. Compressed Hydrogen Storage System Raw Material Cost Assumptions

Raw Material Cost Estimates, 2005$/kg	Base Cases	Comment/Basis
Hydrogen	3.0	Consistent with DOE H_2 delivery target
HDPE liner	1.6	Plastics Technology (2008), deflated to 2005$
Aluminum (6061-T6)	9.6	Bulk price from Alcoa (2009), deflated to 2005$
Carbon fiber (T700S) prepreg	36.6	Discussion w/ Toray (2007) re: T700S fiber ($10-$16/lb, $13/lb base case in 2005$); 1.27 prepreg/fiber ratio (Du Vall 2001)
Glass fiber prepreg	4.7	Discussions with AGY (2007) for non-structural fiber glass, deflated to 2005$
Foam end caps	6.4	Plastics Technology (2008), deflated to 2005$
Stainless steel (304)	4.7	Average monthly costs from Sep '06 – Aug '07 (MEPS International 2007) deflated to 2005$s by ~6%/yr
Standard steel	1.0	Estimate based on monthly cost range for 2008-2009 (MEPS International 2009), , deflated to 2005$

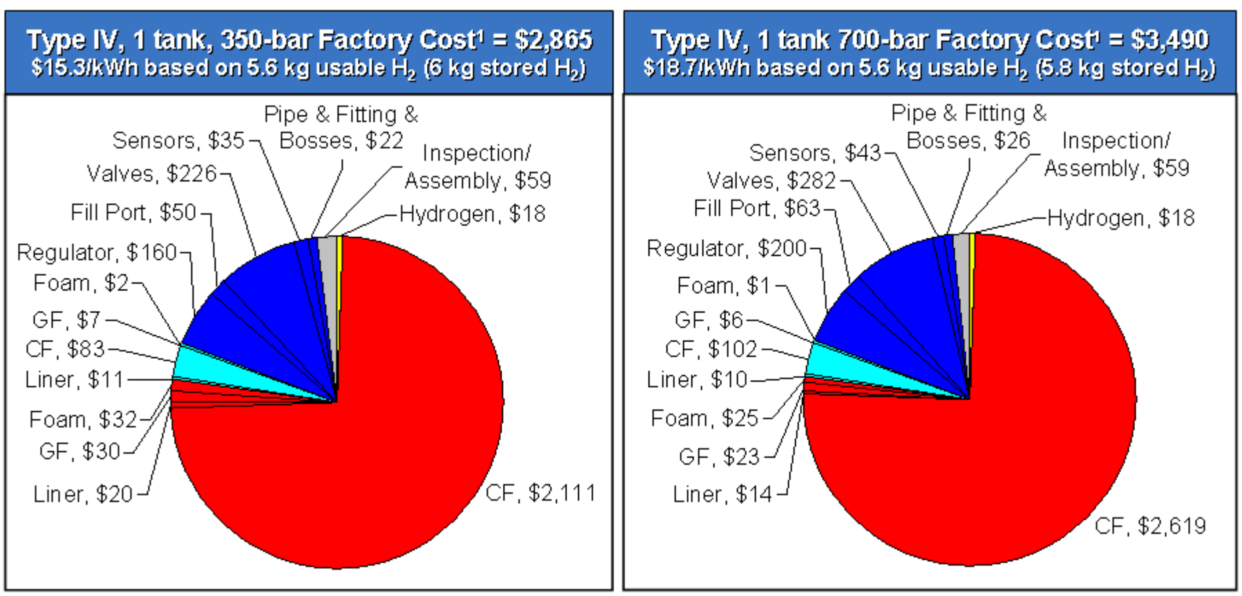
TIAX evaluated the costs of compressed 350- and 700-bar onboard storage systems using Type III and Type IV pressure vessels with both single and dual-tank configurations. Our cost assessment projects that the single tank, Type IV 350- and 700-bar on-board storage systems will cost $15/kWh and $19/kWh, respectively. Dual tank systems are projected to cost on the order of $1/kWh more than single tank systems, while Type III tanks are projected to cost $1 to $2/kWh more than 350-bar and 700-bar Type IV tanks, respectively. The results presented below focus on TIAX's analysis of Type IV (single and dual tank systems) and Type III (single tank systems).

As seen in Figure 9, the main cost contributor to both the 350- and 700-bar single tank Type IV systems is the CF layer, which accounts for 77 and 78 percent of the 350- and 700-bar total system costs, respectively. The figure shows material costs in red and processing costs in light blue.

Dual tank systems cost about $70-80 more than single tank systems due to a relatively small (less than five percent) increase in material costs, and a 20-25 percent increase in the tank processing cost. Like the single tank systems, the main cost contributor for the 350- and 700-bar dual tank Type IV systems is the CF layer; it accounts for 76 and 77 percent of the 350- and 700-bar total system costs, respectively (Figure 10). The figure shows material costs in red and processing costs in light blue.

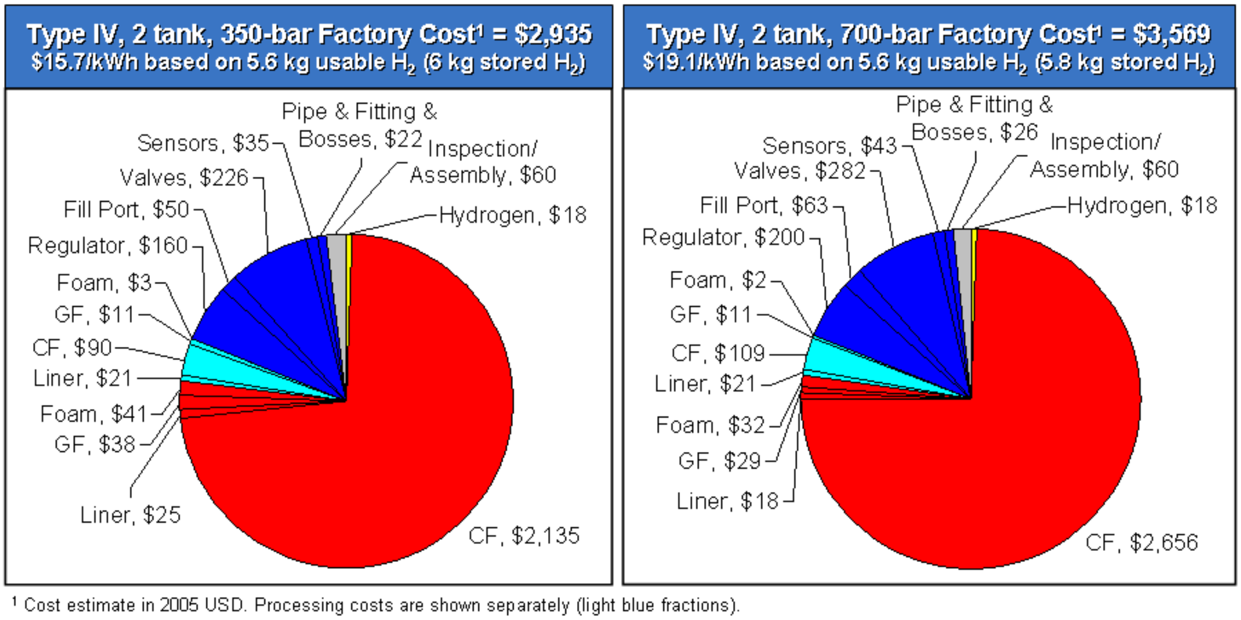
As seen in Figure 11, the carbon fiber composite layer accounts for a smaller fraction of the Type III system cost compared to the Type IV system, but the Type III aluminum liner adds significant additional expense. Compared to Type IV single tank systems, the increase in cost of the aluminum liner is $500 to $550. Once again, the main cost contributor to both the 350- and 700-bar single tank Type III systems is the CF layer, which accounts for 62 and 66 percent of the 350- and 700-bar total system costs, respectively. The figure shows material costs in red and processing costs in light blue.

The Type III dual tank systems cost about $38 to $44 more than single tank systems due to increases in the cost of the pressure vessel. As seen in Figure 12, the main cost contributor to both the 350- and 700-bar dual tank Type III systems is again the CF layer, which accounts for 62 to 65 percent of the 350- and 700-bar total system costs, respectively. The figure shows material costs in red and processing costs in light blue.



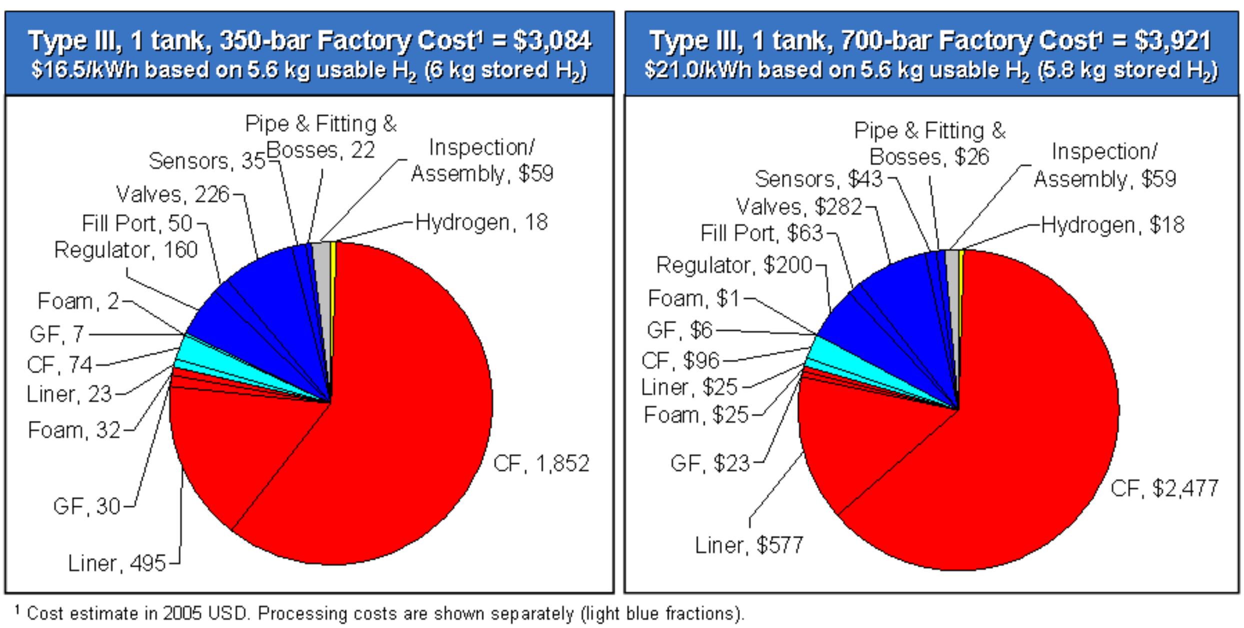
[1] Cost estimate in 2005 USD. Processing costs are shown separately (light blue fractions).

Figure 9. Base Case Component Cost Breakout for the Type IV Single Tank Compressed Hydrogen Storage Systems (with Pre-Preg CF)



[1] Cost estimate in 2005 USD. Processing costs are shown separately (light blue fractions).

Figure 10. Base Case Component Cost Breakout for the Type IV Dual Tank Compressed Hydrogen Storage Systems (with Pre-Preg CF)



[1] Cost estimate in 2005 USD. Processing costs are shown separately (light blue fractions).

Figure 11. Base Case Component Cost Breakout for the Type III Single Tank Compressed Hydrogen Storage Systems (with Pre-Preg CF)

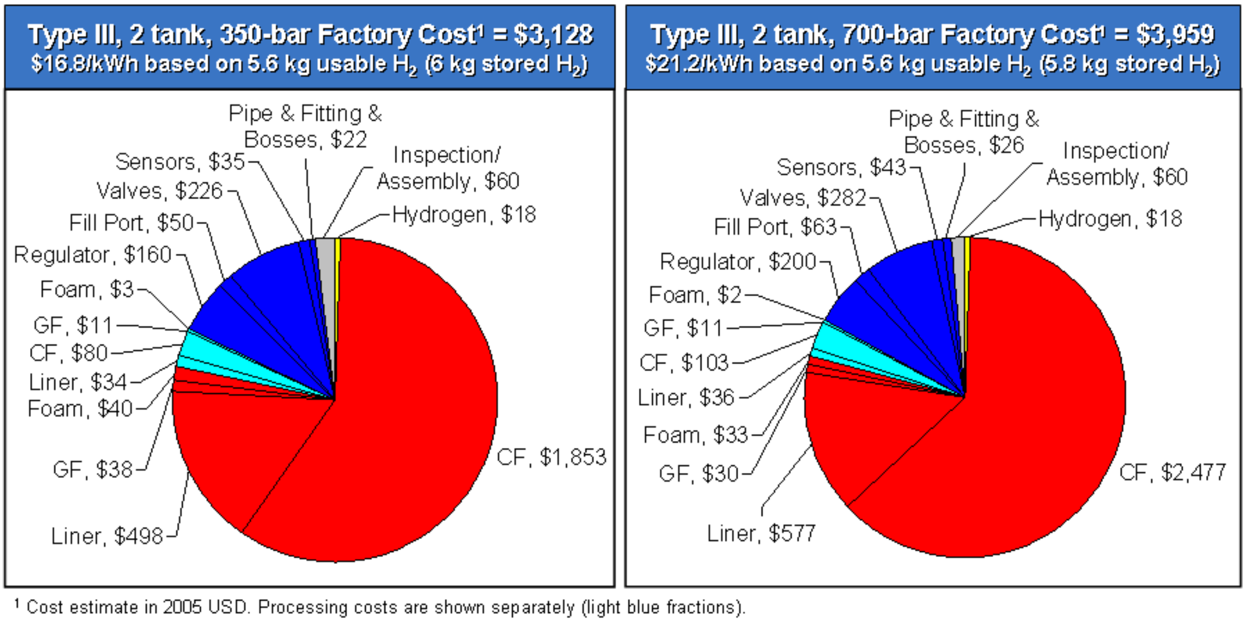


Figure 12. Base Case Component Cost Breakout for the Type III Dual Tank Compressed Hydrogen Storage Systems (with Pre-Preg CF)

As shown in Tables 15 through 18, processing costs make up just five to six percent of total system costs due to the assumed high-production volumes and number of purchased components. These processing cost fractions are low compared to industry costs to manufacture similar tank systems at low volumes. Manufacturing a compressed gas tank today using relatively low-volume (fewer than 500,000 units per year) production techniques requires more complex and labor-intensive processes to create the carbon fiber composite overwrap than high-volume production. There is uncertainty and disagreement among different developers and automotive OEMs about the level of automation that can be achieved in the future, but we have assumed that cost savings could occur with economies of scale for both tank and BOP component manufacturing, once high production volumes are achieved over a sustained period of time.

Table 6. Base Case Material vs. Processing Cost Breakout for Type IV Single Tank Compressed Hydrogen Storage Systems (with Pre-Preg CF)

On-board System Cost Breakout – Compressed Gas	Type IV, 1 tank, 350-bar Base Case				Type IV, 1 tank, 700-bar Base Case			
	Material, $	Material Fraction	Processing, $	Processing Fraction	Material, $	Material Fraction	Processing, $	Processing Fraction
Hydrogen	$18	100%	(purchased)	-	$18	100%	(purchased)	-
Compressed Vessel	$2,193	96%	$102	4%	$2,681	96%	$119	4%
Liner & Fittings	$20	66%	$11	34%	$14	57%	$10	43%
Carbon Fiber Layer	$2,111	96%	$83	4%	$2,619	96%	$102	4%
Glass Fiber Layer	$30	82%	$7	18%	$23	79%	$6	21%
Foam	$32	95%	$2	5%	$25	95%	$1	5%
Regulator	$160	100%	(purchased)	-	$200	100%	(purchased)	-
Valves	$226	100%	(purchased)	-	$282	100%	(purchased)	-
Other BOP	$107	100%	(purchased)	-	$132	100%	(purchased)	-
Final Assembly & Inspection	-	-	$59	-	-	-	$59	-
Total Factory Cost	**$2,704**	**94%**	**$161**	**6%**	**$3,313**	**95%**	**$178**	**5%**

Table 7. Base Case Material vs. Processing Cost Breakout for Type IV Dual Tank Compressed Hydrogen Storage Systems (with Pre-Preg CF)

On-board System Cost Breakout – Compressed Gas	Type IV, 2 tank, 350-bar Base Case				Type IV, 2 tank, 700-bar Base Case			
	Material, $	Material Fraction	Processing, $	Processing Fraction	Material, $	Material Fraction	Processing, $	Processing Fraction
Hydrogen	$18	100%	(purchased)	-	$18	100%	(purchased)	-
Compressed Vessel	$2,239	96%	$126	6%	$2,735	95%	$143	5%
Liner & Fittings	$25	54%	$21	46%	$18	46%	$21	54%
Carbon Fiber Layer	$2,135	96%	$90	4%	$2,656	96%	$109	4%
Glass Fiber Layer	$38	78%	$11	22%	$29	72%	$11	28%
Foam	$41	93%	$3	7%	$32	94%	$2	6%
Regulator	$160	100%	(purchased)	-	$200	100%	(purchased)	-
Valves	$226	100%	(purchased)	-	$282	100%	(purchased)	-
Other BOP	$107	100%	(purchased)	-	$132	100%	(purchased)	-
Final Assembly & Inspection	-	-	$59	-	-	-	$59	-
Total Factory Cost	**$2,750**	**94%**	**$185**	**6%**	**$3,367**	**95%**	**$202**	**6%**

Table 8. Base Case Material vs. Processing Cost Breakout for Type III Single Tank Compressed Hydrogen Storage Systems (with Pre-Preg CF)

On-board System Cost Breakout – Compressed Gas	Type III, 1 tank, 350-bar Base Case				Type III, 1 tank, 700-bar Base Case			
	Material, $	Material Fraction	Processing, $	Processing Fraction	Material, $	Material Fraction	Processing, $	Processing Fraction
Hydrogen	$18	100%	(purchased)	-	$18	100%	(purchased)	-
Compressed Vessel	$2,409	96%	$106	4%	$3,102	96%	$128	4%
Liner & Fittings	$495	96%	$23	4%	$577	96%	$25	4%
Carbon Fiber Layer	$1,852	96%	$74	4%	$2,477	96%	$96	4%
Glass Fiber Layer	$30	81%	$7	19%	$23	79%	$6	21%
Foam	$32	94%	$2	6%	$25	96%	$1	4%
Regulator	$160	100%	(purchased)	-	$200	100%	(purchased)	-
Valves	$226	100%	(purchased)	-	$282	100%	(purchased)	-
Other BOP	$107	100%	(purchased)	-	$132	100%	(purchased)	-
Final Assembly & Inspection	-	-	$59	-	-	-	$59	-
Total Factory Cost	**$2,920**	**95%**	**$165**	**5%**	**$3,734**	**95%**	**$197**	**5%**

Table 9. Base Case Material vs. Processing Cost Breakout for Type III Dual Tank Compressed Hydrogen Storage Systems (with Pre-Preg CF)

On-board System Cost Breakout – Compressed Gas	Type III, 2 tank, 350-bar Base Case				Type III, 2 tank, 700-bar Base Case			
	Material, $	Material Fraction	Processing, $	Processing Fraction	Material, $	Material Fraction	Processing, $	Processing Fraction
Hydrogen	$18	100%	(purchased)	-	$18	100%	(purchased)	-
Compressed Vessel	$2,429	95%	$129	5%	$3,117	95%	$152	5%
Liner & Fittings	$498	94%	$34	6%	$577	94%	$36	6%
Carbon Fiber Layer	$1,853	96%	$80	4%	$2,477	96%	$103	4%
Glass Fiber Layer	$38	78%	$11	22%	$30	73%	$11	27%
Foam	$40	93%	$3	7%	$33	94%	$2	6%
Regulator	$160	100%	(purchased)	-	$200	100%	(purchased)	-
Valves	$226	100%	(purchased)	-	$282	100%	(purchased)	-
Other BOP	$107	100%	(purchased)	-	$132	100%	(purchased)	-
Final Assembly & Inspection	-	-	$59	-	-	-	$59	-
Total Factory Cost	**$2,940**	**94%**	**$188**	**6%**	**$3,749**	**95%**	**$211**	**5%**

These costs compare well to industry factory cost projections for similarly sized tanks.[2] Industry factory cost projections for low-volume manufacturing (i.e., 1,000 units per year) range from $45-55/kWh for 350-bar systems and $55-65/kWh for 700-bar systems without valves and regulators. Removing valve and regulator costs from the TIAX base case projections results in high-volume factory costs of $13/kWh and $16/kWh for 350- and 700-bar tank systems, respectively. These results compare well to the lower-volume industry projections assuming PR of 85 to 90 percent.[3] While this PR range is reasonable, it is perhaps a bit on the high end of what would be expected (PR of 60 to 90 percent are typical) due to CF representing such a large fraction of the overall system cost. Unlike other system components, CF is already produced at very high volumes for the aerospace and other industries, so it is not expected to become significantly less expensive due to the typical learning curves assumed by a projection based on PR.[4]

Overall, Type III designs are projected to increase factory costs by $200 to $400 per system. The lower costs from reducing CF enabled by the load-bearing qualities of a Type III aluminum liner are more than offset by the liner's higher cost compared to the Type IV HDPE liner. Two-tank systems are projected to increase factory costs by less than $100. We have assumed that the dual tank system's BOP is similar to that of the single tank system. Sensitivity analysis is used to assess the cost impact of doubling the BOP part count. As shown in Figure 13, for each configuration examined, CF material cost dominates the total system cost at a range of 75 to 80 percent.

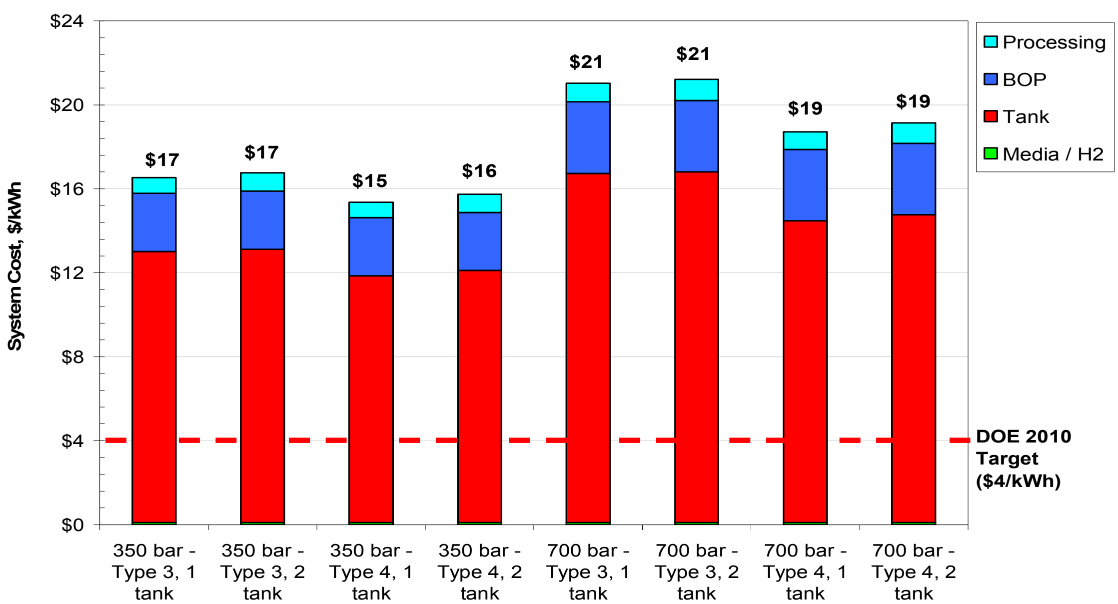


Figure 13. System Costs for Type III and Type IV Single and Dual Tank Systems (with Pre-Preg CF)

2 Industry projections are for 100-120 liter water capacity tanks vs. 149-258 liter water capacity tank designs evaluated here.

3 PR is defined by speed of learning (e.g., how much costs decline for every doubling of capacity).

4 However, there are DOE programs that are looking at ways to significantly decrease CF costs [2].

Single-variable sensitivity analysis was performed by varying one parameter at a time, while holding all others constant. TIAX varied overall manufacturing assumptions, economic assumptions, key performance parameters, direct material cost, capital equipment cost, and process cycle time for individual components. The range of uncertainty of CF cost and safety factor assumptions have the biggest impact on the Type IV single tank system cost projections (Figure 14). For duel tank systems, single-variable sensitivity analysis was used to characterize the cost impact of doubling the BOP part count. As show in Figure 15, a second BOP system increases the cost of a dual tank system by \$2/kWh and \$3/kWh for 350-bar and 700-bar systems, respectively.

As shown in Figure 16, for Type III systems, the cost and thickness of the aluminum liner (which are specific to Type III tanks) are also among the most significant drivers of system cost.

Multi-variable (Monte Carlo) sensitivity analysis was performed by varying all the parameters simultaneously, over a specified number of trials, to determine the probability distribution of the cost. TIAX assumed a triangular Probability Distribution Function (PDF) for the parameters, with the “high” and “low” value of the parameter corresponding to a minimum probability of occurrence, and the base case value of the parameter corresponding to a maximum probability of occurrence. The parameters and range of values considered were the same as for the single-variable sensitivity analysis. Based on the 95 percent confidence level (Figure 17), the factory cost is likely to be \$11 to \$20/kWh ($\pm 2\sigma$, μ=15, base case=15) for the 350-bar system and \$14 to \$27/kWh ($\pm 4\sigma$, μ=20, base case=19) for the 700-bar system.

As seen in Figure 18, multi-variable cost sensitivity analysis of dual tank systems projects that the factory cost is likely to be \$12 to \$21/kWh ($\pm 3\sigma$, μ=16, base case=16) for the 350-bar system and \$15 to \$30/kWh ($\pm 4\sigma$, μ=21, base case=19) for the 700-bar tank system.

As seen in Figure 19, the factory cost of Type III single tank systems is likely to be \$12.5 to \$21/kWh ($\pm 2\sigma$, μ=16, base case=17) for the 350-bar system and \$17 to \$30/kWh ($\pm 4\sigma$, μ=23, base case=21) for the 700-bar tank system.

TIAX also performed an ownership cost analysis that included refueling costs. Refueling costs for the complete fuel cycle necessary to support 350- and 700-bar compressed tank systems were estimated using DOE’s Hydrogen Delivery Scenarios Analysis Model (HDSAM) version 2.06 [4]. These refueling costs are converted to the refueling portion of the ownership cost by making assumptions about the fuel economy of the hydrogen fuel cell vehicle (FCV). The on-board storage system cost is converted to the fuel system purchased cost portion of the ownership cost by applying the appropriate retail price equivalent multiplier,[5] annual discount factor, and annual mileage to calculate an equivalent dollar per mile estimate.

[5] Manufacturer’s Suggested Retail Price (MSRP) relative to the cost of manufacturing

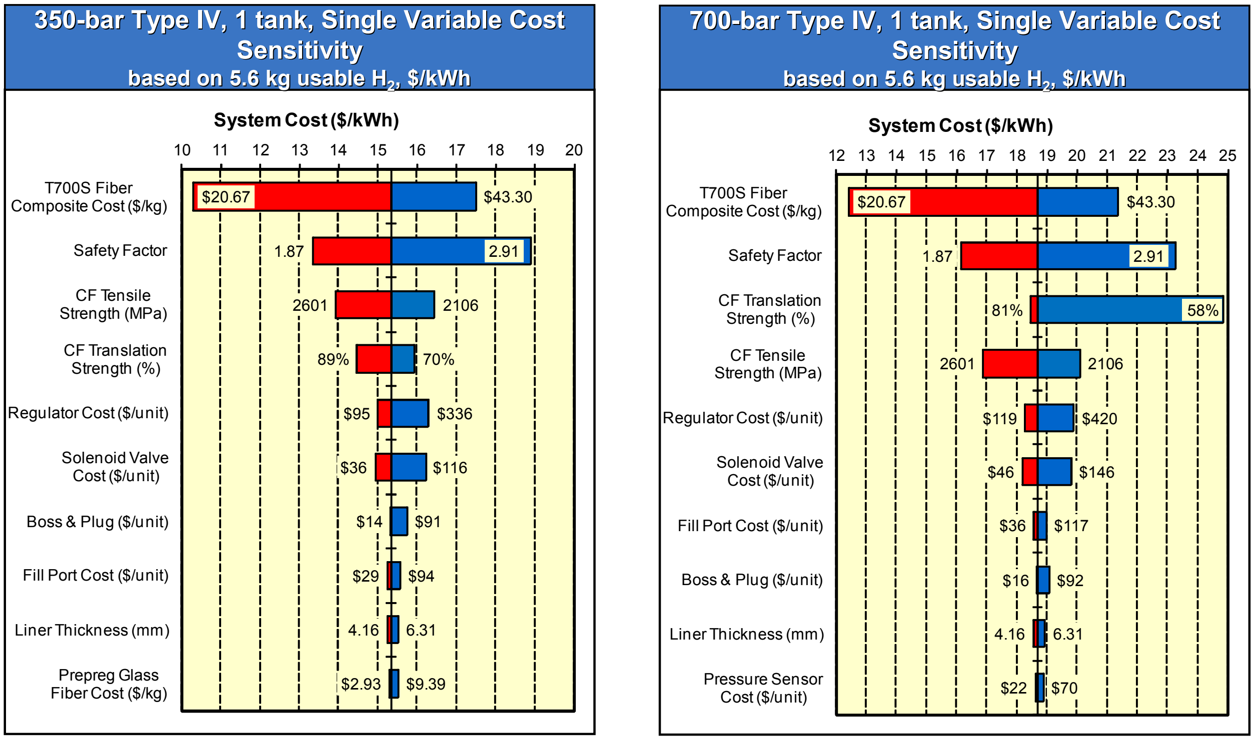


Figure 14. Single-Variable Cost Sensitivity for Type IV Single Tank Systems (with Pre-Preg CF)

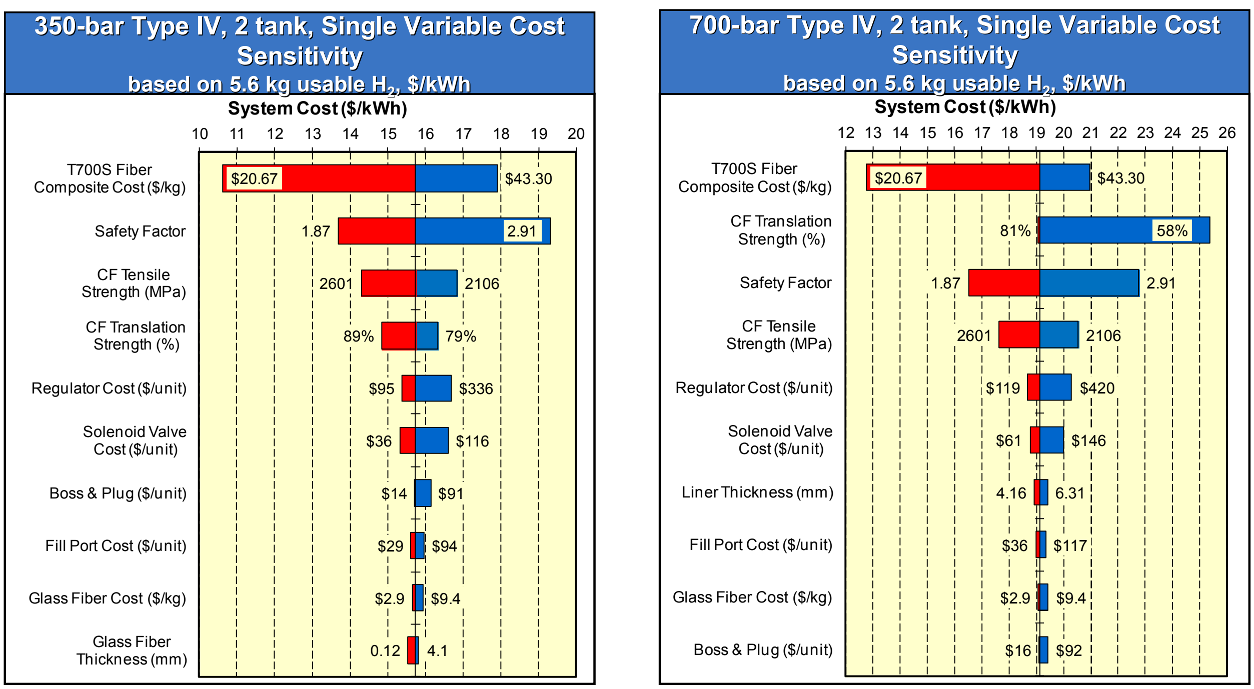


Figure 15. Single-Variable Cost Sensitivity for Type IV Dual Tank Systems (with Pre-Preg CF)

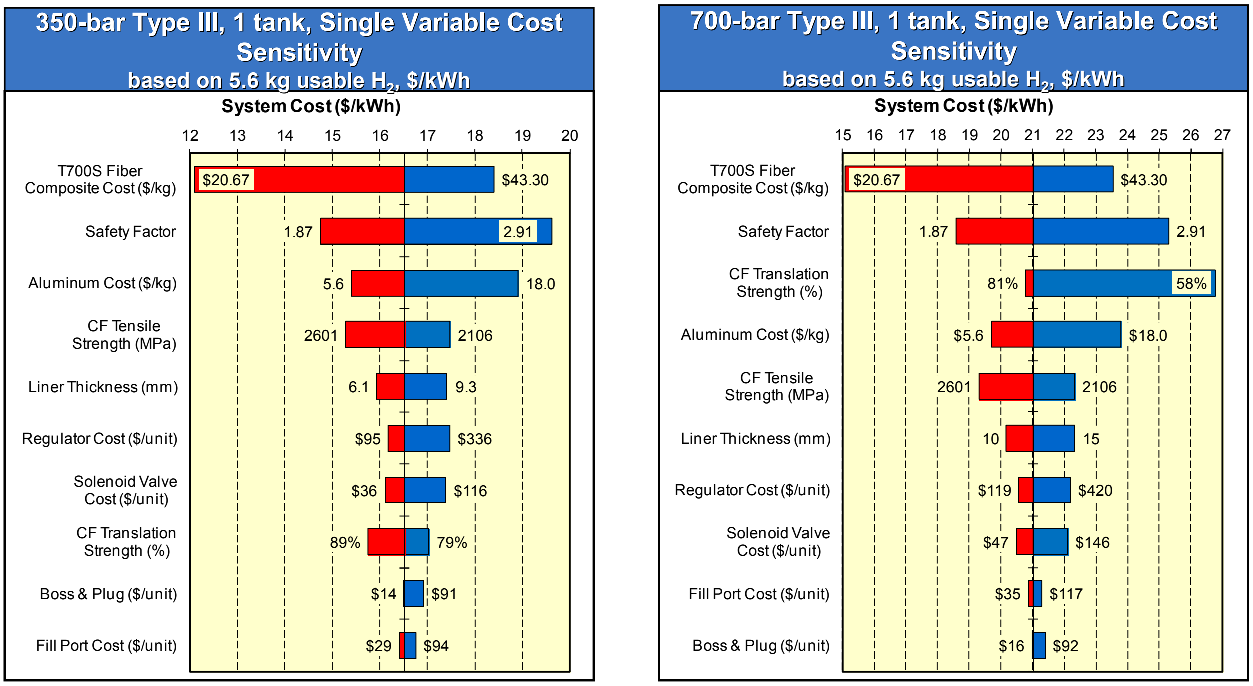


Figure 16. Single-Variable Cost Sensitivity for Type III Single Tank Systems (with Pre-Preg CF)

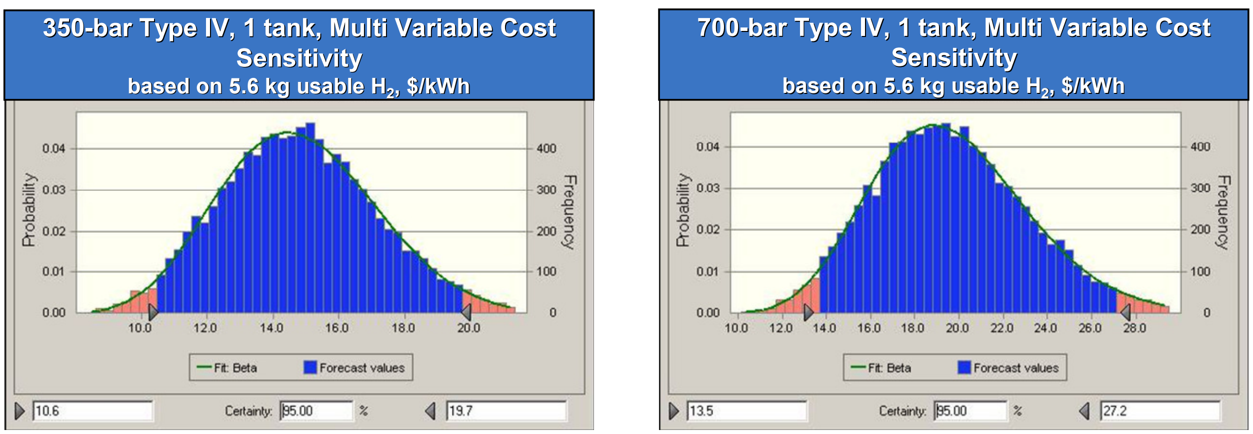


Figure 17. Multi-Variable Cost Sensitivity for Type IV Single Tank Systems (with Pre-Preg CF)

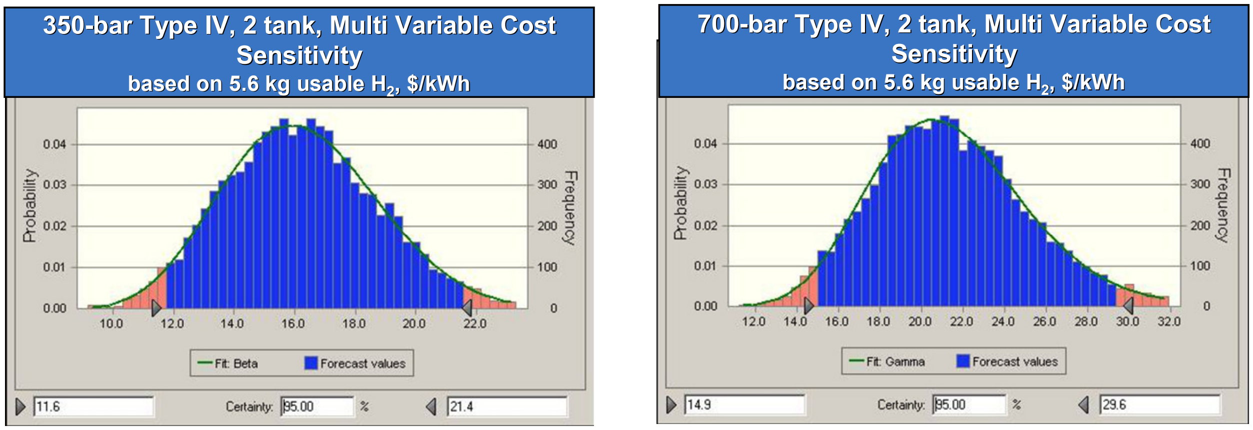


Figure 18. Multi-Variable Cost Sensitivity for Type IV Dual Tank Systems (with Pre-Preg CF)

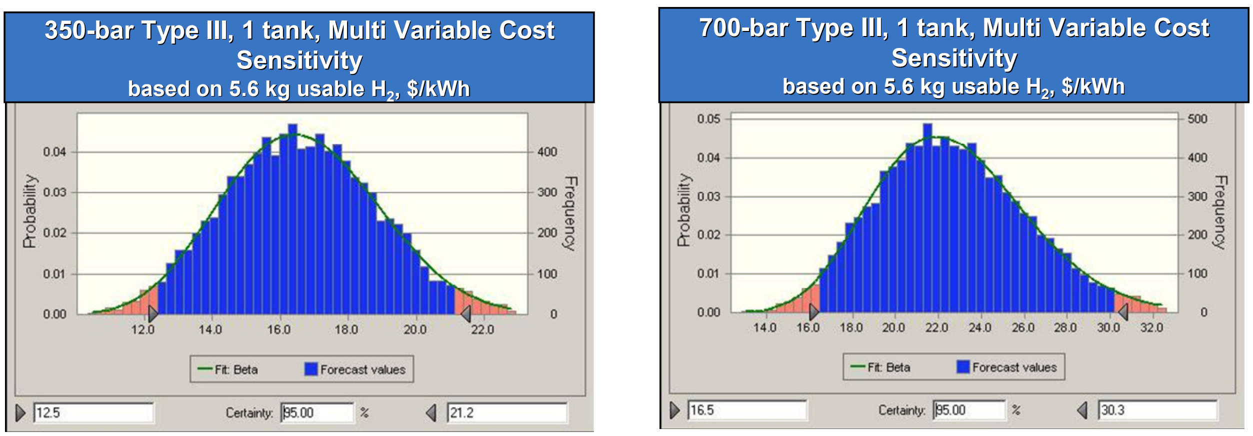


Figure 19. Multi-Variable Cost Sensitivity for Type III Single Tank Systems (with Pre-Preg CF)

The compressed hydrogen fuel cost for the reference SMR production and compressed hydrogen delivery scenario is \$4.22 and \$4.33 per gasoline gallon equivalent (gge) for the 350-bar and 700-bar cases, respectively (Table 10). This is approximately 6 to 120 percent higher than the DOE fuel cost threshold of \$2 to \$4 per gge. When on-board and off-board costs are combined, the 350-bar compressed system has potential to have similar ownership costs as a gasoline internal combustion engine vehicle (ICEV), albeit about 20 percent (2¢/mi or \$240/yr) higher when gasoline is \$3.00/gal. The 700-bar system is projected to have 50 percent higher ownership cost compared to an ICEV when gasoline is \$3.00/gal.

Table 10. Fuel and Ownership Cost of 350- and 700-Bar CH_2 FCV

	Equivalent Price (\$/gge)	Ownership Cost (\$/mile)
350-bar CH_2 FCV	4.22	0.13
700-bar CH_2 FCV	4.33	0.15
Gasoline ICEV	3.00	0.10

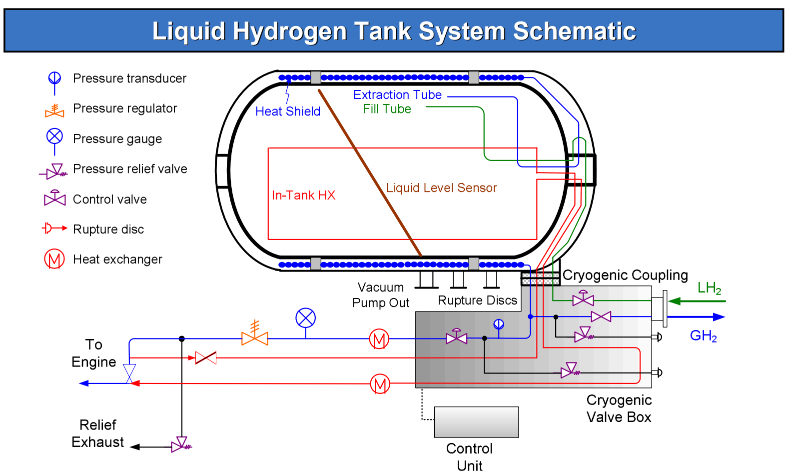
The main conclusion of the assessment is that the 350-bar compressed storage system, as designed, is not projected to meet the DOE target for storage system cost, given our base case assumptions. The same is true for the 700-bar compressed storage system, despite the fact that its volumetric capacity is much higher than the 350-bar system. CF composite material cost reductions and/or performance improvements (e.g., much higher translation strength efficiency) to reduce the amount of CF required may allow the hydrogen storage system to meet the DOE target.

4.1.2 Liquid Hydrogen Storage (April 30, 2010)

TIAX developed liquid hydrogen (LH_2) tank design assumptions (Figure 20) based on existing designs (e.g., Linde in Figure 21), other cryo-tank designs and input from ANL, Lawrence Livermore National Laboratory (LLNL), and BMW (

Table 11). The 5.6 and 10.4 kg LH_2 storage capacities were designed for the midsized and larger vehicles, respectively, based upon ANL's drive-cycle modeling for FCVs that can achieve a 350-mile range.

The base case cost projections for the major BOP components range from \$15 to \$140 per unit assuming high-volume (i.e., 500,000 units per year) production (Table 12). The total costs of the BOP components add up to \$363. The raw material cost assumptions are presented in Table 13.



Source: ANL (personal communication)

Liquid Hydrogen Tank Specifications

- 168 & 311 liters (5.6 & 10.4 kg usable LH_2)
- 7.5% tank ullage
- 4 bar (60 psi) nominal pressure; 6 bar (90 psi) max pressure
- 3.0 mm inner tank thickness
- -247 °C min temp
- 25 & 38 mm vacuum gap w/ MLVSI, 10^{-5} torr (~1 W HT) (5.6 & 10.4 kg usable LH_2)
- 2.0 mm outer shell thickness

Modifications compared to cryo-compressed tank system:

- No carbon fiber pressure vessel due to the lower pressure
- 7.5% ullage requirement
- Added layers of MLVSI, heat shield and insulated valve box
- Cryogenic valves are assumed to weigh and cost less due to the lower pressure

Figure 20. Liquid Hydrogen Tank System Schematic

Linde CooLH2 System

- Extended autonomy time by 4x over traditional LH_2 tank
- Liquid air serves as phase change material
- Extracted LH_2 used to re-liquefy air during operation
- Added components:
  - Liquid air vessel
  - Cooling tubes
  - Cooling plates
  - Dryer heat exchanger

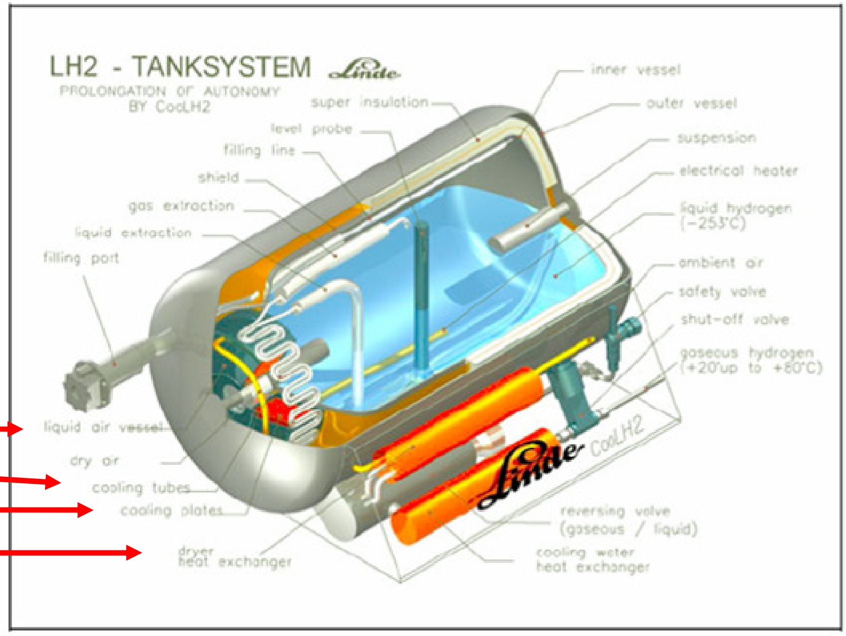


Figure 21. Linde CooLH2 Tank System

Table 11. LH_2 Storage System Design Assumptions

Design Parameter	Base Case Value	Basis/Comment
Maximum (venting) pressure	6 bar	Developer feedback; necessary to prevent excessive LH_2 boiloff
Minimum (empty) pressure	4 bar	Design assumption; required to meet DOE delivery pressure target
Usable LH_2 storage capacity	5.6 and 10.4 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range for midsized (5.6 kg) and larger vehicle (10.4 kg)
Recoverable hydrogen (fraction of stored hydrogen)	57%	ANL calculation based on hydrogen storage density at maximum and minimum pressure and temperature conditions and 40% boil-off based on industry feedback
Tank ullage (fraction of total volume)	7.5%	ANL calculation; required to allow for thermal expansion of the liquid hydrogen
Tank size (water capacity)	168 and 311 L[1]	ANL calculation for 5.6 kg and 10.4 kg usable H_2 capacity (9.8 and 18.3 kg total H_2 capacity)
L/D ratio	2.0	Consistent with other cryo-tank assessments and discussions with LLNL and SCI, 2008; based on the outside of the inner tank
Inner tank thickness	3 mm Al	Discussions with industry, 2010
Insulation type	MLVSI	Aluminized Mylar sheets, Dacron spacer, 10^{-5} torr
Minimum temperature	-247 ºC	ANL calculation; saturation temperature at 4 bar
Vacuum gap	25 and 38 mm	ANL calculation to achieve ~1 W heat transfer rate with MLVSI
Outer shell	2 mm Steel	Discussions with industry, 2010

[1] The larger tank (10.4 kg usable H_2) LH_2 case is not applicable for most vehicular application due to its excessive volume

Table 12. LH_2 Storage System Cost Projections for Major BOP Components

Purchased Component Cost Est.	Base Cases ($ per unit)	Comments/Basis
Fill tube/port	$140	Industry feedback; capable of 2-way flows at low temperatures without leaks and accepting signals from the nozzle at the fueling station to open or close; includes control valve; 0.7 derating factor for lower pressure compared to cryo-compressed
Control valve	$66	Industry feedback validated with quotes and discussion with Bertram Controls for Circle Seal solenoid control valve (2009); 0.7 derating factor for lower pressure compared to cryo-compressed
Heat exchanger	$50	Industry feedback; includes a valve, ~3 meters of tubing and a conventional flat plat heat exchanger (or connection to vehicle waste heat source)
Pressure transducers	$30	Industry feedback validated with quotes and discussion with Taber Industries (2009)
Pressure relief valves	$20	Based on DFMA® cost modeling software; 0.7 derating factor for lower pressure compared to cryo-compressed
Level sensor (in tank)	$25	Industry feedback validated with discussions with tank developers; although some developers thought this cost was too low, it represents a target for level sensor or other suitable technology
Pressure gauge (in engine feed zone)	$17	Based on quotes from Emerson Process Management/ Tescom/ Northeast Engineering (2009)
Boss and plug (in tank)	$15	Based on price estimate from tank developers (2009), validated with Al raw material price marked up for processing

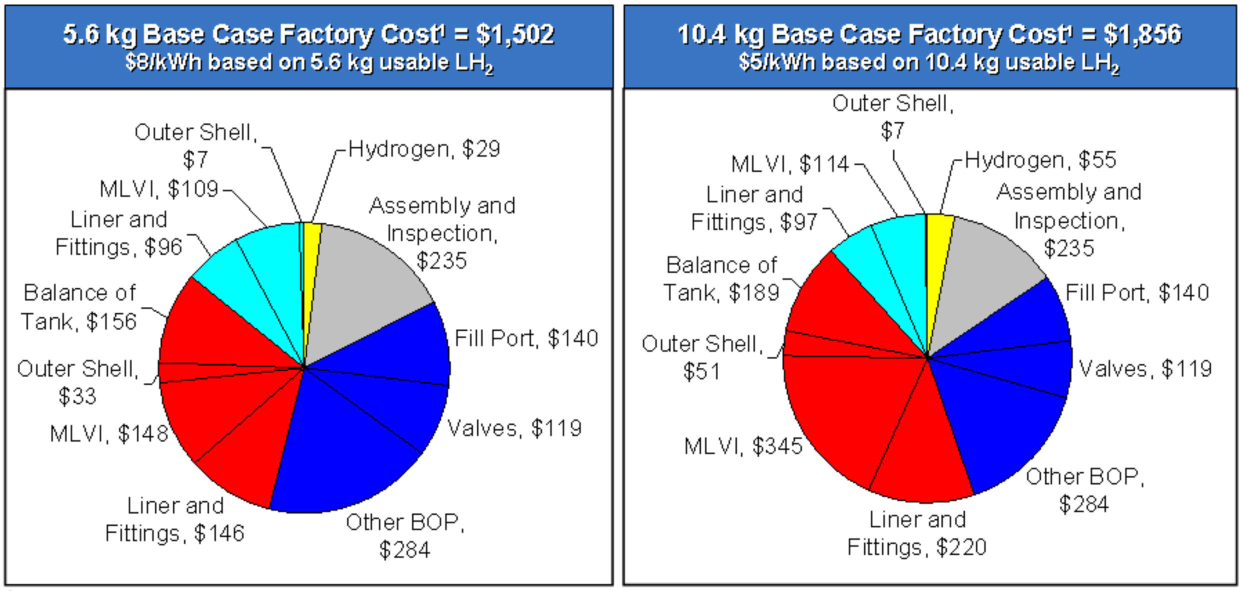
Table 13. LH_2 Storage System Raw Material Cost Assumptions

Raw Material Cost Estimates, $/kg	Base Cases	Comment/Basis
Hydrogen	3.0	Consistent with DOE H_2 delivery target
Aluminum (6061-T6)	9.6	Bulk price from Alcoa (2009)
Multi-layer vacuum insulation (MLVI)	50 ($0.15/ft^2)	Discussion with MPI (2007)
Stainless steel (304)	4.7	Average monthly costs from Sep '06 – Aug '07 (MEPS International 2007) deflated to 2005$s by ~6%/yr
Standard steel	1.0	Estimate based on monthly costs for 2008-2009 (MEPS International 2009)

As seen in Figure 22, the multi-layer vacuum insulation (MLVI) is the single most expensive component and accounts for about 17 to 25 percent of system costs.

At the base case, the BOP components account for 36 percent and 29 percent of the 5.6 and 10.4 kg system costs, respectively. The cost of hydrogen itself is only 2-3 percent of the base factory costs. The 5.6 and 10.4 kg on-board storage systems will cost $8/kWh and $5/kWh, respectively. The figure shows material costs in red and processing costs in light blue.

As shown in Table 14, processing costs make up 24 to 30 percent of the total system cost, even at assumed high production volumes. The material fraction is 70 percent of $1,502, the total cost of the 5.6 kg factory base case. For the 10.4 kg factory base case of $1,856, the material fraction is 76 percent.



[1] Cost estimate in 2005 USD. Processing costs are shown separately (light blue fractions).

Figure 22. Base Case Component Cost Breakout for the LH_2 Storage Systems

Table 14. Base Case Material vs. Processing Cost Breakout for LH_2 Systems

On-board System Cost Breakout – Cryogenic Liquid	5.6 kg Base Case				10.4 kg Base Case			
	Material, $	Material Fraction	Processing, $	Processing Fraction	Material, $	Material Fraction	Processing, $	Processing Fraction
Hydrogen	$29	100%	(purchased)	-	$55	100%	(purchased)	-
Cryogenic Vessel	$483	70%	$211	30%	$805	79%	$218	21%
Liner & Fittings	$146	60%	$96	40%	$220	69%	$97	31%
MLVI	$148	58%	$109	42%	$345	75%	$114	25%
Outer Shell	$33	72%	$7	18%	$51	87%	$7	13%
Balance of Tank	$118	100%	(purchased)	-	$118	100%	(purchased)	-
Fill Port	$140	100%	(purchased)	-	$140	100%	(purchased)	-
Valves	$119	100%	(purchased)	-	$119	100%	(purchased)	-
Other BOP	$284	100%	(purchased)	-	$284	100%	(purchased)	-
Final Assembly & Inspection	-	-	$235	-	-	-	$235	-
Total Factory Cost	**$1,055**	**70%**	**$446**	**30%**	**$1,403**	**76%**	**$453**	**24%**

As shown in Figure 23, aluminum liner thickness and the cost of insulation have the strongest effects on system cost.

As seen in Figure 24, system costs will likely range (95 percent confidence) from \$9 to \$13/kWh ($\pm 1\sigma$, μ=11, base case=8) for the 5.6 kg system and \$6 to \$9/kWh ($\pm 1\sigma$, μ=7, base case=5) for the 10.4 kg system

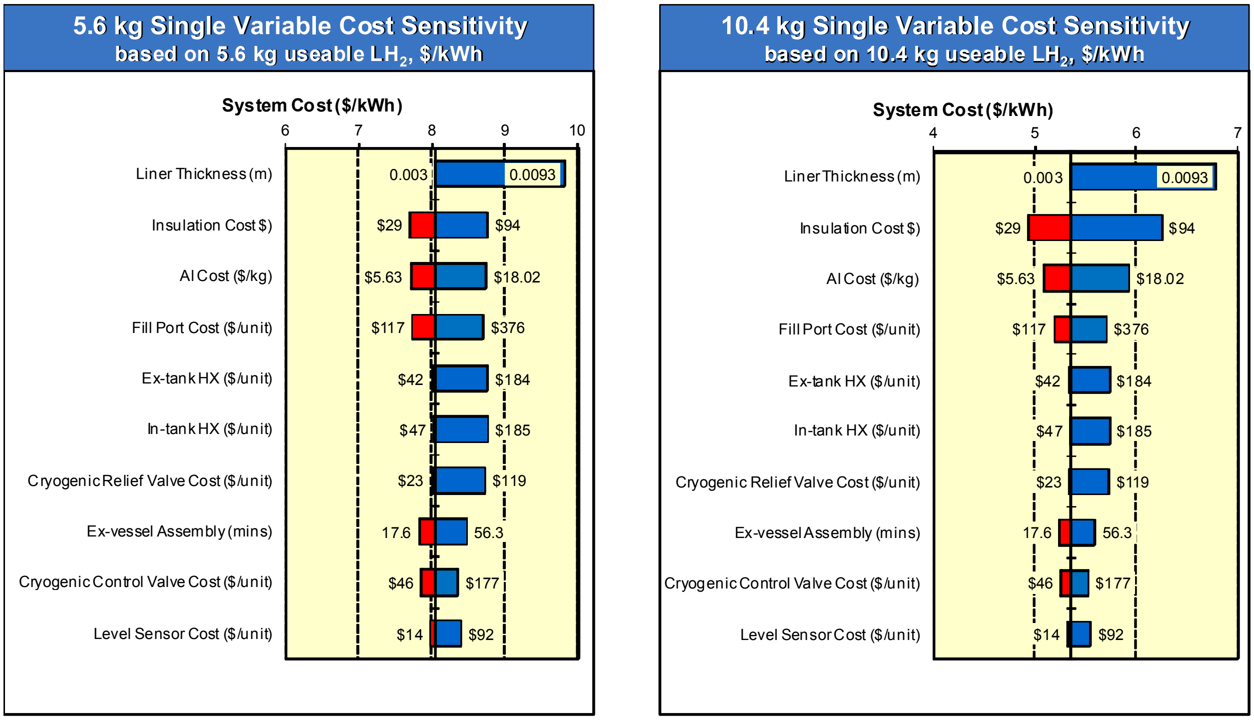


Figure 23. Single-Variable Cost Sensitivity for the LH_2 Storage Systems

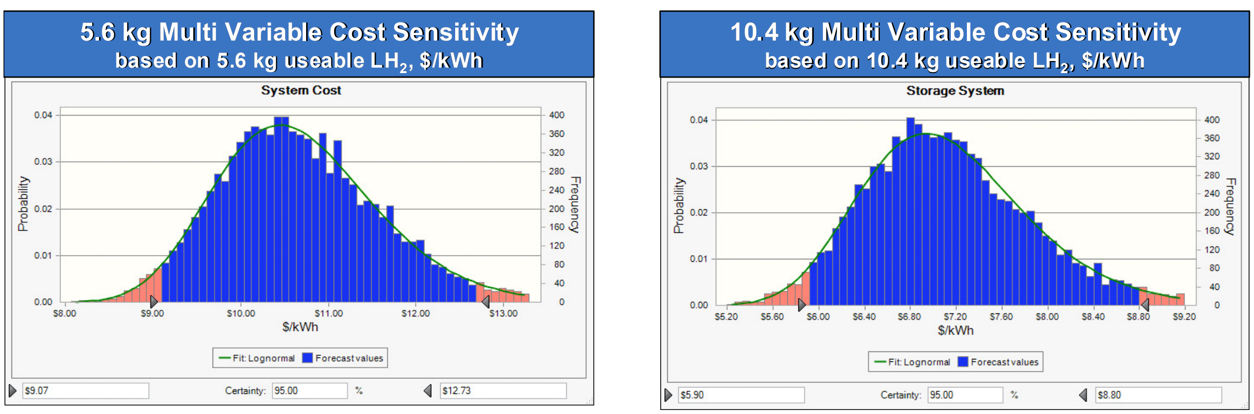


Figure 24. Multi-Variable Cost Sensitivity for LH_2 Storage Systems

Refueling cost, based on LH_2 delivery and high-pressure LH_2 dispensing, is projected to be $4.74/kg hydrogen. Central plant/regeneration costs account for approximately half of the cryogenic hydrogen cost in the 5.6 kg base case. Ownership cost for the 5.6 kg system will likely be about 20 percent (2¢ to 3¢/mi or $250-$350/yr) higher than a conventional gasoline ICEV when gasoline is $3.00/gal. Fuel storage cost accounts for 15 percent of total vehicle ownership costs for the cryo-compressed FCV. Ownership costs for a cryo-compressed FCV would be comparable to a gasoline ICEV with gasoline at a price of $4.00 per gallon.

4.1.3 Cryo-Compressed Hydrogen Storage (November 30, 2009)

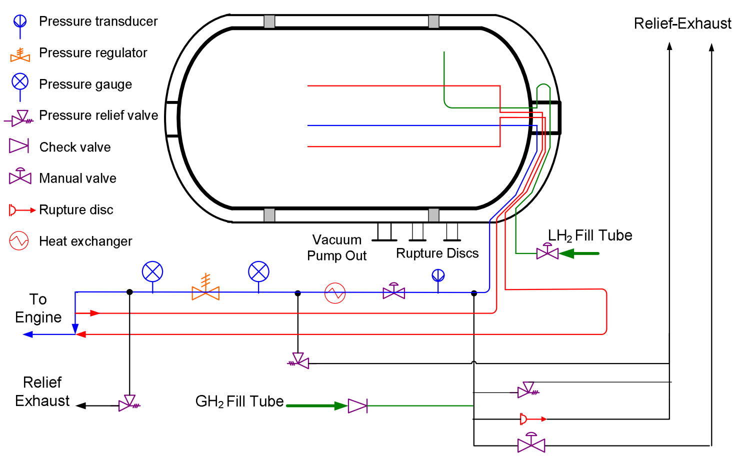
The cost of cryo-compressed hydrogen storage has been assessed and compared to the DOE 2010 target for automotive applications. The on-board and high-volume manufacturing (500,000 units per year) costs were determined for cryo-compressed hydrogen tanks capable of storing 5.6 kg and 10.4 kg of usable hydrogen. The design assumptions for the cryo-compressed hydrogen storage system are presented in Table 15. This cost analysis is based on LLNL's Gen-3 cryo-compressed storage system (Figure 25), with modifications made by ANL.

The base case cost projections for the major BOP components range from \$15 to \$200 per unit assuming high-volume (i.e., 500,000 units per year) production (Table 16). The total cost of the BOP components add up to \$619. The raw material cost assumptions are presented in Table 17.

The results of the cost assessment estimate that the scaled LLNL Gen-3 system (5.6 kg usable LH_2 capacity) and the prototype Gen-3 system (10.4 kg usable LH_2 capacity) will cost \$11/kWh and \$8/kWh, respectively using a set of base-case assumptions considered to be most likely.

Table 15. Cryo-Compressed Storage System Design Assumptions

Design Parameter	Base Case Value	Basis/Comment
Nominal pressure	272 atm	Tank design assumption based on discussions with LLNL
Maximum pressure	340 atm	125% of nominal design pressure is assumed required for dormancy
Filling pressure (max)	4 atm	ANL assumption for "Cryo-compressed H_2 Storage Option"
"Empty" pressure	4 atm	ANL assumption; depending on initial temperature and H_2 charge
Usable LH_2 storage capacity	5.6 and 10.4 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range (5.6 kg) and LLNL tank design (10.4 kg)
Tank size (water capacity)	81 and 151 L	Required for 5.6 kg and 10.4 kg useable H_2 capacity (5.7 and 10.7 kg total H_2 capacity, calculated by ANL)
Safety factor	2.25	Industry standard criteria (e.g., ISO/TS 15869) applied to nominal storage pressure (i.e., 272 bar)
Length/Diameter Ratio	2.0	ANL assumption based on discussions with LLNL and SCI design, 2008; based on the outside of the CF wrapped tank
Carbon fiber type	Toray T700S	Discussions with LLNL, Quantum and other developers, 2008
Composite tensile strength	2,550 MPa	Toray material data sheet for 60% fiber by volume
Translation strength factor	86%	ANL assumption based on discussions and data from Quantum, 2004-09
Tank liner thickness	9.5 mm Al	ANL assumption based on discussions with LLNL and SCI design, 2008
Minimum temperature	-253 ºC	Typical for liquid hydrogen storage
Vacuum gap	10 and 17 mm	ANL assumption to achieve ~1.5 W heat transfer rate with Mylar layers
Outer shell	3.2 mm Steel	Discussions with LLNNL and industry, 2008-09
CF Weight	5.6 kg: 11.7 kg 10.4 kg: 21.8 kg	Design assumptions from ANL



Gen 3 Cryo-compressed Tank Modifications from Gen 2

- Two tank sizes: 80.8 & 151 liters (5.6 kg & 10.4 kg usable LH_2)
- Reduced pressure vessel rating: 272 bar (4,000 psi) max pressure
- Increased Al liner thickness: 9.5 mm
- Reduced insulation: 10 & 17 mm vacuum gap w/ MLVI, 10^{-5} torr (~1.5 W HT rate)
- Vacuum valve box eliminated
- Better packaging

Additional modifications assumed for high-volume production

- Cryogenic valves assumed to be electronically controlled
- Added liquid level sensor[1]
- Valves and tubing assumed for in-tank heat exchange system
- Assumed low-carbon steel instead of SS304 for outer shell to save cost
- Did not include electronic boards and computer
- Insulated LH_2 fill/gas vent port included

[1] Other methods of accounting of fuel could be used (e.g. close mass -balance accounting with flow sensor).

Figure 25. LLNL Gen-3 Cryo-compressed Storage System Schematic

Table 16. Cryo-Compressed Storage System Cost Projections for Major BOP Components

Purchased Component Cost Est.	Rating	Base Cases ($ per unit)	Comments/Basis
Fill tube/port	350 bar, cryogenic H_2	$200	Industry feedback; capable of 2-way flows at high pressures and low temperatures without leaks and accepting signals from the nozzle at the fueling station to open or close; includes control valves
Pressure regulator	350 bar cH_2	$160	Industry feedback validated with top-down approach based on quotes and discussion with Emerson Process Management/Tescom/Northeast Engineering (2009), and bottom-up approach using DFMA® software
Control valve	350 bar, cryogenic H_2	$94	Industry feedback and quotes and discussion with Bertram Controls for Circle Seal solenoid control valve (2009)
Heat exchangers	350 bar, cryogenic H_2	$50	Industry feedback; includes a valve, ~3 meters of tubing and a conventional flat plat heat exchanger (or connection to vehicle waste heat source)
Pressure transducers	350 bar and 10^{-5} Torr, cryogenic H_2	$30	Industry feedback and quotes and discussion with Taber Industries (2009)
Pressure relief valves	350 bar, cryogenic H_2	$28	Bottom-up approach using DFMA® cost modeling software
Level sensor (in tank)	350 bar LH_2	$25	Industry feedback and discussions with tank developers
Pressure gauge (in engine feed zone)	250 psi cH_2	$17	Top-down approach based on quotes from Emerson Process Management/Tescom/Northeast Engineering (2009)
Boss and plug (in tank)	350 bar, cryogenic H_2	$15	Top-down approach based on price estimate from tank developers (2009), validated with bottom-up approach based on Al raw material price marked up for processing

Table 17. Cryo-Compressed Storage System Raw Material Cost Assumptions

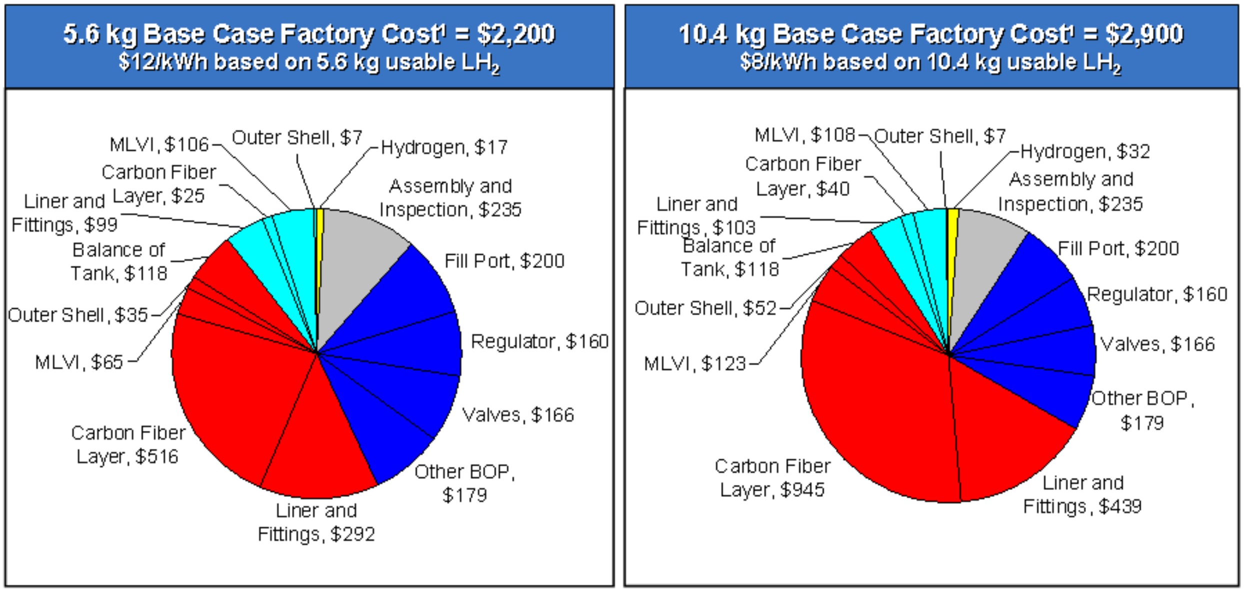
Raw Material Cost Estimates, $/kg	Base Cases	Comment/Basis
Hydrogen	3.0	Consistent with DOE H_2 delivery target
Aluminum (6061-T6)	9.6	Bulk price from Alcoa (2009)
Carbon fiber (T700S) prepreg	36.6	Discussion w/ Toray (2007) re: T700S fiber ($10-$16/lb, $13/lb base case); 1.27 prepreg/fiber ratio (Du Vall 2001)
Multi-layer vacuum insulation (MLVI)	50 ($0.15/ft^2)	Discussion with MPI (2007)
Stainless steel (304)	4.7	Average monthly costs from Sep '06 – Aug '07 (MEPS International 2007) deflated to 2005$s by ~6%/yr
Standard steel	1.0	Estimate based on monthly costs for 2008-2009 (MEPS International 2009)

As seen in Figure 26, the CF layer is the most expensive single component and accounts for about 25 percent and 35 percent of the base case 5.6 kg and 10.4 kg systems costs. BOP component costs are also important, accounting for approximately 30 percent and 25 percent of the base case 5.6 kg and 10.4 kg system costs, respectively. The figure shows material costs in red and processing costs in light blue.

As shown in Table 18, processing cost makes up 15 to 20 percent of the total system cost. This is high compared to projections for other tank designs (e.g., 350 and 700-bar compressed hydrogen storage with 4 to 5 percent processing costs) but very low compared to today's cost to manufacture similar tank systems. Manufacturing a cryo-compressed tank today using relatively low volume production techniques requires complex and very labor intensive processes due to the simultaneous high pressure (e.g., CF wrapped tank) and low temperature (e.g., vacuum insulation) requirements. There is uncertainty about the level of automation that can be achieved in the future, as scale-up of production volumes is ongoing, but we have assumed that cost savings could occur with economies of scale, once high production volumes are achieve over a sustained period of time. For example, we based our MLVSI processing costs on the assumption that, like other winding processes in manufacturing, insulation wrapping could be done at high speeds with automated equipment. This is much more efficient and could be significantly less costly than the slow and meticulous hand-wrapping process used today.

As seen in Figure 27 , the range of uncertainty for aluminum and CF cost assumptions have the biggest impact on the system cost projections (i.e., sensitivity results for these assumptions are roughly 15 to 20 percent of the total system cost each due to the time-consuming processing steps, even at assumed high production volumes).

According to the multi-variable sensitivity analysis results (Figure 28), the factory cost will likely range (95 percent confidence) between $11 and $16/kWh ($\pm1\sigma$, μ=14, base case=12) for the 5.6 kg system and between $8 and $11/kWh ($\pm1\sigma$, μ=9, base case=8) for the 10.4 kg system.



[1] Cost estimate in 2005 USD. Processing costs are shown separately (light blue fractions).

Figure 26. Base Case Component Cost Breakout for the Cryo-Compressed Storage Systems (with Pre-Preg CF)

Table 18. Base Case Material vs. Processing Cost Breakout for the Cryo-Compressed Systems

On-board System Cost Breakout – Cryo-Compressed Gas	5.6 kg Base Case				10.4 kg Base Case			
	Material, $	Material Fraction	Processing, $	Processing Fraction	Material, $	Material Fraction	Processing, $	Processing Fraction
Hydrogen	$17	100%	(purchased)	-	$32	100%	(purchased)	-
Cryo-Compressed Vessel	$1,027	81%	$238	19%	$1,678	87%	$259	13%
Liner & Fittings	$292	75%	$99	25%	$439	81%	$103	19%
Carbon Fiber Layer	$516	95%	$25	5%	$945	96%	$40	4%
MLVI	$65	38%	$106	62%	$123	53%	$108	47%
Outer Shell	$35	83%	$7	17%	$52	88%	$7	12%
Balance of Tank	$118	100%	(purchased)	-	$118	100%	(purchased)	-
Fill Port	$200	100%	(purchased)	-	$200	100%	(purchased)	
Regulator	$160	100%	(purchased)	-	$160	100%	(purchased)	-
Valves	$166	100%	(purchased)	-	$166	100%	(purchased)	-
Other BOP	$179	100%	(purchased)	-	$179	100%	(purchased)	-
Final Assembly & Inspection	-	-	$235	-	-	-	$235	-
Total Factory Cost	**$1,748**	**79%**	**$473**	**21%**	**$2,414**	**83%**	**$494**	**17%**

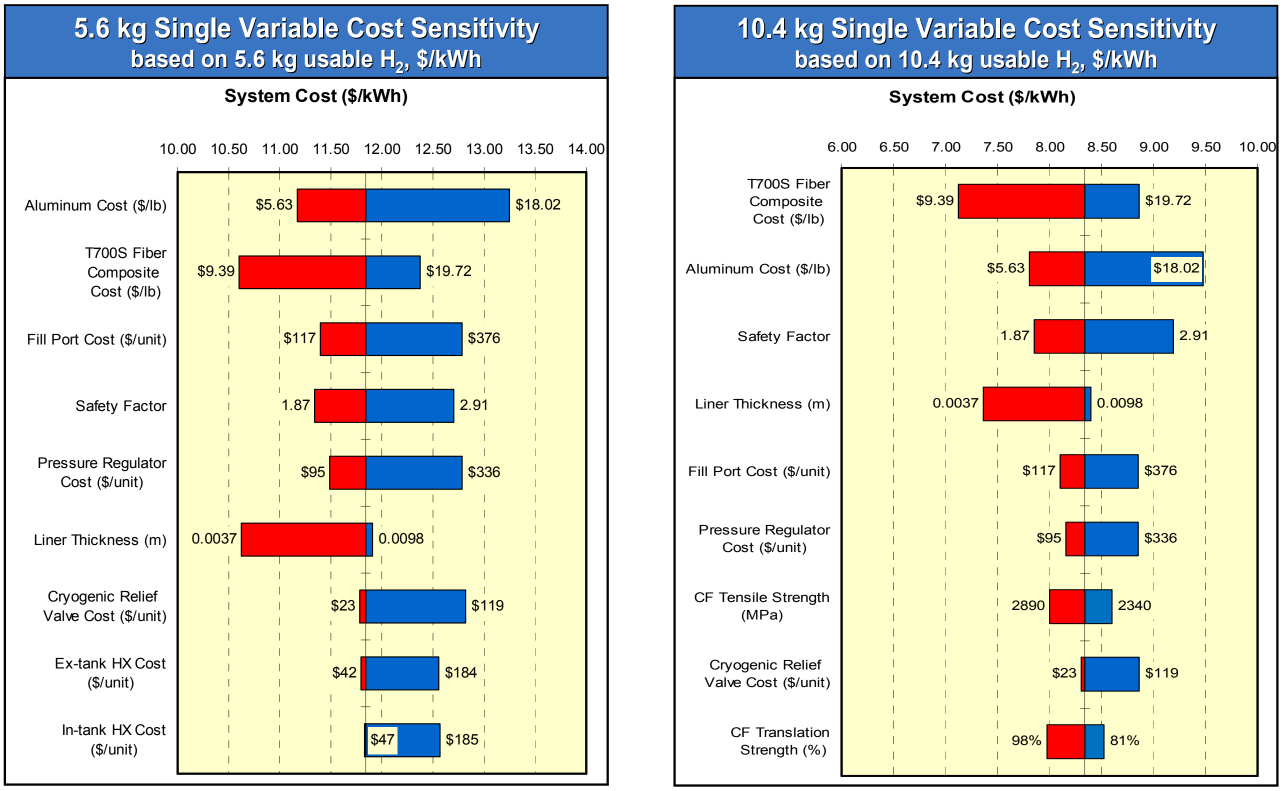


Figure 27. Single-Variable Cost Sensitivity for Cryo-Compressed Hydrogen Storage Systems

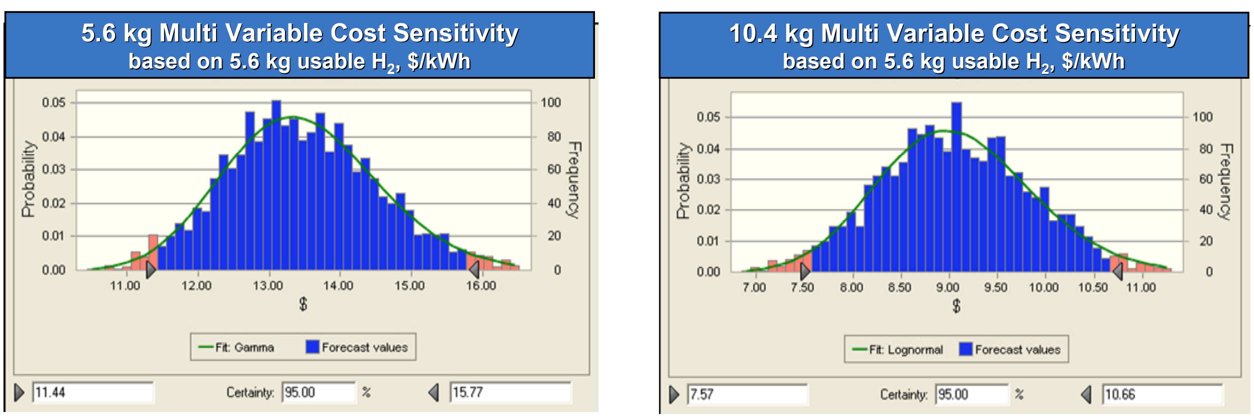


Figure 28. Multi-Variable Cost Sensitivity for Cryo-Compressed Hydrogen Storage Systems

4.1.4 Sodium Alanate Hydrogen Storage (March 31, 2007)

Sodium alanate ($NaAlH_4$) is a medium-temperature complex hydride with high reversible hydrogen content at moderate conditions. The $NaAlH_4$ storage tank base case design and storage system schematic are shown in Figures 49 and 50. The $NaAlH_4$ system may be cost competitive

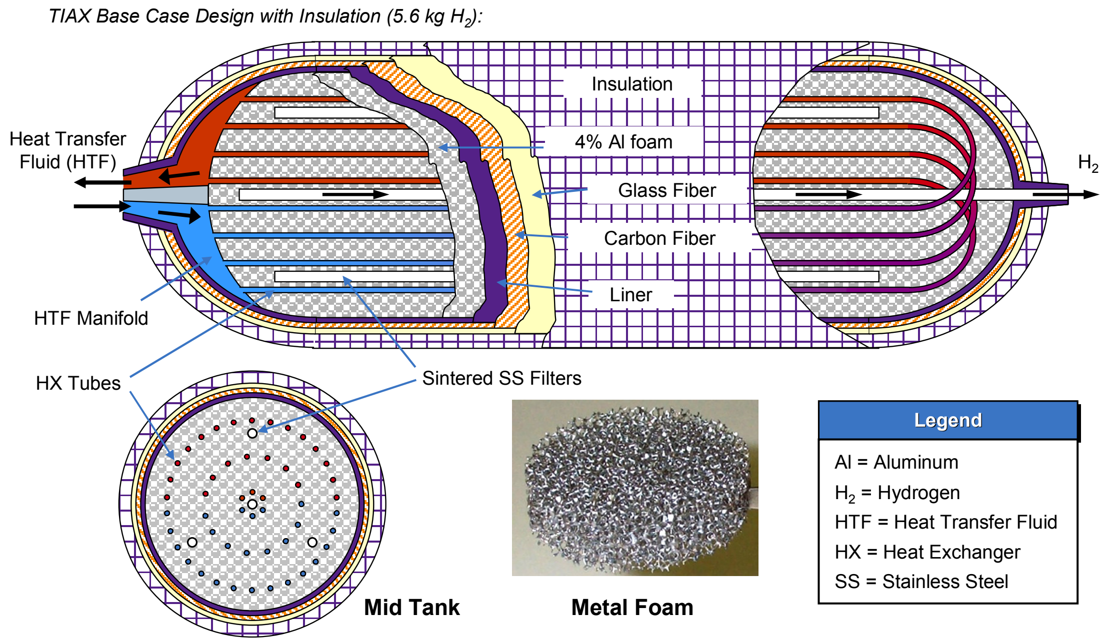


Figure 29. Sodium Alanate Storage Tank Design

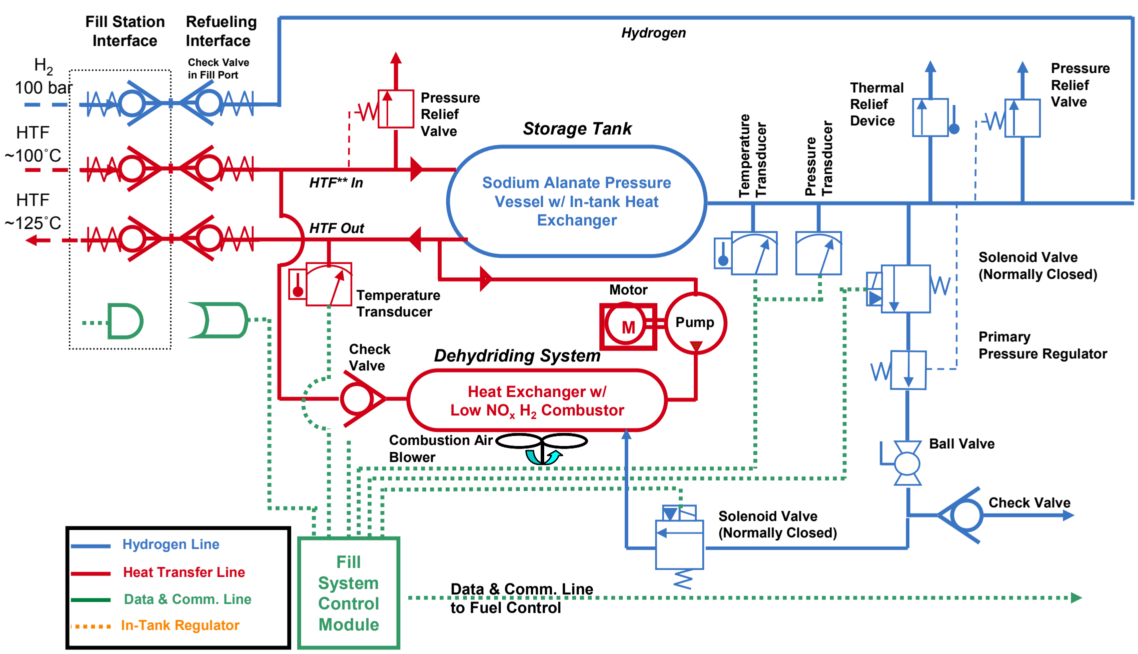


Figure 30. Sodium Alanate Storage System Schematic

with compressed hydrogen storage, provided fuel cell waste heat can be used for desorption energy. The design and raw materials assumptions for the $NaAlH_4$ hydrogen storage system are presented in Tables 28 and 29. The catalyzed material cost (excluding processing) is dependent on the type of catalyst precursor assumed.

Table 19. Sodium Alanate Storage System Design Assumptions

Tank Design Parameter		Value	Basis
Media	H_2 Storage Capacity	5.6 kg	ANL drive-cycle modeling
	$NaAlH_4$ H_2 Capacity	4 wt%	UTRC (Anton, Merit Review, May 04)
	Catalyst	$TiCl_3$	Bogdanovic & Schwickardi, JAC 97
	Catalyst Concentration	4 mol%	Bogdanovic & Sandrock, MRS 02
	Powder Packing Density	0.6	UTRC (Anton, Merit Review, May 04)
Thermal	Heat of Decomposition	41 kJ/mol H_2	Reaction thermodynamics
	Min. Temperature	100 °C	SNL (Wang, Merit Review, May 04)
	Max. Temperature	186 °C	SNL (Gross, JAC 02)
	Media Conductivity	< 1 W/m K	SNL (Wang, Merit Review, May 04)
	Media (hydrided) Specific Heat	1,418 J/kg K	SNL (Dedrick, JAC 04 - draft)
	Al Foam Conductivity	~52 W/m K	Metal Foams ~ k_{eff}=0.28$k_{Al@473K}$
	Al Specific Heat	~912 J/kg K	Aluminum alloy 2024 @473K
Mechanical	Max. Pressure	100 bar (1470 psi)	UTRC (Anton, Merit Review, May 04)
	Pressure Safety Factor	2.25	Industry standard
	Liner Thickness	2 mm (14 ga)	Estimate required for integrity

Table 20. Sodium Alanate Storage System Raw Material Design Assumptions

Raw Material	Material Cost $/kg	Weight Percent w/ $TiCl_3$	Weight Percent w/ Ti	Basis / Comment
Aluminum	1.80	45.4%	48.3%	London Metals Exchange
Sodium Hydride	3.50	40.3%	42.9%	"Sodium Hydride-based Hydrogen Storage", Powerball, Oct. 1999, DOE contract #DE-FC36_98GO10291.
Hydrogen	3.00	5.0%	5.4%	Consistent with DOE targets
Titanium Trichloride	4.70	9.3%	--	Average cost, including processing, listed in Kirk-Othmer
Titanium Powder	66	--	3.4%	"Summary of Emerging Titanium Cost Reduction Technologies", EHK Technologies, Jan. 2004, ORNL subcontract #4000023694.
Catalyzed NaAlH4 – mat'l only		**$2.81/kg**	**$4.80/kg**	Industry representatives roughly estimate material cost to be $3-5/kg, and ~$10/kg with processing costs at high volume (>100 t/yr)

The assumed material synthesis process is scaled-up from lab-scale production of catalyzed $NaAlH_4$. Table 21 shows the material flows of Al, NaH, H_2, and catalyst with two types of catalyst precursors ($TiCl_3$ and Ti).

The system cost for $NaAlH_4$ system is estimated to be $11/kWh. The main cost contributors for the 350-bar and 700-bar systems are the tank and BOP components, whereas in the $NaAlH_4$ system, both costs are reduced by more than half. However, in the $NaAlH_4$, a major cost factor is the media/hydrogen, at about 40 percent of the total cost.

As shown in Table 22, processing cost is estimated to be a relatively significant fraction of overall cost (14 percent), even at high production volumes (500,000 units per year).

Table 21. Sodium Alanate Storage System Catalyst Precursor Material Flows

Material Flows[1] (tonnes/yr)	Catalyst Precursor	
	$TiCl_3$	Ti
Al	39,170	34,973
NaH	34,840	31,107
H_2	4,355	3,885
Catalyst	*7,998*	*2,484*
$NaAlH_4$	**86,364**[2]	**72,449**

[1] Metric tons based on 500,000 units/yr, 5.6 kg/unit, and 100% process yield
[2] Includes weight of excess aluminum and inactive species, e.g., NaCl

Table 22. Base Case Material vs. Processing Cost Breakout for $NaAlH_4$ Systems

On-board System Cost Breakdown $NaAlH_4$ Storage System – 5.6 kg H_2	Material, $	Material Fraction	Processing, $	Processing Fraction
Catalyzed Media	$832	79%	$227	21%
Tank	$493	82%	$87	18%
Liner	$93	94%	$6	6%
Carbon Fiber	$258	92%	$21	8%
Glass Fiber	$25	63%	$15	37%
Al Foam	$44	68%	$20	32%
SS Filters	$19	70%	$8	30%
In-Tank HX	$39	73%	$15	27%
In-Tank Manifold	$15	89%	$2	11%
Dehydriding Syb-System	$445	94%	$186	6%
Dehydriding HX	$53	68%	$37	32%
Combustor	$32	96%	$32	4%
Accessories	$360	100%	$107	-
Balance of Plant	$512	100%	-	-
Assembly & Inspection	-	-	$40	-
Total Factory Cost	**$2,282**	**86%**	**$380**	**14%**

As seen in Figure 31, reversible hydrogen capacity of a media has the greatest impact on system cost. Low hydrogen capacity increases system cost by about 50 percent.

As seen in Figure 32, single-variable sensitivity analysis of the catalyzed media cost shows that $NaAlH_4$ ball mill yield and NaH costs have the biggest impact on the system cost projections. Both of these factors together account for 88 percent of the total media cost.

Multi-variable sensitivity analysis focuses on the catalyzed media costs, which range from \$4 to \$8/kg ($\pm 1\sigma$, μ=6, base case=5), driven primarily by ball mill yield and NaH raw material costs (Figure 33).

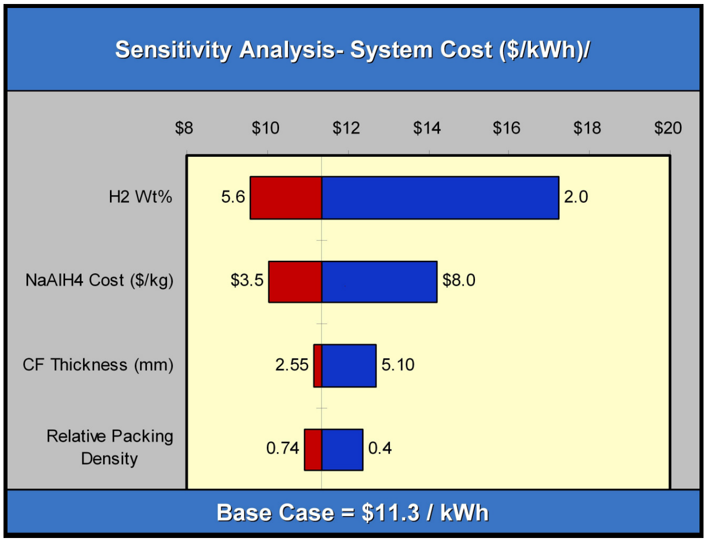


Figure 31. Single-Variable Cost Sensitivity for $NaAlH_4$ Systems

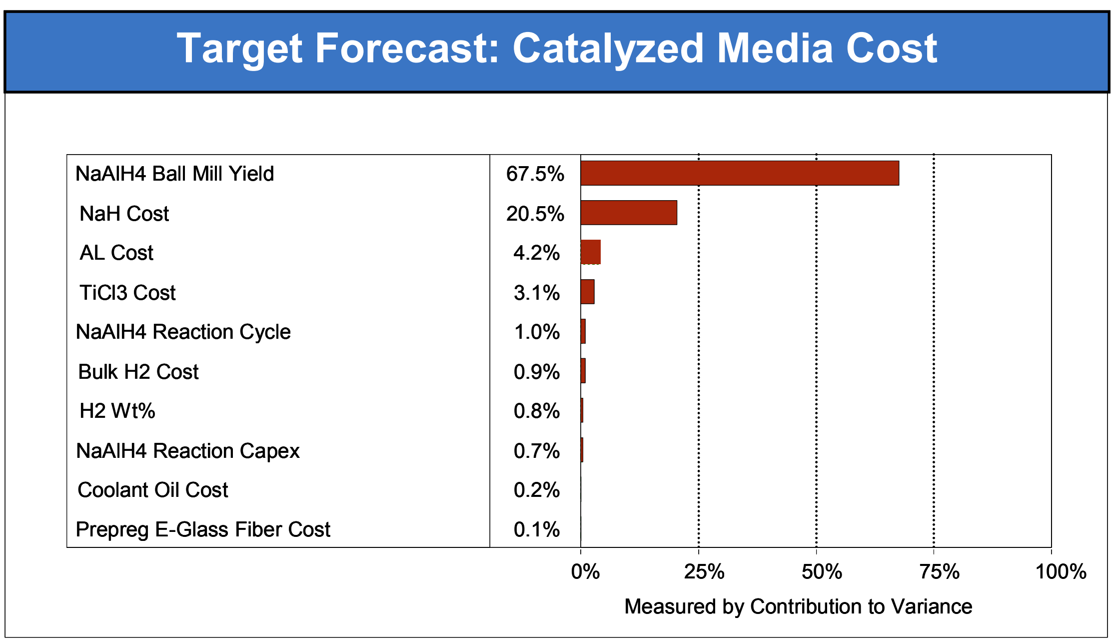


Figure 32. Single-Variable Catalyzed Media Cost Sensitivity for $NaAlH_4$ Systems

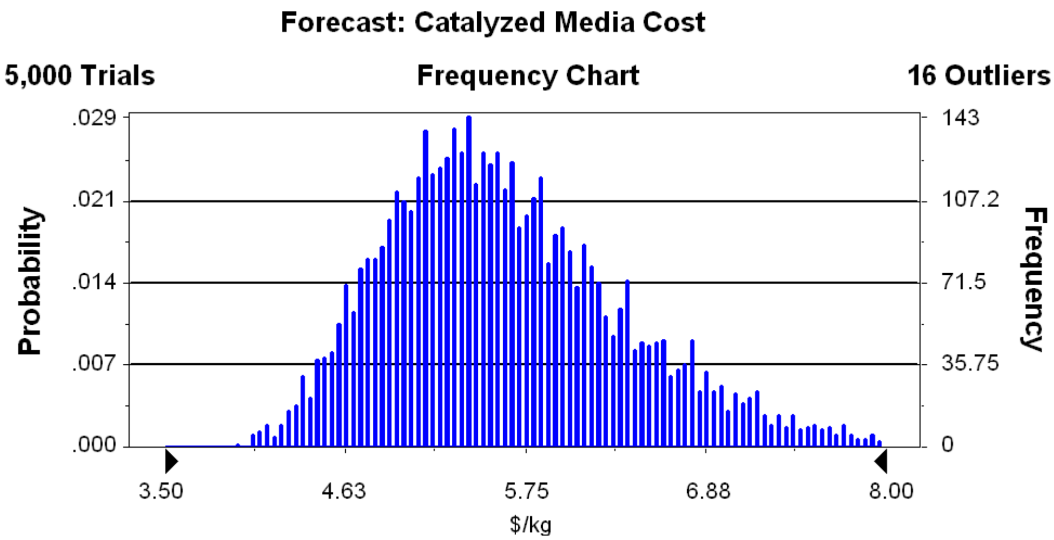


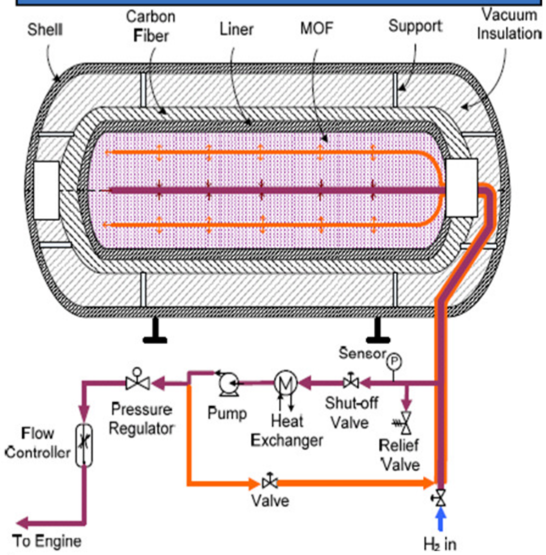
Figure 33. Multi-Variable Catalyzed Media Cost Frequency Chart for $NaAlH_4$ Systems

Better media storage capacity and thermal integration with the vehicle's power unit are critical to help achieve the DOE cost target for the sodium alanate system. Catalyzed $NaAlH_4$ cost of approximately $5.00/kg is too high for a material that achieves approximately 3 wt percent hydrogen capacity, which results in $5/kWh hydrogen for catalyzed material alone. In addition, high pressure requires the use of an expensive CF composite tank to keep the overall system weight down. Some alanates could have higher reversible weight percent but may have more challenging thermal requirements (i.e. desorption temperature and energy). Other technical material issues are kinetics, slow refueling and transient response, and cycling and poisoning impacts on hydrogen capacity over time. Finally, system integration is also a challenge. Thermal integration with the motive power source (e.g., fuel cell) is critical to meeting WTW efficiency and the on-board cost target. If hydrogen is needed for the dehydriding reaction, the system integration cost will be 1.24 times more.

4.1.5 MOF-177 Hydrogen Storage (March 20, 2012)

TIAX assessed the cost estimates for 5.6 and 10.4 kg systems using metal-organic framework (MOF)-177 storage media at high-volume (500,000 units per year) production (Figure 34). The cost of the MOF-177 system was assessed and compared to the DOE target. The analysis is based on a system designed by ANL to meet critical performance criteria. Costs are projected from a bottom-up estimate of raw material costs and manufacturing processing costs, plus purchased BOP components. With input and review from Ford and BASF, the cost of the MOF-177 media is estimated by examining the chemical reaction steps required to synthesize the material. The design assumptions for the MOF-177 system are presented in Table 23. The cost projections for major BOP components (estimated from vendor quotes, industry feedback, and bottom-up cost models) are presented in Table 24, with raw material cost assumptions shown in Table 25.

Sorbent System Design[1]



[1] Source: ANL. The Activated Carbon system uses an AX-21, rather than MOF sorbent but is similar in other respects

Parameter	Key System Specifications		
Sorbent material	AX-21	MOF-177	MOF-5
Nominal pressure & Temperature	250 atm, 110 K; and 50 atm, 147 K	250 atm, 100K	150 bar, 60 K
Usable H_2 storage capacity	5.6 kg	5.6 kg and 10.4 kg	5.6 kg
Carbon fiber	Toray T700S	Toray T700S	Toray T700S
Tank liner	Type III, Al6061-T6	Type III, Al6061-T6	Type III, Al6061-T6
Insulation type	MLVSI - Aluminized Mylar sheets w/Dacron spacer, 10^{-5} torr	MLVSI - Aluminized Mylar sheets w/Dacron spacer, 10^{-5} torr	MLVSI - Aluminized Mylar sheets w/Dacron spacer, 10^{-5} torr
Outer shell	Aluminum	Aluminum	Aluminum

Figure 34. Sorbent System Design

Table 23. MOF-177 Hydrogen Storage System Design Assumptions

MOF-177 Assumptions		
Design Parameter	**Base Case Value**	**Basis/Comment**
Nominal pressure	250 bar	ANL design assumption; optimized for storage densities
Minimum temperature	100 K	ANL design assumption; optimized for storage density
Minimum (empty) pressure	4 bar	Design assumption; required to meet DOE delivery pressure target
Usable LH_2 storage capacity	5.6 and 10.4 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range for midsized (5.6 kg) and larger vehicle (10.4 kg)
Recoverable hydrogen (fraction of stored H2)	95%	ANL calculation based on hydrogen storage density at maximum and minimum pressure and temperature conditions
Safety factor	2.25	Industry standard criteria (e.g., ISO/TS 15869) applied to nominal storage pressure
L/D ratio	2.0	Consistent with other cryo-tank assessments and discussions with LLNL and SCI, 2008; based on the outside of the CF wrapped tank
Carbon fiber type	Toray T700S	Discussions with LLNL, Quantum and other developers, 2008; assumed to have a composite strength of 2,550 MPa for 60% fiber by volume
Carbon fiber strength	2,550 MPa	Discussions with LLNL, Quantum and other developers, 2008; 60% fiber by volume
Adjustment for CF quality	10%	Reduction in average tensile strength to account for variance in CF quality, based on discussion with Quantum and other developers, 2010
Translation strength factor	86%	ANL assumption based on discussions and data from Quantum, 2004-09
Tank liner	8.6 mm Al6061-T6	ANL calculation based on cycle analysis, 5,500 PT cycles, 125% NWP
CF Weight	5.6 kg: 14.5 kg 10.4 kg: 26.4 kg	Design assumptions from ANL

Table 24. MOF-177 Hydrogen Storage System Cost Projections for Major BOP Components

Purchased Component Cost Est.	Base Cases ($ per unit)	Comments/Basis
Balance of Plant - $814		
Fill tube/port	$200	Capable of 2-way flows at high pressures and low temperatures without leaks; accepts signals from the nozzle at the fueling station to open or close; includes control valve
Blower	$126	From bottom-up costing of the Parker Hannifin Model 55 Univane rotary compressor
Pressure regulator	$160	Industry feedback validated with quotes and discussion with Emerson Process Mgmt/Tescom/Northeast Engineering (2009) and DFMA® cost modeling software
Control valve	$94	Industry feedback validated with quotes and discussion with Bertram Controls for Circle Seal solenoid control valve (2009)
Heat exchangers	$50	Industry feedback; includes a valve, ~3 meters of tubing and a conventional flat plat heat exchanger (or connection to vehicle waste heat source)
Pressure transducers	$60	Industry feedback validated with quotes and discussion with Taber Industries (2009)
Pressure relief valves	$70	Based on DFMA® cost modeling software
Pressure gauge	$17	Based on quotes from Emerson Process Mgmt/ Tescom/ Northeast Engineering (2009)
Other BOP	$38	Includes comm port, rupture disks, brackets, tubing, wiring, and misc hardware.
Balance of Tank - $68		
Level sensor (in tank)	$25	Industry feedback validated with discussions with tank developers
Boss and plug (in tank)	$15	Based on price estimate from tank developers (2009), validated with Al raw material price marked up for processing
Other Bal. of Tank	$18	Includes evacuation port & getter

Table 25. MOF-177 Hydrogen Storage System Raw Material Cost Assumptions

Raw Material Cost Estimates, $/kg	Base Cases	Comment/Basis
Hydrogen	3.0	Consistent with DOE H_2 delivery target
MOF-177	15.7	Estimates developed from bottom up analysis of MOF production process (details in the Appendix)
Aluminum (6061-T6)	9.6	Bulk price from Alcoa (2009), deflated to 2005$
Carbon fiber (T700S) prepreg	36.6	Discussion w/ Toray (2007) re: T700S fiber ($10-$16/lb, $13/lb base case, in 2005$); 1.27 prepreg/fiber ratio (Du Vall 2001)
Multi-layer vacuum insulation (MLVI)	50 ($0.15/ft^2)	Discussion with MPI (2007), reflects 2005$
Stainless steel (304)	4.7	Average monthly costs from Sep ’06 – Aug ’07 (MEPS International 2007) deflated to 2005$s by ~6%/yr
Standard steel	1.0	Estimate based on monthly costs for 2008-2009 (MEPS International 2009), deflated to 2005$

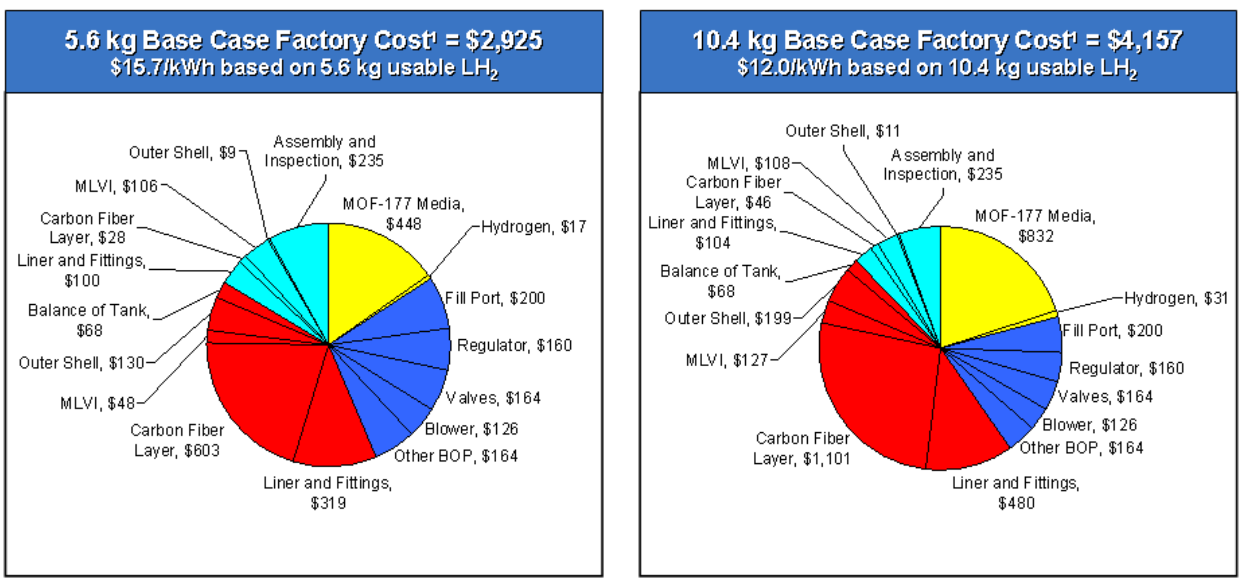
TIAX's MOF-177 cost assessment using base case assumptions projects system costs of $16 and $12/kWh for the 5.6 and 10.4 kg systems, respectively. As seen in Figure 35, the major cost drivers for both systems are storage media and CF. These two factors account for approximately 15 percent and 20 percent of the total system costs for the 5.6 kg system, and 20 and 25 percent of the total system costs for the 10.4 kg system. The figure shows material costs in red and processing costs in light blue. Achieving the 2010 DOE cost target of $4/kWh will likely require significant reductions in each of these costs, as well as further reductions in the cost of purchased BOP components.

As shown in Table 26, processing costs make up 16 and 12 percent of total system costs for the 5.6 kg and 10.4 kg systems, respectively.

As seen in Figure 36, the costs of aluminum and CF, and the safety factor have the biggest impact on the system cost projections.

According to the multi-variable sensitivity analysis results (Figure 37), the factory cost of the MOF-177 systems will likely range (95 percent confidence) between $15 and $20/kWh ($\pm 1\sigma$, $\mu=17$, base case=16) for the 5.6 kg system and between $11 and $15/kWh ($\pm 1\sigma$, $\mu=13$, base case=12) for the 10.4 kg system.

Meeting the DOE target with the MOF-177 storage system as designed will likely require significant reductions in the key cost components identified above or new system concepts. Using TIAX's base case assumptions, the storage media alone accounts for 15 to 20 percent of the total system cost, but given the lack of a commercial market, there is uncertainty in this estimate.

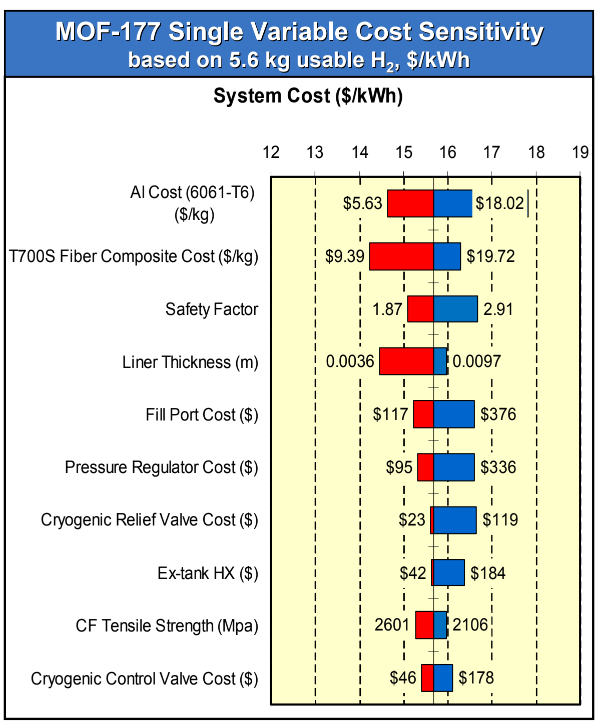


[1] Cost estimate in 2005 USD. Processing costs are shown separately (light blue fractions).

Figure 35. Base Case Component Cost Breakout for the MOF-177 Hydrogen Storage Systems (with Pre-Preg CF)

Table 26. Base Case Material vs. Processing Cost Breakout for MOF-177 Hydrogen Storage Systems

On-board System Cost Breakout – MOF-177	5.6 kg Base Case				10.4 kg Base Case			
	Material, $	Material Fraction	Processing, $	Processing Fraction	Material, $	Material Fraction	Processing, $	Processing Fraction
Hydrogen	$17	100%	(purchased)	-	$31	100%	(purchased)	-
MOF-177	$448	100%	(purchased)	-	$832	100%	(purchased)	-
Cryogenic Vessel	$1,168	83%	$243	17%	$1,976	88%	$269	12%
Liner & Fittings	*$319*	*76%*	*$100*	*24%*	*$480*	*82%*	*$104*	*18%*
Carbon Fiber Layer	*$603*	*96%*	*$28*	*4%*	*$1,101*	*96%*	*$46*	*4%*
MLVI	*$48*	*31%*	*$106*	*69%*	*$127*	*54%*	*$108*	*46%*
Outer Shell	*$130*	*93%*	*$9*	*7%*	*$199*	*95%*	*$11*	*5%*
Balance of Tank	*$68*	*100%*	*(purchased)*	*-*	*$68*	*100%*	*(purchased)*	*-*
Fill Port	$200	100%	(purchased)	-	$200	100%	(purchased)	-
Regulator	$160	100%	(purchased)	-	$160	100%	(purchased)	-
Valves	$164	100%	(purchased)	-	$164	100%	(purchased)	-
Blower	$126	100%	(purchased)	-	$126	100%	(purchased)	-
Other BOP	$164	100%	(purchased)	-	$164	100%	(purchased)	-
Final Assembly & Inspection	-	-	$235	-	-	-	$235	-
Total Factory Cost	**$2,447**	**84%**	**$478**	**16%**	**$3,653**	**88%**	**$504**	**12%**



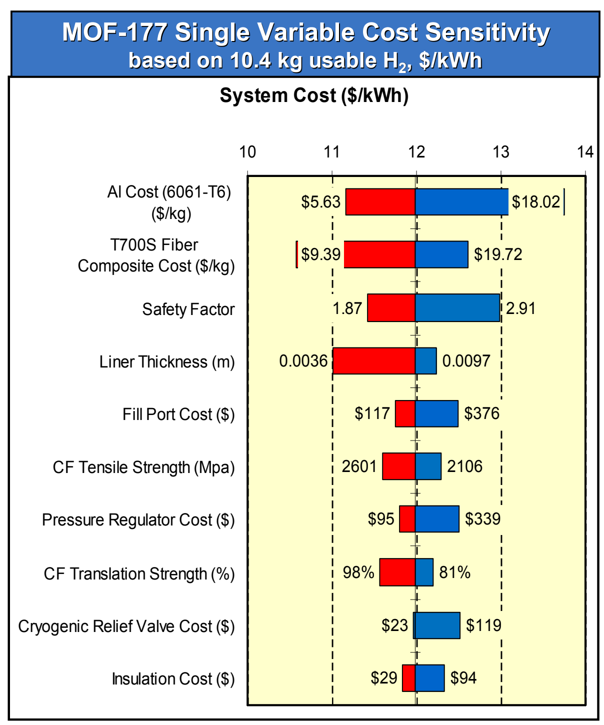


Figure 36. Single-Variable Cost Sensitivity for MOF-177 Systems

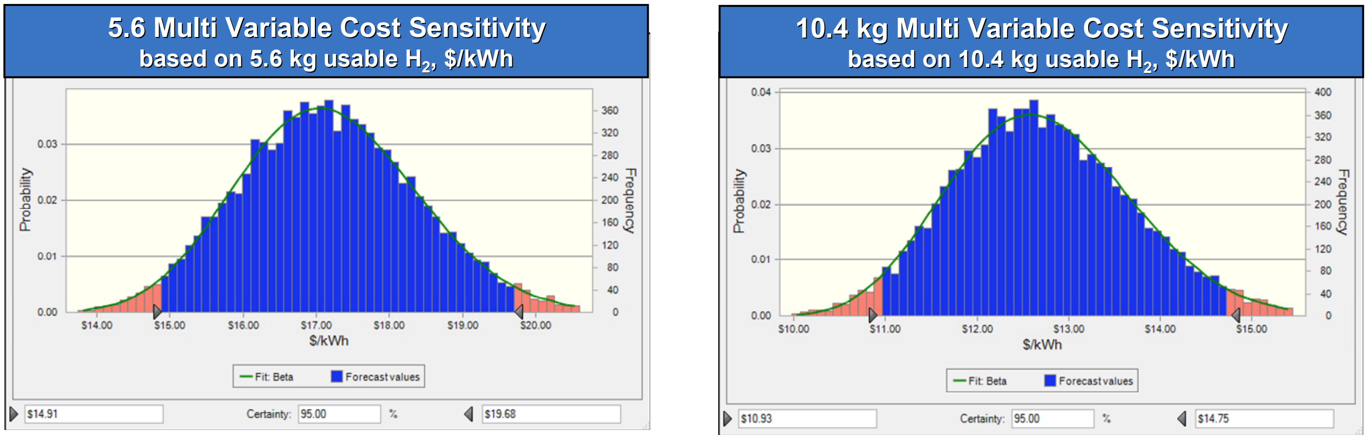


Figure 37. Multi-Variable Cost Sensitivity for the MOF-177 Systems

4.1.6 MOF-5 Hydrogen Storage (March 20, 2012)

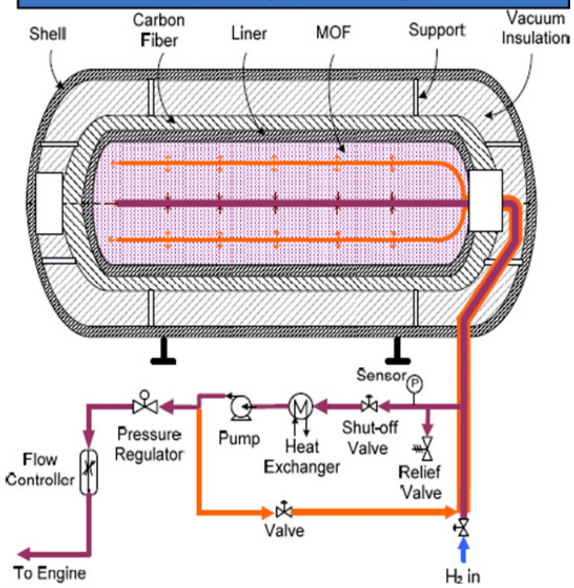
TIAX further assessed the cost estimates for a 5.6 kg system using MOF-5 storage media at high-volume (500,000 units per year) production (Figure 38). The cost of the MOF-5 system was based on the MOF-177 system, with input and review from Ford and BASF. The design assumptions for the MOF-5 system are presented in Table 27. The input assumptions for MOF-5 cost assessment are derived from ANL's performance models and discussions with developers. The cost projections for major BOP components are presented in Table 28, with raw material cost assumptions shown in Table 29.

The costs of key processing steps are estimated from capital equipment, labor, and other operating costs assuming a high level of automation. Compared to MOF-177, the final inspection and assembly process step for MOF-5 includes the additional costs associated with a facility built to handle moisture-sensitive materials, which increases costs by $0.2/kWh within the cost model.

The chemical precursors used to synthesize MOF-5 and MOF-177 differ, but they have similar production processes and the same manufacturing steps. The process for manufacturing MOF-5 and MOF-177 entails heating a mixture of organic linker and metal salt (ZnO or ZnNO3) in a solvent. TIAX has assumed that both materials are manufactured using the same processes, and reactions occur under identical process conditions. In reality, the scaled-up manufacturing processes are likely to differ, but available information is insufficient to capture these nuances.

MOF-5 and MOF-177 costs differ due to the differing cost of the organic linker and their differing reactant flow rates (Tables 39 and 40). The MOF-5 linker (terephthalic acid, BDC) is commercially available. The existing market is about 40 million metric tons per year. The MOF-177 linker (benzene tribenzoate, BTB) does not have a commercial market and requires a more complex manufacturing process. Our "high" BTB cost includes a 2.5 times premium relative to BDC due to the process complexity, and a three times premium due to expected lower-volume production (consistent with a PR of 0.85). Due to its lower molecular weight and higher ratio of linker to product, MOF-5 uses more zinc salt on a mass basis than MOF-177, leading to higher equipment size, utility usage, and non-linker reactant costs.

Sorbent System Design[1]



[1] Source: ANL. The Activated Carbon system uses an AX-21, rather than MOF sorbent but is similar in other respects

Parameter	Key System Specifications		
Sorbent material	AX-21	MOF-177	MOF-5
Nominal pressure & Temperature	250 atm, 110 K; and 50 atm, 147 K	250 atm, 100K	150 bar, 60 K
Usable H_2 storage capacity	5.6 kg	5.6 kg and 10.4 kg	5.6 kg
Carbon fiber	Toray T700S	Toray T700S	Toray T700S
Tank liner	Type III, Al6061-T6	Type III, Al6061-T6	Type III, Al6061-T6
Insulation type	MLVSI - Aluminized Mylar sheets w/Dacron spacer, 10^{-5} torr	MLVSI - Aluminized Mylar sheets w/Dacron spacer, 10^{-5} torr	MLVSI - Aluminized Mylar sheets w/Dacron spacer, 10^{-5} torr
Outer shell	Aluminum	Aluminum	Aluminum

Figure 38. Sorbent System Design

Table 27. MOF-5 Hydrogen Storage System Design Assumptions

MOF-5 Assumptions		
Design Parameter	**Base Case Value**	**Basis/Comment**
Nominal pressure	150 bar	ANL design assumption; optimized for storage densities
Minimum temperature	60 K	ANL design assumption; optimized for storage density
Minimum (empty) pressure	4 bar	Design assumption; required to meet DOE delivery pressure target
Usable LH_2 storage capacity	5.6 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range for midsized (5.6 kg) and larger vehicle (10.4 kg)
Recoverable hydrogen (fraction of stored H2)	90%	ANL calculation based on hydrogen storage density at maximum and minimum pressure and temperature conditions
Safety factor	2.25	Industry standard criteria (e.g., ISO/TS 15869) applied to nominal storage pressure
L/D ratio	2.0	Consistent with other cryo-tank assessments and discussions with LLNL and SCI, 2008; based on the outside of the CF wrapped tank
Carbon fiber type	Toray T700S	Discussions with LLNL, Quantum and other developers, 2008; assumed to have a composite strength of 2,550 MPa for 60% fiber by volume
Carbon fiber strength	2,550 MPa	Discussions with LLNL, Quantum and other developers, 2008; 60% fiber by volume
Adjustment for CF quality	10%	Reduction in average tensile strength to account for variance in CF quality, based on discussion with Quantum and other developers, 2010
Translation strength factor	86%	ANL assumption based on discussions and data from Quantum, 2004-09
Tank liner	5.5 mm Al6061-T6	ANL calculation based on cycle analysis, 5,500 PT cycles, 125% NWP
CF Weight	8.1 kg	Design assumptions from ANL

Table 28. MOF-5 Hydrogen Storage System Cost Projections for Major BOP Components

Purchased Component Cost Est.	Base Cases ($ per unit)	Comments/Basis
Balance of Plant - $814		
Fill tube/port	$200	Capable of 2-way flows at high pressures and low temperatures without leaks; accepts signals from the nozzle at the fueling station to open or close; includes control valve
Blower	$126	From bottom-up costing of the Parker Hannifin Model 55 Univane rotary compressor
Pressure regulator	$160	Industry feedback validated with quotes and discussion with Emerson Process Mgmt/Tescom/Northeast Engineering (2009) and DFMA® cost modeling software
Control valve	$94	Industry feedback validated with quotes and discussion with Bertram Controls for Circle Seal solenoid control valve (2009)
Heat exchangers	$50	Industry feedback; includes a valve, ~3 meters of tubing and a conventional flat plat heat exchanger (or connection to vehicle waste heat source)
Pressure transducers	$60	Industry feedback validated with quotes and discussion with Taber Industries (2009)
Pressure relief valves	$70	Based on DFMA® cost modeling software
Pressure gauge	$17	Based on quotes from Emerson Process Mgmt/ Tescom/ Northeast Engineering (2009)
Other BOP	$38	Includes comm port, rupture disks, brackets, tubing, wiring, and misc hardware.
Balance of Tank - $68		
Level sensor (in tank)	$25	Industry feedback validated with discussions with tank developers
Boss and plug (in tank)	$15	Based on price estimate from tank developers (2009), validated with Al raw material price marked up for processing
Other Bal. of Tank	$18	Includes evacuation port & getter

Table 29. MOF-5 Hydrogen Storage System Raw Material Cost Assumptions

Raw Material Cost Estimates, $/kg	Base Cases	Comment/Basis
Hydrogen	3.0	Consistent with DOE H_2 delivery target
MOF-5	11.8	Estimates developed from bottom up analysis of MOF production process (details in the Appendix)
Aluminum (6061-T6)	9.6	Bulk price from Alcoa (2009), deflated to 2005$
Carbon fiber (T700S) prepreg	36.6	Discussion w/ Toray (2007) re: T700S fiber ($10-$16/lb, $13/lb base case, in 2005$); 1.27 prepreg/fiber ratio (Du Vall 2001)
Multi-layer vacuum insulation (MLVI)	50 ($0.15/ft^2)	Discussion with MPI (2007), reflects 2005$
Stainless steel (304)	4.7	Average monthly costs from Sep '06 – Aug '07 (MEPS International 2007) deflated to 2005$s by ~6%/yr
Standard steel	1.0	Estimate based on monthly costs for 2008-2009 (MEPS International 2009), deflated to 2005$

Table 30. Input Assumptions for MOF-5 and MOF-177

Input Assumptions (per kg MOF)		
Design Parameter	**MOF-5**	**MOF-177**
Zn(AC)2 Usage	1.0 kg	0.7 kg
Linker Usage	0.7 kg	0.8 kg
DEF[1] (99% recycle)	118 kg	62 kg
Nitrogen	2.9 kg	1.5 kg
Acetone	0.28 kg	0.15 kg
Electricity	6.3 kWh	3.3 kWh
Natural Gas	0.0002 GJ	0.0001 GJ
Process Water	16 gal	7
Linker cost	$1.45	$8
Capital Cost (Total)	$85M	$66M

Table 31. Estimated MOF-5 and MOF-177 Production Costs

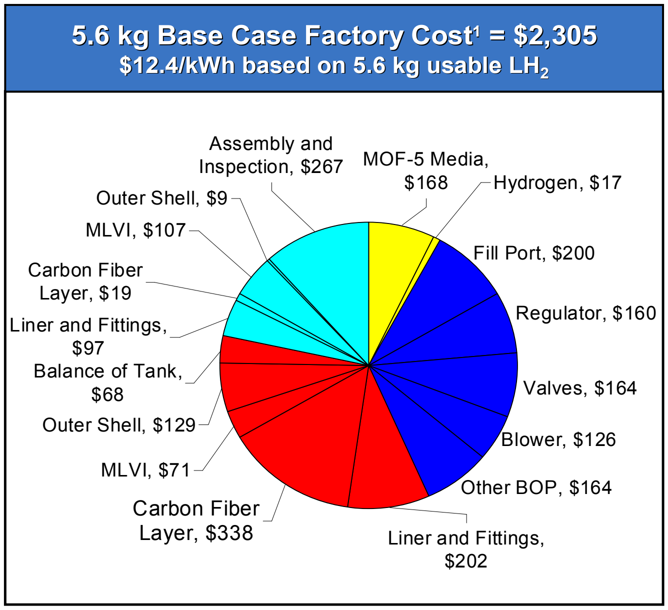
Price Comparison ($/kg MOF)		
Design Parameter	**MOF-5**	**MOF-177**
Linker Cost	$1.0	$6.4
Other Material Cost	$5.2	$3.2
Utility Cost	$0.4	$0.2
Fixed O&M	$1.0	$1.1
Capital Cost	$2.3	$1.9
Sub-total	$9.9	$12.8
Total (w/1.3X Markup)	**$11.8**	**$15.7**

As shown in Figure 39, MOF-5 system cost includes roughly equal contributions from CF, liner and fittings, MOF storage media, and assembly and inspection. BOP components account for about 35 percent of the total system cost. The figure shows material costs in red and processing costs in light blue. Table 32 shows that processing costs make up 22 percent of the total cost due to the time-consuming processing steps, even at assumed high production volumes.

As shown in Figure 40, the cost and thickness of the aluminum liner for MOF-5 systems have relatively strong effects on system cost.

As seen in Figure 41, the factory cost of the MOF-5 system will likely range (95 percent confidence) between $12 and $16/kWh ($\pm 2\sigma$, μ=13, base case=12).

Meeting the DOE target with the MOF-5 storage system as designed will likely require significant reductions in the key cost components identified above, and/or new system concepts.



[1] Cost estimate in 2005 USD. Processing costs are shown separately (light blue fractions).

Figure 39. Base Case Component Cost Breakout for MOF-5 System (with Pre-Preg CF)

Table 32. Base Case Material vs. Processing Cost Breakout for MOF-5 Systems

On-board System Cost Breakout – MOF-5	5.6 kg Base Case			
	Material, $	Material Fraction	Processing, $	Processing Fraction
Hydrogen	$17	100%	(purchased)	-
MOF-5	$168	100%	(purchased)	-
Cryogenic Vessel	$807	78%	$232	22%
Liner & Fittings	$202	68%	$97	32%
Carbon Fiber Layer	$338	95%	$19	5%
MLVI	$71	40%	$107	60%
Outer Shell	$129	93%	$9	7%
Balance of Tank	$68	100%	(purchased)	-
Fill Port	$200	100%	(purchased)	-
Regulator	$160	100%	(purchased)	-
Valves	$164	100%	(purchased)	-
Blower	$126	100%	(purchased)	-
Other BOP	$164	100%	(purchased)	-
Final Assembly & Inspection	-	-	$267	-
Total Factory Cost	**$1,806**	**78%**	**$499**	**22%**

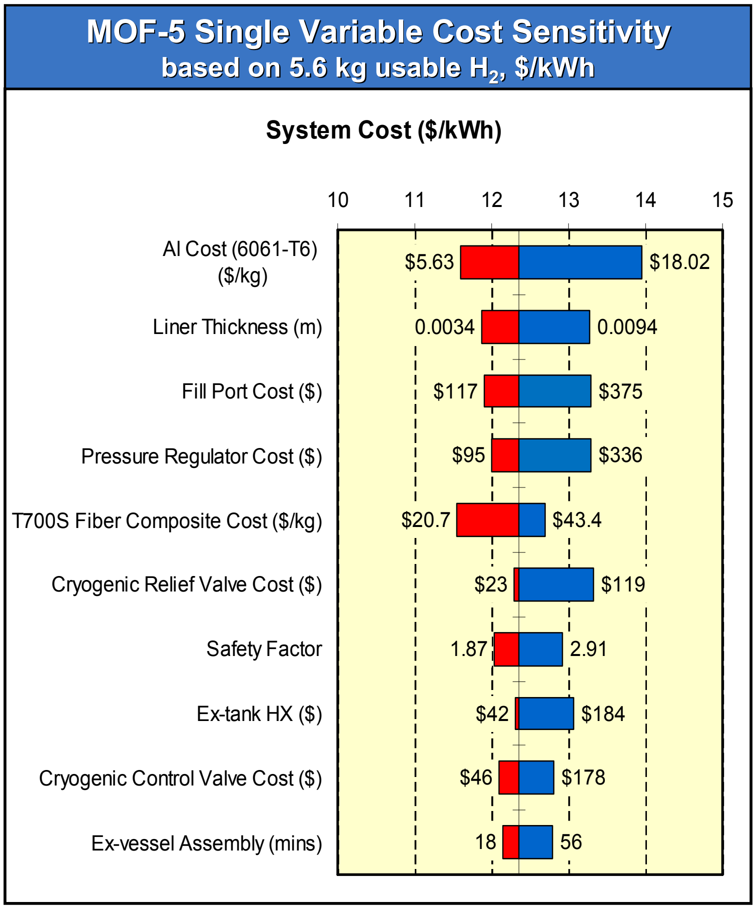


Figure 40. Single-Variable Cost Sensitivity for MOF-5

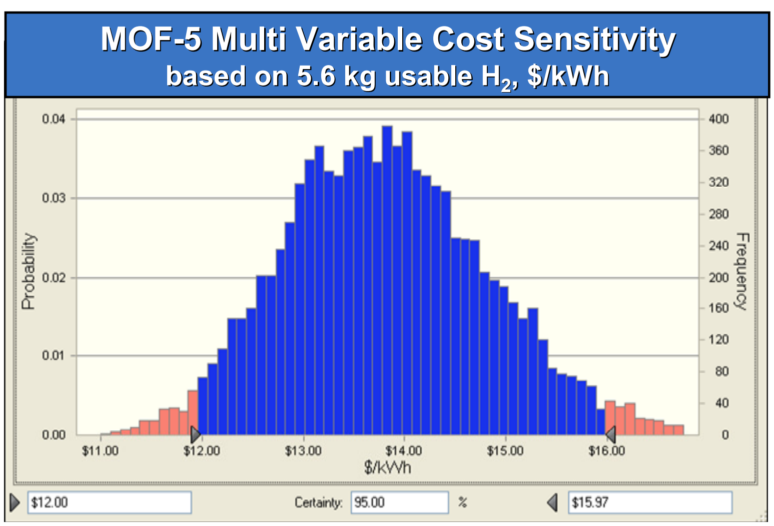


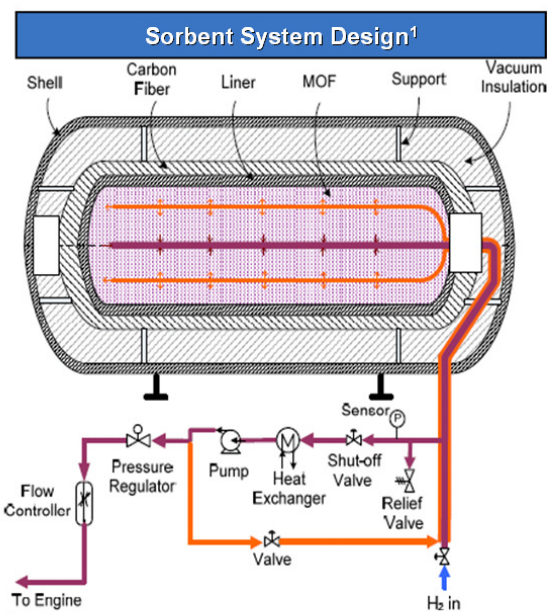
Figure 41. Multi-Variable Cost Sensitivity for MOF-5 Systems

4.1.7 AX-21 Activated Carbon Hydrogen Storage (March 20, 2012)

The cost of the activated carbon (AC) storage system has been assessed and compared to the DOE target. The on-board and high-volume manufacturing (500,000 units per year) costs were determined for AC system of 5.6 kg usable hydrogen, with design pressures of 250 atm and 50 atm for storing 6.4 kg and 6.8 kg of total hydrogen, respectively (Figure 42). The design assumptions for the AC storage system are presented in Table 33. The cost projections for major BOP components are presented in Table 34, with raw material cost assumptions shown in Table 35.

TIAX's AC system cost assessment project results indicate that the 250-atm activated carbon system will cost $18/kWh at high production volumes. The 50-atm AC system, which requires a much larger tank, is projected to cost $27/kWh. As seen in Figure 43, the major cost drivers for the 250-atm AC system include the storage media, BOP, and the CF vessel. Each accounts for approximately 20 percent of the system cost. The major cost driver for the 50-atm AC system is the storage media, which accounts for 45 percent of the system cost. The figure shows material costs in red and processing costs in light blue.

As shown in Table 36, processing cost makes up 16 percent of the 250-atm AC system and 11 percent of the 50-atm AC system cost, even at assumed high production volumes. For reference, this estimate is similar to those for the MOF-177 system evaluated in Section 4.1.5 (12 to 16 percent) and the cryo-compressed system in Section 4.1.3 (17 to 21 percent). However, the processing cost fraction is significantly higher than the processing cost for previously evaluated 350 and 700-bar systems in Section 4.1.1 (4 to 5 percent). This additional cost is due to the complexity associated with the low temperature, insulated tanks compared to the compressed systems. The AX-21 media are major cost drivers for both systems, with the CF, liner, and assembly costs also contribute significant fractions.



[1] Source: ANL. The Activated Carbon system uses an AX-21, rather than MOF sorbent but is similar in other respects

Parameter	Key System Specifications		
Sorbent material	AX-21	MOF-177	MOF-5
Nominal pressure & Temperature	250 atm, 110 K; and 50 atm, 147 K	250 atm, 100K	150 bar, 60 K
Usable H_2 storage capacity	5.6 kg	5.6 kg and 10.4 kg	5.6 kg
Carbon fiber	Toray T700S	Toray T700S	Toray T700S
Tank liner	Type III, Al6061-T6	Type III, Al6061-T6	Type III, Al6061-T6
Insulation type	MLVSI - Aluminized Mylar sheets w/Dacron spacer, 10^{-5} torr	MLVSI - Aluminized Mylar sheets w/Dacron spacer, 10^{-5} torr	MLVSI - Aluminized Mylar sheets w/Dacron spacer, 10^{-5} torr
Outer shell	Aluminum	Aluminum	Aluminum

Figure 42. Sorbent System Design

Table 33. AC Hydrogen Storage System Design Assumptions

Activated Carbon Assumptions			
Design Parameter	**250 atm**	**50 atm**	**Basis/Comment**
Minimum temperature	110 K	147 K	ANL design assumption for 250 atm and 50 atm, respectively
Minimum (empty) pressure	4 bar	4 bar	Design assumption; required to meet DOE delivery pressure target
Media packing density	300 kg/m^3	300 kg/m^3	Richard et al 2009[1]
Usable LH_2 storage capacity	5.6 kg	5.6 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range for midsized (5.6 kg) vehicle
Recoverable hydrogen (fraction of stored hydrogen)	87.5%	82.4%	ANL calculation based on hydrogen storage density at maximum and minimum pressure and temperature conditions for 250 atm and 50 atm, respectively
Tank Liner	8.6 mm Al6061-T6	2.2 mm Al6061-T6	ANL calculation based on cycle analysis for AL6061-T6 alloy, 5,500 PT cycles, 125% NWP
Safety factor	2.25	2.25	Industry standard criteria (e.g., ISO/TS 15869) applied to nominal storage pressure
L/D ratio	2.0	2.0	Consistent with other cryo-tank assessments and discussions with LLNL and SCI, 2008; based on the outside of the CF wrapped tank
Carbon fiber strength	2,550 MPa	2,550 MPa	Discussions with LLNL, Quantum and other developers, 2008; 60% fiber by volume
Adjustment for CF quality	10%	10%	Reduction in average tensile strength to account for variance in CF quality, based on discussion with Quantum and other developers, 2010
Translation strength factor	86.4%	89.3%	Linear correlation based on data from Quantum, 2004-2009, for 250 atm, and 50 atm, respectively
CF Weight	17.3 kg	11.0 kg	Design assumptions from ANL

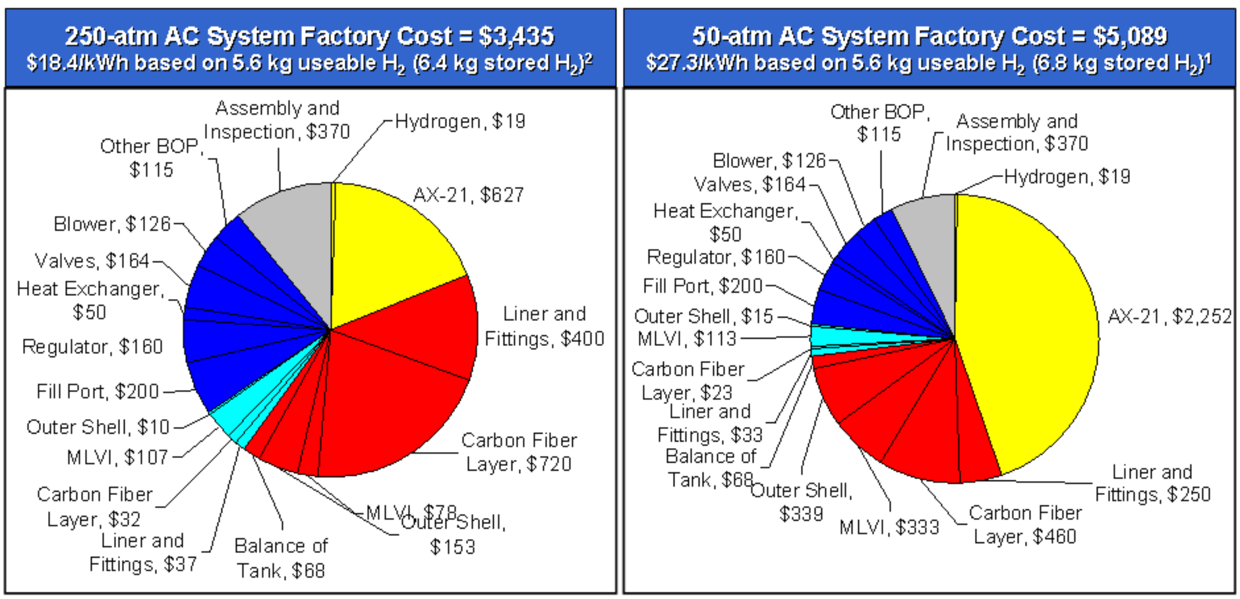
[1]M-A Richard, P. Benard, R. Chahine. "Gas Adsorption Process in Activated Carbon Over a Wide Temperature Range Above the Critical Point. Part 1: Modified Dubinin-Astakhov Model." Adsorption, 15, 43-51, 2009.

Table 34. AC Hydrogen Storage System Cost Projections for Major BOP Components

Purchased Component Cost Est.	Base Cases ($ per unit)	Comments/Basis
Balance of Plant - $814		
Fill tube/port	$200	Capable of 2-way flows at high pressures and low temperatures without leaks; accepts signals from the nozzle at the fueling station to open or close; includes control valve
Blower	$126	From bottom-up costing of the Parker Hannifin Model 55 Univane rotary compressor
Pressure regulator	$160	Industry feedback validated with quotes and discussion with Emerson Process Mgmt/Tescom/Northeast Engineering (2009) and DFMA® cost modeling software
Control valve	$94	Industry feedback validated with quotes and discussion with Bertram Controls for Circle Seal solenoid control valve (2009)
Heat exchangers	$50	Industry feedback; includes a valve, ~3 meters of tubing and a conventional flat plat heat exchanger (or connection to vehicle waste heat source)
Pressure transducers	$60	Industry feedback validated with quotes and discussion with Taber Industries (2009)
Pressure relief valves	$70	Based on DFMA® cost modeling software
Pressure gauge	$17	Based on quotes from Emerson Process Mgmt/ Tescom/ Northeast Engineering (2009)
Other BOP	$38	Includes comm port, rupture disks, brackets, tubing, wiring, and misc hardware.
Balance of Tank - $68		
Level sensor (in tank)	$25	Industry feedback validated with discussions with tank developers
Boss and plug (in tank)	$15	Based on price estimate from tank developers (2009), validated with Al raw material price marked up for processing
Other Bal. of Tank	$18	Includes evacuation port & getter

Table 35. AC Hydrogen Storage System Raw Material Cost Assumptions

Raw Material Cost Estimates, $/kg	Base Cases	Comment/Basis
Hydrogen	3.0	Consistent with DOE H_2 delivery target
AX-21	15.4	Cost estimate from Kansai Coke and Chemical Co DTI (1996), projected for high volume and 2005 dollars (details in the appendix).
Aluminum (6061-T6)	9.6	Bulk price from Alcoa (2009), deflated to 2005$
Carbon fiber (T700S) prepreg	36.6	Discussion w/ Toray (2007) re: T700S fiber ($10-$16/lb, $13/lb base case, in 2005$); 1.27 prepreg/fiber ratio (Du Vall 2001)
Multi-layer vacuum insulation (MLVI)	50 ($0.15/ft^2)	Discussion with MPI (2007), reflects 2005$
Stainless steel (304)	4.7	Average monthly costs from Sep '06 – Aug '07 (MEPS International 2007) deflated to 2005$s by ~6%/yr
Standard steel	1.0	Estimate based on monthly costs for 2008-2009 (MEPS International 2009), deflated to 2005$



Note: Cost estimates are in 2005 USD. Processing costs are shown separately (light blue fractions).
[1] 50 atm results are based on 14.0 kg of H_2 per cubic meter of media total, 11.5 kg of H_2 per cubic meter of media recoverable.
[2] 250 atm results are based on 47.2 kg of H2 per cubic meter of media total, 41.3 kg of H2 per cubic meter of media recoverable.

Figure 43. Base Case Component Breakout for the AC Hydrogen Storage Systems (with Pre-Preg CF)

Table 36. Base Case Material vs. Processing Cost Breakout for AC Hydrogen Storage Systems

On-board System Cost Breakout – AX-21	250 atm Base Case				50 atm Base Case			
	Material, $	Material Fraction	Processing, $	Processing Fraction	Material, $	Material Fraction	Processing, $	Processing Fraction
Hydrogen	$19	100%	(purchased)	-	$19	100%	(purchased)	-
AX-21	$627	100%	(purchased)	-	$2,252	100%	(purchased)	-
Cryogenic Vessel	$1,419	88%	$186	12%	$1,450	89%	$184	11%
Liner & Fittings	$400	82%	$37	8%	$250	88%	$33	12%
Carbon Fiber Layer	$720	96%	$32	4%	$460	95%	$23	5%
MLVI	$78	42%	$107	58%	$333	75%	$113	25%
Outer Shell	$153	94%	$10	6%	$339	96%	$15	4%
Balance of Tank	$68	100%	(purchased)	-	$68	100%	(purchased)	-
Fill Port	$200	100%	(purchased)	-	$200	100%	(purchased)	-
Regulator	$160	100%	(purchased)	-	$160	100%	(purchased)	-
Heat Exchanger	$50	100%	(purchased)	-	$50	100%	(purchased)	-
Valves	$164	100%	(purchased)	-	$164	100%	(purchased)	-
Blower	$126	100%	(purchased)	-	$126	100%	(purchased)	-
Other BOP	$115	100%	(purchased)	-	$115	100%	(purchased)	-
Final Assembly & Inspection	-	-	$370	-	-	-	$370	-
Total Factory Cost	**$2,880**	**84%**	**$556**	**16%**	**$4,535**	**89%**	**$554**	**11%**

As shown in Figure 44, the costs of aluminum and AX-21 media have the strongest effects on the total costs of the 250- and 50-atm systems, while AX-21 storage density also has a strong effect on total cost of the 50-atm system.

According to the multi-variable sensitivity analysis results (Figure 45), the factory cost of the AC systems will likely range (95 percent confidence) between \$16 and \$19/kWh ($\pm 1\sigma$, μ=17, base case=18) for the 250-atm system and between \$23 and \$32/kWh ($\pm 2\sigma$, μ=27, base case=27) for the 50-atm system.

The AX-21 system is projected to be more expensive, on a per-kWh basis, than the MOF-177 systems above. The high-pressure (250-atm) AX-21 system cost is projected to be \$18/kWh. The onboard characteristics of the 50-atm AC system are significantly less attractive than the 250-atm system at a projected cost of \$27/kWh.

The major cost drivers for the AC systems are similar to those of the MOF-177 systems. They include the cost of storage media, aluminum, CF, and the BOP components. As is the case for the MOF-177 system, meeting the DOE 2010 cost target with the AC system as designed will require across-the-board cost reductions and/or new system designs. The storage media alone contributes \$3/kWh for the 250-atm system, and \$12/kWh for the 50-atm system.

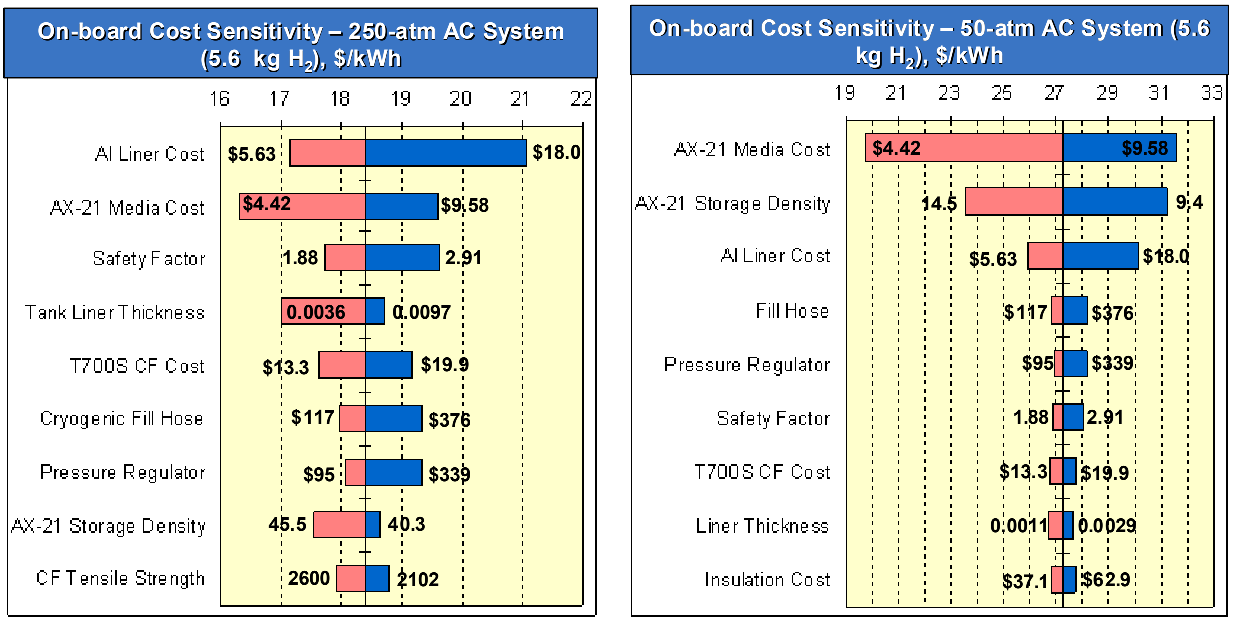


Figure 44. Single-Variable Cost Sensitivity for the AC Systems

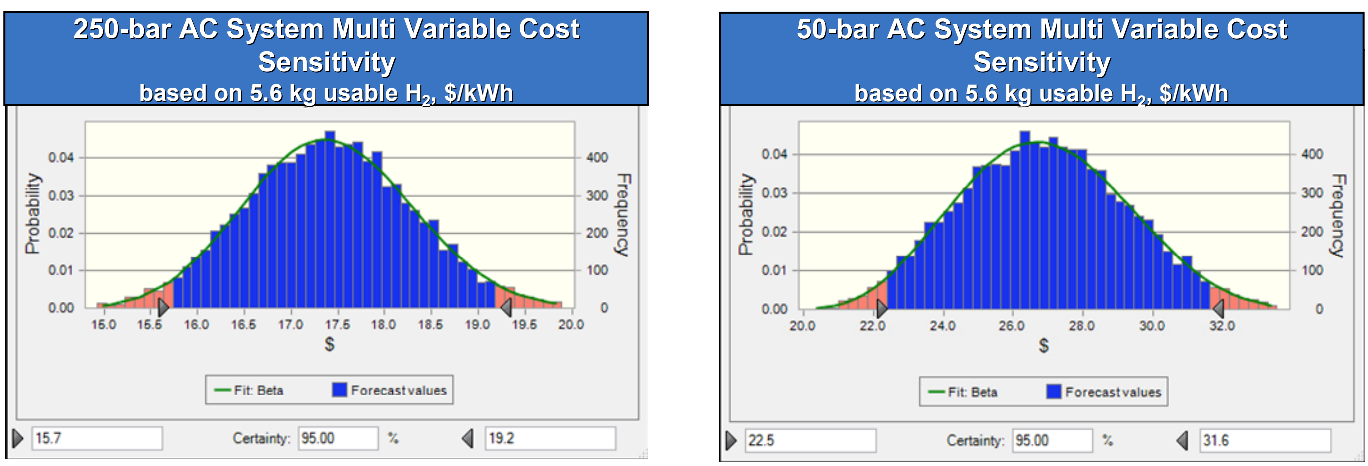


Figure 45. Multi-Variable Cost Sensitivity for AC Systems

4.2 Off-Board Analysis

4.2.1 Liquid Hydrogen Carrier (September 14, 2010)

The cost assessment performed by TIAX is based on N-ethylcarbazole, a liquid hydrogen carrier (LCH_2) investigated by Air Products (APCI), to reversibly adsorb and desorb hydrogen. The liquid carrier is hydrogenated (regenerated) at a central facility and dehydrogenated on-board the vehicle (Figure 46). The benefits of a liquid carrier over compressed, liquid, and other forms of hydrogen storage are ease of and safety during transport and storage. The regenerated liquid carrier can be transported and stored in tanks designed for standard hydrocarbons. The main drawbacks of a liquid carrier, and specifically this liquid carrier, are increased thermal requirements for dehydrogenation that exceed the PEM operating temperatures and the requirement of insulated or heated storage and transport tanks of the dehydrogenated carrier to keep it above its melting point of 70°C.

TIAX used 2008 prices for the key raw materials of LCH_2 and subsequently deflated all material prices by 9.27 percent to 2005 USD (Table 37).

We based the cost of purchased components on vendor quotes/catalog prices, using our judgment to adjust for high-volume production (Table 38). Costs range from \$44 for pressure regulators to \$400 for the heat transfer fluid (HTF) pump and hydrogen/air non-catalytic burner. The costs of the purchased components add up to a total cost of \$1,294.

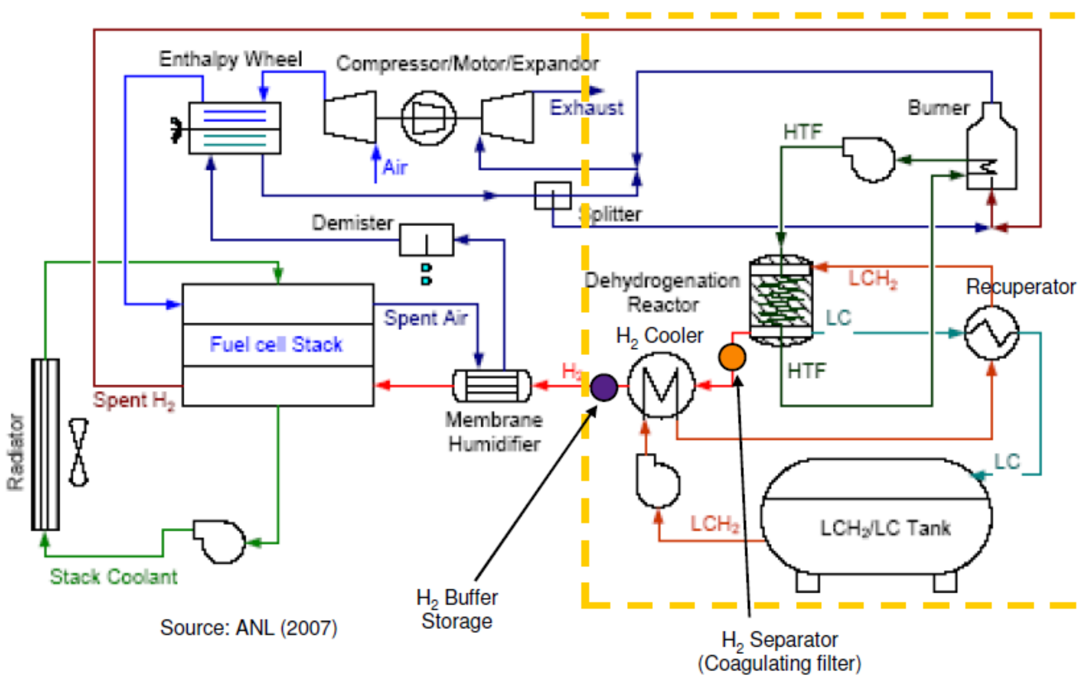


Figure 46. Schematic of Liquid Hydrogen Carrier System

Table 37. Liquid Carrier Raw Material Prices

System Element	Raw Material	Price (2005$)	Basis/Comment
Media	N-ethylcarbazole	$6.35/gal	APCI; $2-12/gal range (2008$), deflated to 2005$; consistent with TIAX off-board LCH_2 storage system assessment
LCH_2/LC Storage Tank	HDPE	$1.6/kg	Plastics Technology, May 2008, pg. 95, deflated to 2005$
Dehydrogenation Reactor	Pd catalyst	$12.7/g ($395/tr.oz.)	www.metalprices.com; June, 2008, deflated to 2005$
	Li Aluminate	$43.8/kg	Sigma-Aldrich[1], deflated to 2005$
	Al-6101	$9.6/kg	Bulk price from Alcoa (2009), deflated to 2005$
	Al-2219-T81	$12.7/kg	Assumed 30% higher price than AL-6101, based on spread in price between Al-6101 and Al-2219 from 2008
	HTF (XCelTherm® 600)	$7.26/gal	RadCo Industries, Inc., June 2008, deflated to 2005$
HEX Burner	Inconel 600	$15.0/kg	www.metalprices.com; June, 2008, deflated to 2005$
H_2 Cooler, Recuperator	SS316	$7.26/kg	www.metalprices.com; June, 2008, 1-year avg, deflated to 2005$.

Table 38. Liquid Carrier Major Purchased Component Costs Based upon Weight and Volume

Purchased Component	Weight (kg)	Volume (L)	Cost ($)	Basis/Comment
HTF Pump	40	30	$400	0.4X McMaster-Carr catalog price, ANL[1], XCelTherm® 600, 458 L/min, 320 °C, ΔP=1 bar
LCH_2 Pump	20	10	$200	0.4X McMaster-Carr catalog price; ANL[1], LCH_2, 2.65 L/min, 70 °C, ΔP=8 bar
H_2/air Non-catalytic Burner	2	1	$400	0.4X McMaster-Carr catalog price $1,000 for NG burner, 180,000 Btu/h; ANL[1], 82 kW, 5% excess O_2, Inconel
H_2 Blower	2.0	5	$18	0.5X Modine OEM $37 not including tooling and capital cost markup 1.2
Coagulating filter	1.8	0.8	$21	Same as for SBH system; 0.2X retail $105
LCH_2 Tank Heater	0.1	0.0	$4	Bottom-up costing using Boothroyd-Dewhurst DFMA® software, with 1.5X markup for component supplier overhead and profit
Piping & Fittings	7	3	$72	
Sensors & Controls	0.0	0.0	$30	
Valves & Connectors	3	2	$105	
Pressure Regulators	1	1	$44	

The regeneration facility from Figure 47 includes equipment and material for hydrogenation, purification and storage (Table 39). Assuming no losses, hydrogen could be purchased at 20 bar for $1.50/kg. At an assumed cost of $0.42/gallon, the material storage tanks need enough capacity for a 10-day plant shutdown and a 120-day summer peak period. TIAX uses $7.00/gallon for the baseline of N-ethylcarbazole as the carrier material. The initial catalyst and replacement costs are assumed to be $170/kg and $155/kg, respectively.

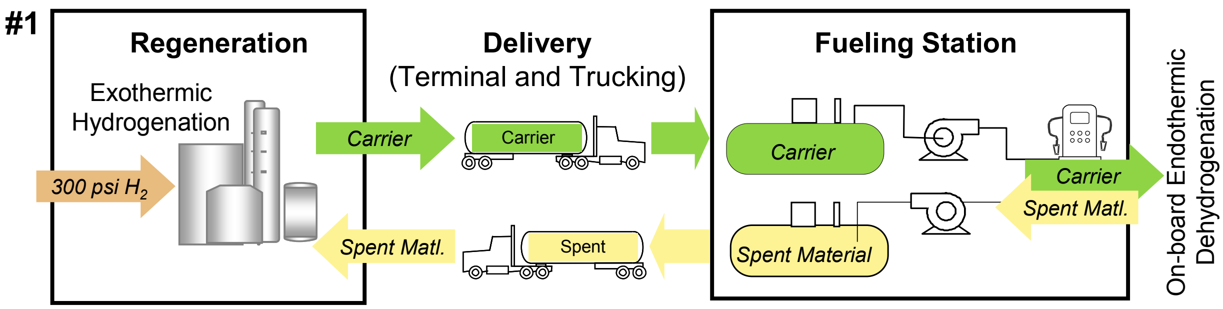


Figure 47. Off-Board Assessment Pathway

Table 39. LCH_2 Design Assumptions for Regeneration

Design Parameter	High/Low Basis/Comment
Hydrogen	-Hydrogen is purchased as a pure gas at 20 bar for $1.50/kg (H2A Central Plant target) -No losses are assumed
Material Storage Tank	-Storage for a 10-day plant shutdown and a 120-day summer peak period (10% above average demand) is included for hydrogenated material -Equal amount of storage included for dehydrogenated material -Two quarantine tanks are included for substandard material (five days of material) -Assumed cost: $0.42/gal (based on similar tanks in H2A)
Carrier Material	-N-ethylcarbazole is estimated to cost between $2-12/gal; $7/gal used for baseline (industry estimate) -Material replacement is estimated to fall between 0.5-5.0% of plant throughput; 2.75% used for baseline (APCI estimate) -Material allocation equals that required to fill all hydrogenated storage tanks
Capital Cost	-Includes: compressors, reactors, tankage, distillation, heat exchangers, fluid power equipment, and power and instrumentation (combination of H2A and industry cost estimates) -Range of 50-150% of estimated equipment capital cost used for sensitivity analysis
Catalyst Loading and Replacement	-Assumed initial catalyst cost is $170/kg and cost for replacement catalyst is 155/kg $ (industry estimate) -Catalysts lifetime based on material processed: 350,000 – 1,000,000kg_m/kg_c; 500,000 baseline (industry estimate)

(H2A, version 2)

Capital cost estimates are derived from developer feedback and baseline H2A model (version 2) assumptions (Table 40). Costs range from $0.20 for distillation to $258 for carrier material. The total cost of the purchased components is $526.

The ability of the liquid carrier to be transported in relatively standard, insulated tank trucks makes for cost-efficient transportation. Transport capacity is determined by the liquid carrier yield (3.7 wt percent net) and the mass of material that can be transported within an insulated aluminum trailer (24,750 kg gross vehicle weight). Insulation will be able to maintain the temperature of the carrier for up to one day. The trailer cost is $90,000 based on quotes from Heil and Polar trailer companies. Loading and unloading time is 1.5 hours combined. Table 41 includes the baseline H2A assumptions below:

This analysis assumes the fueling station receives the liquid carrier via tanker trucks; at the station, the carrier is stored then dispensed to vehicles for on-board dehydrogenation, as previously shown in Figure 47.

Table 40. LCH_2 Regeneration Plant Capital Equipment Cost Estimates

Regeneration Plant Capital Equipment	Installed Cost ($millions)	Basis
Carrier Material	$258	Personal communication with APCI, 2008
Indirect Capital (permitting, project contingency, engineering, site prep, land)	$155	H2A Baseline
Storage (Including quarantine)	$41.7	Personal communication with APCI, 2008
Piping & Instrumentation	$25.7	Personal communication with APCI, 2008
Catalyst	$21.3	Personal communication with APCI, 2008
Compressors	$14.8	H2A Baseline
Pumps	$6.8	Personal communication with APCI, 2008
Reactor	$1.5	Personal communication with APCI, 2008
Heat Exchangers	$1.4	Personal communication with APCI, 2008
Distillation	$0.2	Personal communication with APCI, 2008
Total	**$526**	

Table 41. H2A Delivery Assumptions

H2A Delivery Assumption	Value
Round trip delivery distance	160 km
Delivery labor rate	$50
Truck capital cost	$75,000
Fuel cost	0.44 $(2005)/L

All components (e.g., storage tanks, pumps, dispensers) are specified according to previously established methods for chemical hydrogen systems. On-site storage in each of the hydrogenated and spent carrier tanks is equal to 1.5 truck deliveries. Overall cost includes enough carrier material to fill 1/3 of the hydrogenated carrier tank and the fully-spent carrier tank. Electricity consumption due to carrier pumping and other miscellaneous loads is 0.5 kWh/kg. A range of labor costs were used from $7.75 per hour (minimum wage in California) to $15.00 per hour, with the baseline value of $10.00 per hour.

The cost results indicate that major non-hydrogen costs include capital costs at the regeneration plant (Figure 48). The delivery cost is 5 percent of the total off-board LCH_2 cost, whereas the regeneration plant accounts for over 80 percent.

If the carrier is used as an off-board transportation media only (i.e., fueling station dehydrogenation), the hydrogen selling price would increase to about $5.90/kg.

We estimate the high-volume factory cost of the system to be about $2,930, or $16/kWh (Figure 49). The biggest contributor to the system cost is the dehydrogenation reactor at 37 percent. Within the dehydrogenation reactor cost, the Pd catalyst accounts for 88 percent. At a cost of $915, the Pd catalyst is 32 percent of the total system cost.

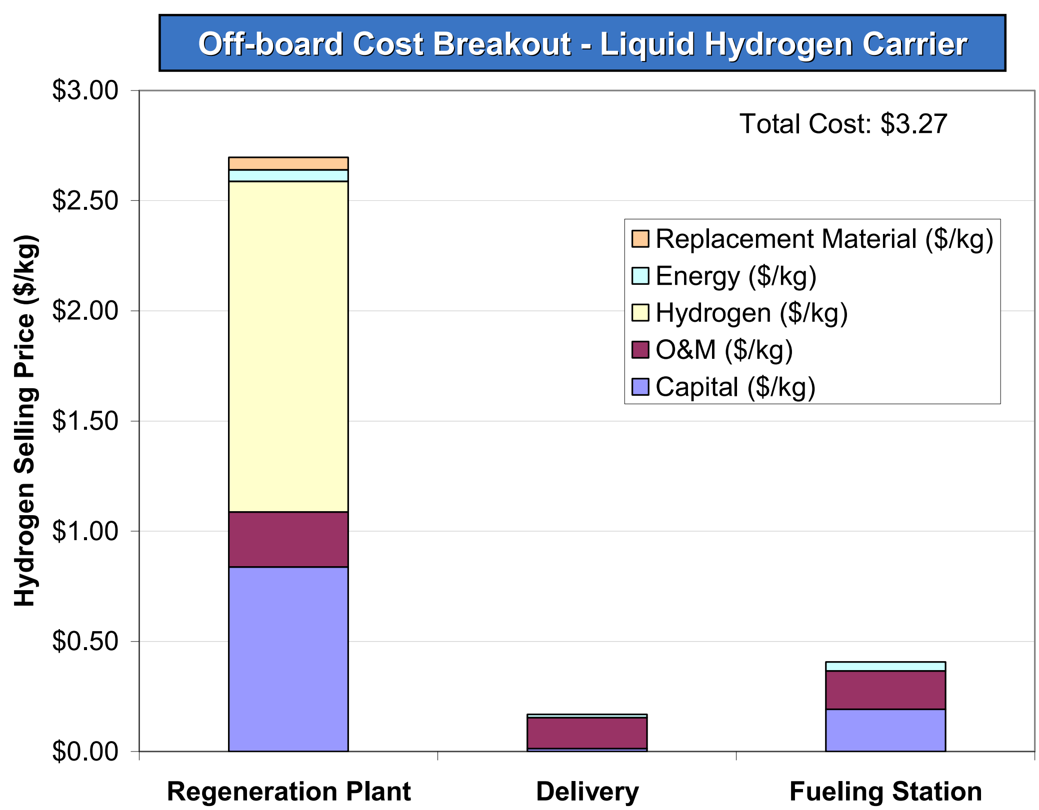
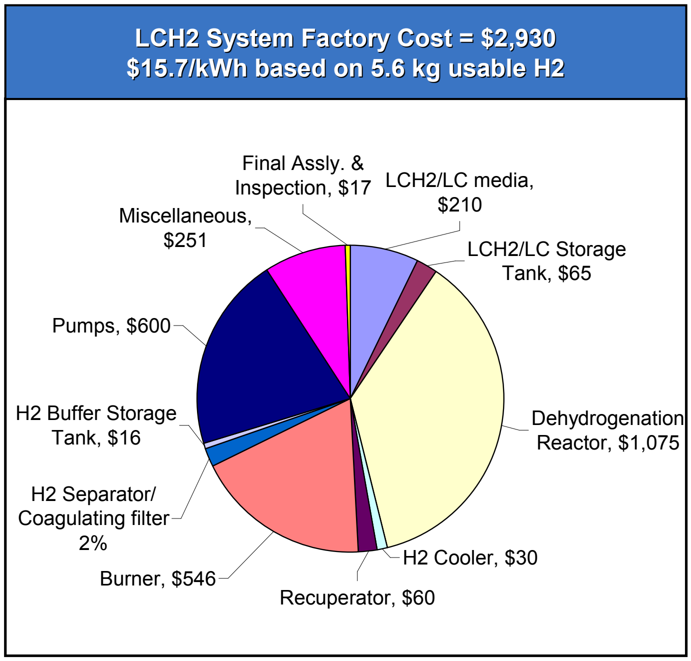
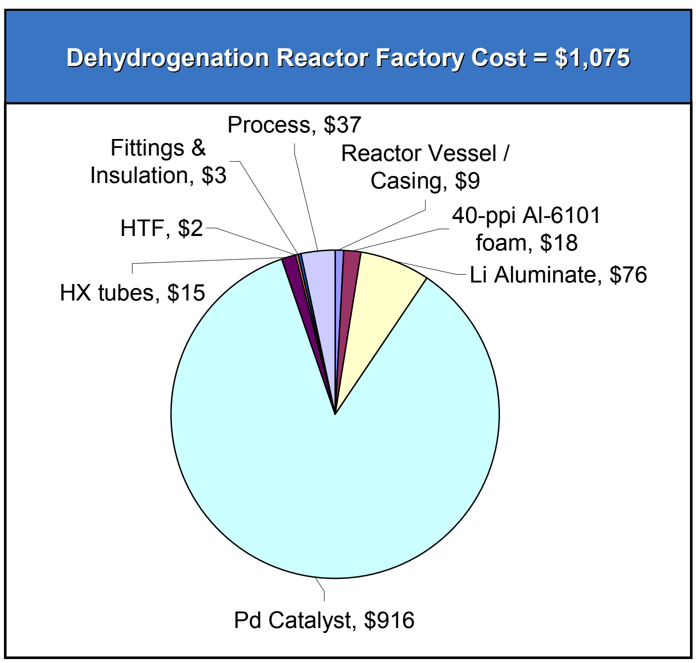


Figure 48. Off-Board Cost Breakout - LCH_2





Note: A trade-off study was not performed on the size/cost of the pumps vs. size/cost of the reactor sub-system and burner.

Figure 49. Base Case Component Cost Breakout for LCH_2 Systems and Dehydrogenation Reactor

Processing costs make up just 5 percent of the total system cost due to the high production volume assumption and large fraction of purchased components (Table 42). The total factory cost is $2930 with material costs accounting for 95 percent. The dehydrogenation reactor material fraction is 97 percent. As shown, some components, such as the Pd catalyst and Li aluminate, have no processing costs since they are purchased. While the material costs for Al-6101 foam substrate, reactor vessel, and HX tubes are low, they have high processing fractions, which range from 18 to 52 percent.

The overall cost of the onboard liquid carrier system is most sensitive to the amount and cost of the catalyst, and purchased component prices (Figure 50).

As seen in Figure 51 , the factory cost of the LCH_2 systems will likely range (95 percent confidence) between $14 and $22/kWh ($\pm 2\sigma$, $\mu=17$, base case=16).

Table 42. Base Case Material vs. Processing Cost Breakout for Liquid Hydrogen Carriers

On-board System Cost Breakout Liquid Hydrogen Carrier – 5.6 kg H_2	Material, $	Material Fraction	Processing, $	Processing Fraction
LCH_2/LC Media[1]	210	100%	(purchased)	-
LCH_2/LC Storage Tank	55	84.6%	10	15.4%
Dehydrogenation Reactor - Pd Catalyst - Li Aluminate - Al-6101 foam substrate - Reactor Vessel (Al-2219-T81) - HX tubes (Al-2219-T81) - Other (HTF, insulation, fittings)	1,038 916 76 18 9 15 5	96.6% 100% 100% 48.2% 81.9% 48.3 100%	37 (purchased) (purchased) 19 2 16 (purchased)	3.4% - - 51.8% 18.1% 51.7% -
H_2 Cooler	6	20%	24	80%
Recuperator	36	60%	24	40%
Burner - Microchannel HX - H_2/air non-catalytic burner - H_2 blower	510 92 400 18	93.4% 71.8% 100% 100%	36 36 (purchased) (purchased)	6.6% 28.2% - -
H_2 Separator/Coagulating filter	52	89.2%	7	11.8%
H_2 Buffer Storage Tank	16	96.9%	0.5	3.1%
Pumps - HTF pump - LCH_2 pump	600 400 200	100% 100% 100%	(purchased) (purchased) (purchased)	- - -
Miscellaneous	251	100%	(purchased)	0%
Final Assembly & Inspection	-	-	17	-
Total Factory Cost	**2,774**	**94.7%**	**156**	**5.3%**

[1] Cost is based on $7/gal LCH_2, consistent with TIAX off-board LCH_2 storage system assessment, which is based on input from APCI.

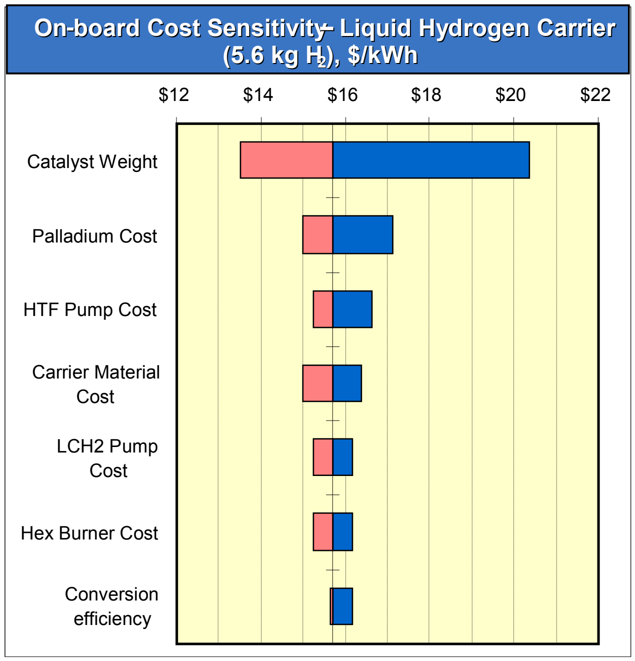


Figure 50. Single-Variable Cost Sensitivity for Liquid Hydrogen Carrier

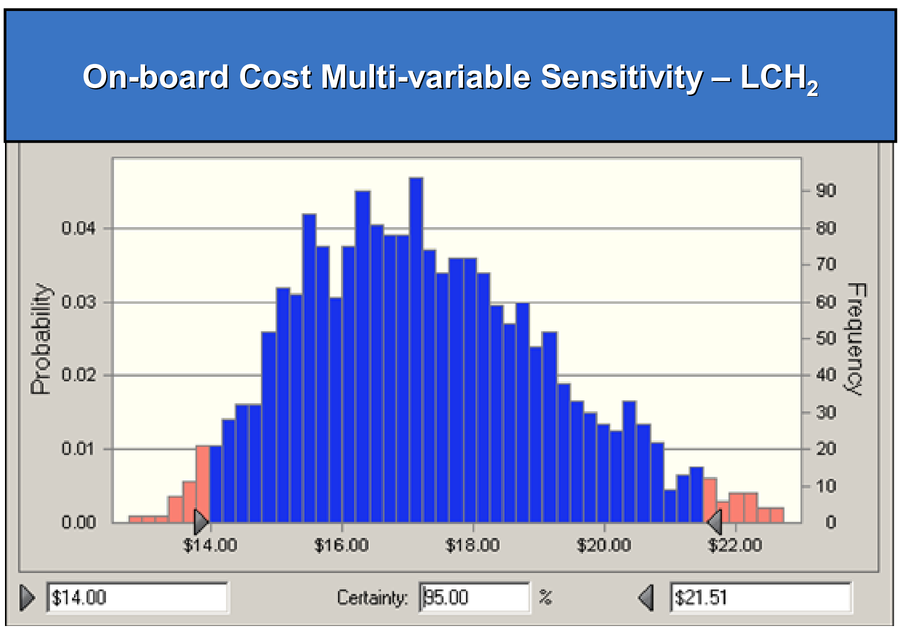


Figure 51. Multi-Variable Cost Sensitivity for Liquid Hydrogen Carrier

A liquid carrier like N-ethylcarbazole has the potential to be an attractive hydrogen delivery media based on the off-board assessment. The carrier evaluated here is very good when accounting for two important attributes: (1) the relatively simple regeneration process (no additional reactant materials and a one step catalytic process); and (2) its straightforward, low-cost transport and dispensing. However, assuming an N-ethylcarbazole-like material is used, the transport and storage of the dehydrogenated material could be made difficult by a high melting point (70°C). Initial estimates of regeneration, delivery and forecourt costs are competitive with the most cost-effective delivery technologies (e.g., CH_2 pipelines, LH_2 trucks). Additional cost reductions are also possible for this carrier. If the carrier material cost is at the low end of the potential cost range ($2 to12/gal), significant cost reductions are possible. Reducing the amount of working capital in the system could reduce the total capital cost. Lower carrier losses (0.5 to 5 percent; baseline 2.75 percent of throughput assumed) and steam or electricity credits at the regeneration facility would also reduce costs.

4.2.2 Sodium Borohydride (September 11, 2007)

The off-board assessment for sodium borohydride (SBH) requires evaluation of regeneration (Figure 52), delivery, and forecourt technologies (Figure 53). As seen in Table 43, the base case values for the aluminum reduction and plasma arc methods are based on estimates provided by Dow Chemical Company (previously Rohm & Haas). Using TIAX base case assumptions, the SBH recovery capital costs for aluminum reduction and plasma arc are $350 million and $300 million, respectively. Thermal energy recovery is 37.3 and 57.2 MJ/kg hydrogen for aluminum reduction and plasma arc, respectively. The aluminum plant capital costs are $1.5 billion with carbon prices of $0.46/kg. The syngas price of $6.00/gigajoule (GJ) for the plasma arc is based on an assumed natural gas price.

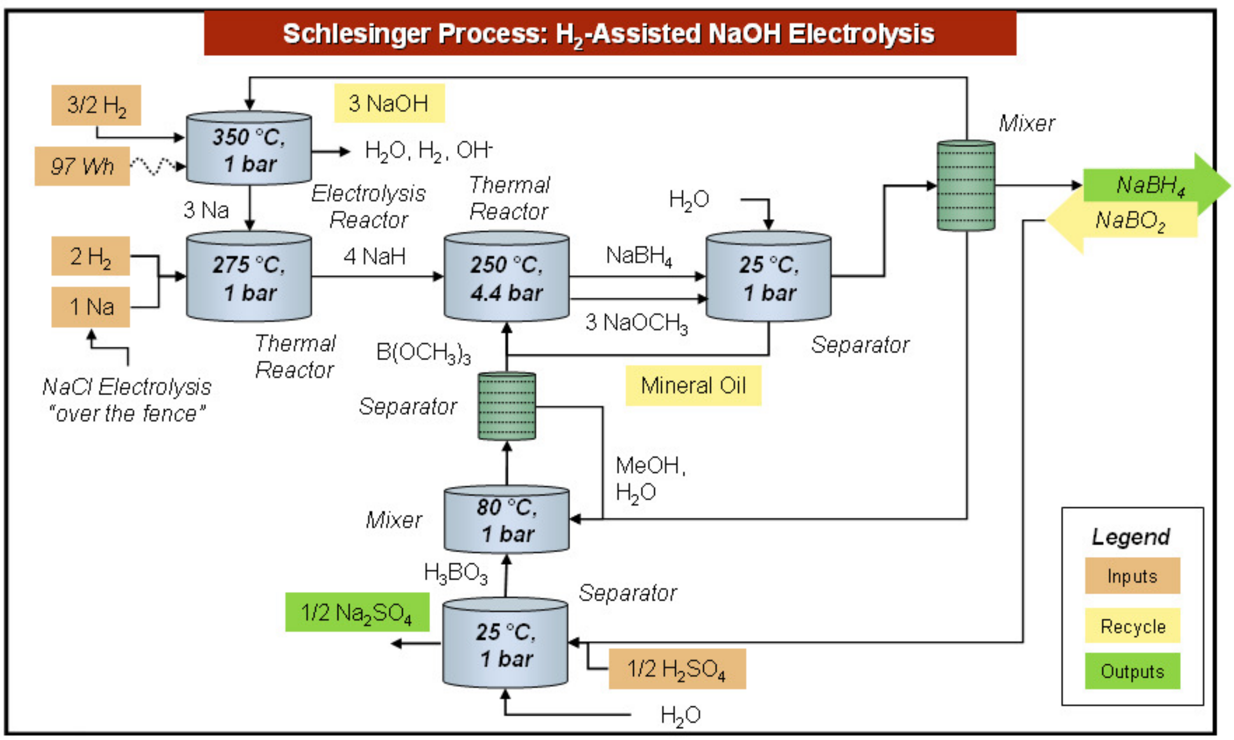
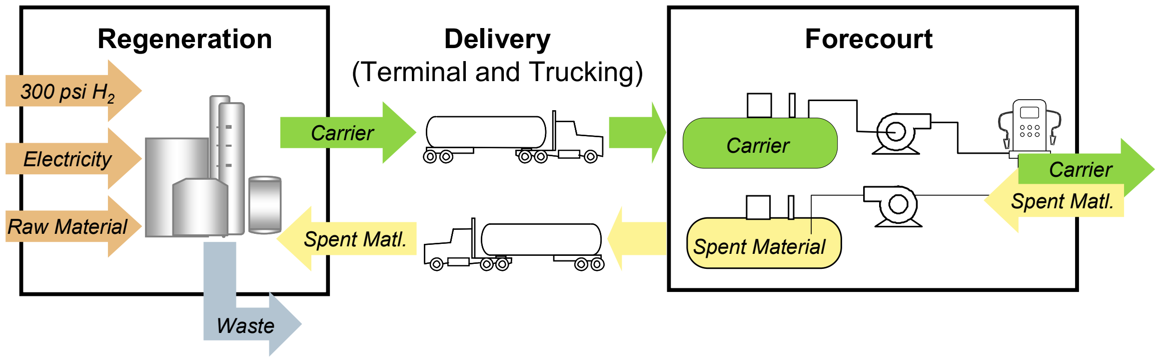


Figure 52. Schematic of SBH Process



- H_2 is supplied "over-the-fence"
- May include electrolysis
- Today's processes may not recycle all spent material

- Transportation of the carrier and spent material in same truck
- Terminal storage may be required at the regeneration site

- May include carrier and spent material storage and dispensing (loading and off-loading)
- Or compressed hydrogen dispensing

Figure 53. Off-Board Assessment Pathway

Table 43. SBH Systems Design Assumptions*

Input	TIAX Base Case	Basis
$NaBO_2$ Recovery Capital Costs	Al Reduction: \$350 million Plasma Arc: \$300 million	Dow Chemical Company estimate derived from Icarus Process Evaluator
Electricity Price	\$0.055/ kWh	Dow Chemical Company evaluated two cases: 1)\$0.030/kWh assuming low-cost hydro-electric power and 2)\$0.055/kWh based on H2A value for industrial electricity
Thermal Energy Recovery	Al Reduction: 37.3 MJ/kgH_2 Plasma Arc: 57.2 MJ/kgH_2	Dow Chemical Company assumption of recovered energy. Al Reduction process assumes 75% recovery efficiency & Plasma Arc process assumes 80-90% efficiency depending on quench temperature
Al Plant Capital Costs (Al Reduction only)	\$1.5 billion	Dow Chemical Company estimate based on Alcoa Economic Analysis (1999) assuming 70% of Hall-Heroult Process Aluminum Plant (\$1.6 Billion in 1999 and 4% inflation to 2005), Alcoa has carbothermal capital cost as 31-44% of H-H Process
Carbon Price (Al Reduction only)	\$0.46 /kg	Dow Chemical Company estimate based on Alcoa Economic Analysis (1999) and escalated from Alcan Presentation (2002)
Syngas Price (Plasma Arc only)	\$6 /GJ	Dow Chemical Company assigns energy value to the synga based on an assumed natural gas price (H2A, industrial natural gas (2005) = \$6.24/GJ)

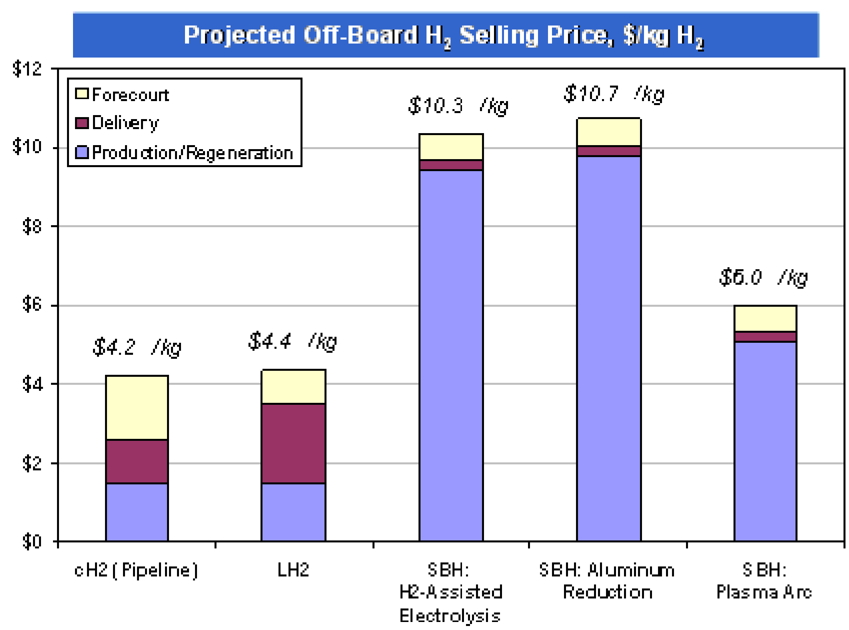
**Some inputs and results are based on Dow Chemical Company proprietary information*

All of the evaluated SBH pathways are projected to cost in excess of the threshold of $2 to $4 per kilogram of hydrogen due to high regeneration costs. The electricity consumption due to the carrier pumping and other miscellaneous loads is 0.5 kWh/kg, which is similar to those for LCH_2. Production/regeneration costs for SBH (hydrogen-assisted electrolysis and aluminum reduction) range from $8 to $10/kg and account for more than 80 percent of the total costs. SBH through plasma arc seems to be an economical choice, since the total cost is about half of the other two SBH options (Figure 54). As shown in the figure, the delivery costs for hydrogen through SBH is about 15 to 30 percent of the delivery costs for CH_2 and LH_2.

As seen in Figure 55, the byproducts are included as financial credits, reducing the regeneration cost to less than $10/kg and $5/kg for the aluminum reduction and plasma arc processes. In order for the SBH via hydrogen-assisted electrolysis system to come closer to meeting the cost target, the price of sodium must be decreased significantly (orders of magnitude). Sodium price is the single most important cost driver in this process at approximately 70 percent.

As for the SBH via aluminum reduction system, aluminum plant capital cost assumptions have a significant impact on hydrogen selling price. Electricity source in the production of aluminum is very important and energy requirement for Al production can make this process cost prohibitive.

SBH via carbothermal with plasma arc has only been performed on a lab scale reactor, further development of the process is necessary. Inexpensive source of electricity combined with the sale of syngas as a feedstock has the possibility to decrease costs.



Note: Production costs assume $1.50/kg H_2 (H2A goal). Near-term H2A SMR production models indicate $1.70/kg at 380 TPD H_2 capacity. Regeneration costs assume 470 TPD SBH plant (100 TPD H_2 equivalent). Delivery and forecourt costs assume 100 km truck delivery from a central plant to the forecourt designed for 1050 kg/day H_2.

Some inputs and results are based on Dow Chemical Company proprietary information

Figure 54. Projected Off-Board Hydrogen Selling Price, $/kg H_2

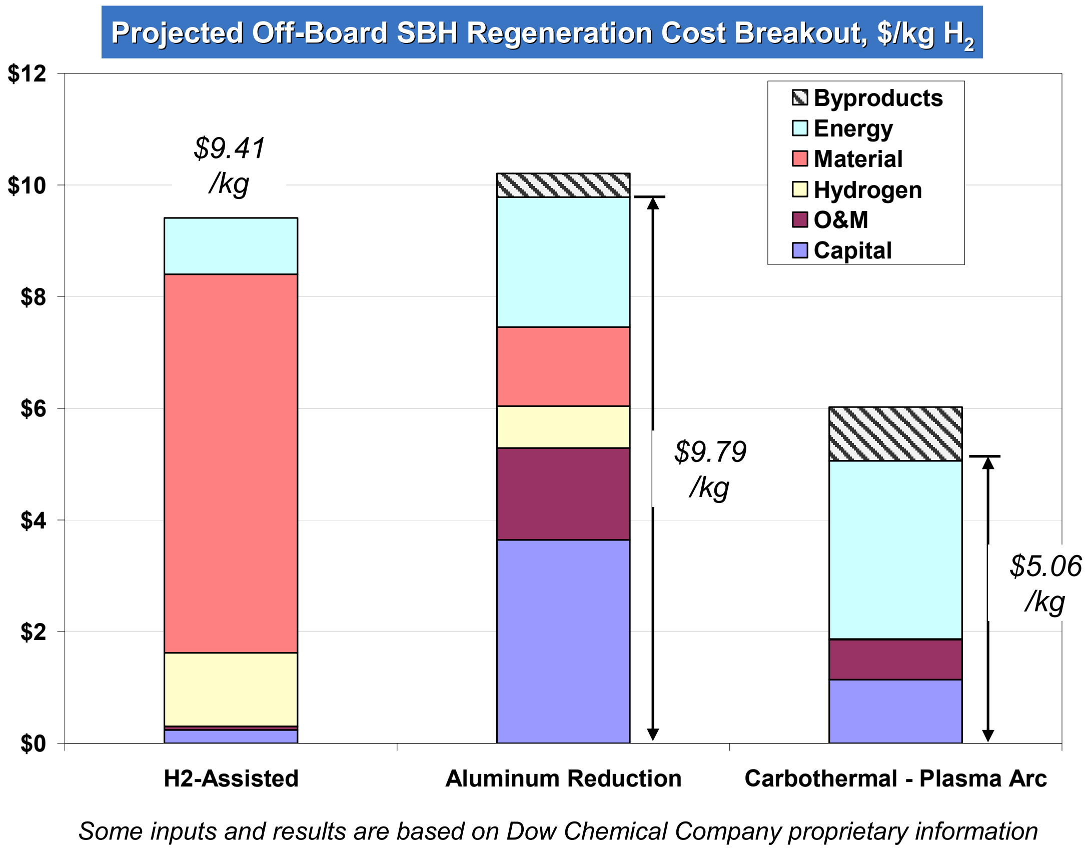


Figure 55. Projected Off-Board SBH Regeneration Cost Breakout, \$/kg H_2

4.2.3 Ammonia Borane (August 25, 2010)

In the case of the ammonia borane (AB) hydrogen storage system, TIAX reviewed and provided comments to the cost analyses conducted by the Dow Chemical Company, a member of the DOE's Chemical Hydrogen Storage Center of Excellence. Dow has calculated the baseline ammonia borane (AB) first fill cost to be \$9.10/kg AB and \$9.48/kg AB for the pressure and cryogenic routes, respectively. Approximately 69 to 72 percent of the first fill AB cost comes from the cost of SBH, which is assumed to be \$5.00/kg SBH for the baseline analysis. The first fill cost can have a large impact on the on-board storage system cost. Assuming the AB hydrogen storage capacity is 13.1 wt percent, 43 kg of AB would be required to provide the targeted 5.6 kg hydrogen on-board the vehicle, resulting in an on-board storage system cost contribution of approximately \$390 for the pressurized process, and \$400 for the cryogenic process. This corresponds to \$2/kWh of stored hydrogen for the pressurized process, and \$2/kWh for the cryogenic process. The DOE 2010 cost target for the complete on-board storage system (inclusive of first fill, storage tanks, reactors, BOP, etc) was \$4/kWh hydrogen.

Key cost reduction opportunities for the first fill system include reducing utility (e.g., cooling) and feedstock costs (e.g., SBH), which represent more than 83 percent of the first fill cost for both the cryogenic and pressure routes. Significant utility costs are associated with separating ammonia from tetrahydrofuran and hydrogen, which requires cryogenic temperatures. Reducing overall energy use will reduce utility costs as well as improve the primary energy use and GHG emissions results. Capital costs will also be appreciably reduced if specialized equipment is not needed for ammonia separation.

Dow has estimated the AB regeneration cost via the hydrazine reduction route to be $45.73/kg hydrogen. The bulk (96 percent) of the regeneration cost is derived from the hydrazine raw material cost ($5.51/kg hydrazine). As such, new methods for hydrazine production are needed for successful implementation of this process. As shown in Table 44 the base case results for the hydrazine AB pathway are on the order of five to ten times the other production pathways shown. Dow estimates a best-case scenario of $0.28/kg hydrazine, or 95 percent reduction in hydrazine cost, which leads to an AB regeneration cost of $4.17/kg hydrogen. This best-case scenario cost is nearly 50 percent lower than the thiacatechol-based process that was previously examined by Dow, but it still exceeds the DOE hydrogen threshold cost of $2 to 4/kg hydrogen. Once delivery and fueling station costs – which were not analyzed as part of this effort – are included, it is also projected to be more expensive than several other production pathways analyzed.

Key plant metrics, as defined by Dow Chemical Company, are as follows:

- AB regeneration: processes 225,000 metric tons per year AB, or the equivalent of 100 metric tons per day of hydrogen, assuming 16.3 wt percent recoverable hydrogen in AB. The plant includes the capacity to store 30 days of AB as well as the spent carrier, and operates at a capacity factor of 90 percent. Dow Chemical Company previously estimated the AB regeneration cost via the thiacatechol route to be $7.90/kg hydrogen.

Table 44. Hydrogen Selling Price Comparison for AB and Previously Analyzed Delivery Pathways

	Hydrazine Cost	Central Plant/Regeneration	Delivery	Fueling Station	Total
350 bar cH_2 (pipeline)	$ -	$1.69	$0.95	$1.58	$4.22
700 bar cH_2 (pipeline)	$ -	$1.69	$0.95	$1.69	$4.33
SBH	$ -	$9.15	$0.34	$0.66	$10.14
LCH_2 (preliminary)	$ -	$2.98	$0.17	$0.41	$3.56
Cryo-compressed (LH_2 truck)	$ -	$3.59	$0.25	$0.90	$4.74
AB – Thiacatechol	$ -	$7.91	Not Estimated		$7.91
AB – Hydrazine, $5.51/kg	$43.80	$1.93	Not Estimated		$45.73
AB – Hydrazine, $0.28/kg	$2.24	$1.93	Not Estimated		$4.17

- AB first fill production: produces 10,000 metric tons per year of AB, operating at a capacity factor of 95 percent. This production rate is sufficient assuming the deployment of 50,000 new hydrogen fuel cell vehicles (FCV) per year, based on the DOE's lowest projection of FCV deployment between 2018 and 2023. Dow Chemical Company estimates the baseline cost of AB production to be $9.00/kg AB.

These results should be considered in the context of meeting other DOE targets, including on-board cost, weight and volume, as well as primary energy use and GHG emissions for the complete fuel supply chain (as has been assessed by the CoEs)

Key cost reduction opportunities include reducing utility and feedstock costs (e.g., electricity, natural gas, hydrogen), which represent over 60 percent of the regeneration cost. Reducing overall energy use will reduce utility costs as well as reduce primary energy use and GHG emissions. The regeneration plant electricity consumption totals 24 kWh/kg hydrogen and natural gas consumption totals 310 MJ/kg hydrogen (lower heating value [LHV] basis). This equates to an overall regeneration plant site energy use of 3.3 J/J hydrogen (23 percent LHV efficiency) and a primary energy use[6] of 4.6 J/J hydrogen (16 percent LHV efficiency).

Dow Chemical Company has calculated the baseline AB first fill cost to be $9.00/kg AB. Approximately 75 percent of the first fill AB cost comes from the cost of SBH, which is assumed to be $5.00/kg SBH for the baseline analysis. The first fill cost has a relatively minor impact on the costs at the regeneration plant (impacting plant storage and material replacement costs), but it can have a bigger impact on the on-board storage system cost. If we assume the AB hydrogen storage capacity is 16.3 wt percent, 34 kg of AB would be required to provide the targeted 5.6 kg hydrogen on-board the vehicle, resulting in an on-board storage system cost contribution of approximately $300 or $2/kWh of stored hydrogen. The DOE 2010 target for the complete on-board storage system (inclusive of first fill, storage tanks, reactors, and BOP) was $4/kWh hydrogen.

4.2.4 Magnesium Hydride (June 7, 2006)

Metal hydrides such as magnesium hydride are used as storage media for hydrogen. The hydrides chosen for storage must have low reactivity and high storage densities. For the magnesium hydride off-board analysis, TIAX reviewed developer estimates and developed preliminary process flow diagram and system energy balances.

Through examination of developer estimates, a major fraction of the reprocessing cost (both grid and nuclear) comes from feedstock/material. The cost of electricity at the reprocessing facility is the most significant variable in the overall cost of delivering hydrogen as MgH_2. Delivery and forecourt costs are about 10 percent the cost of reprocessing. The reprocessing cost does not include a potential cost reduction due to the sale of by-product oxygen, which could be approximately $0.17/kg of hydrogen (Figure 56).

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[6] We used the H2A Delivery Components Model and GREET data to calculate the primary energy use, which includes all upstream energy requirements to produce and deliver the electricity and natural gas inputs. We also assumed a 68 percent efficiency for hydrogen production (i.e., 1.47 J/J H_2)

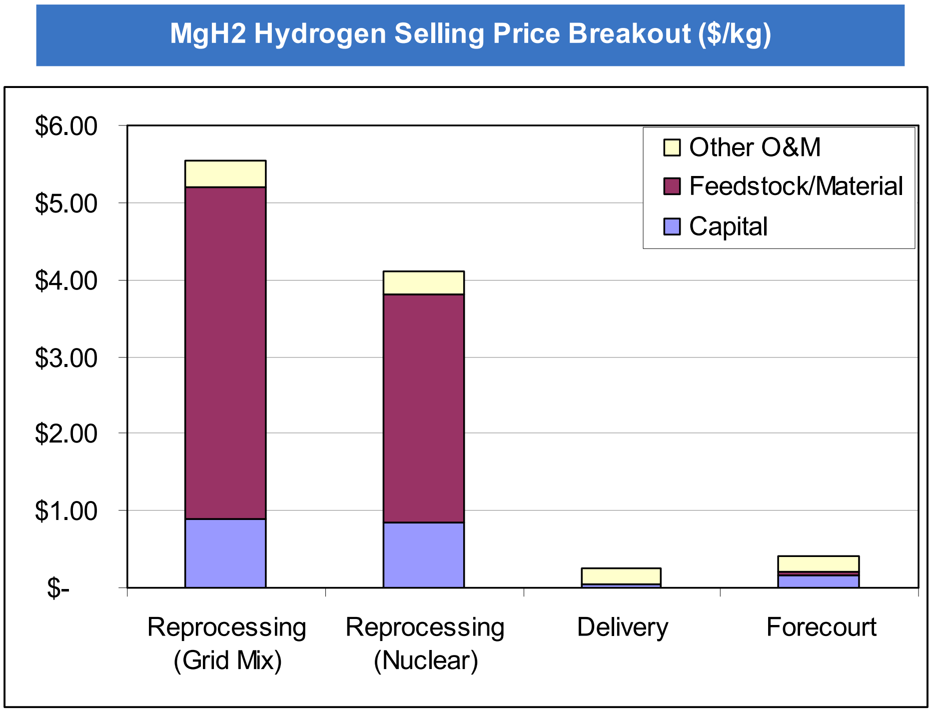


Figure 56. Magnesium Hydride, Hydrogen Selling Price Breakout

Several key issues affect the results of the analysis of the MgH_2 as a hydrogen carrier. Production routes and material inputs affect well-to-tank (WTT) energy input and cost. MgH_2 reprocessing is also possible with chemical routes.

In the electrolysis specifications for hydrogen through MgH_2, the amount produced from 2,002 tons of Mg per day is 332 tons per day. This equals about 16.6 percent of the amount of material electrolyzed. On average, this fraction of hydrogen produced is greater than the other three options, which range from 6 to 11 percent (Table 45).

Delivery capacity depends on hydride chemistry and solution composition (Figure 57). LH_2 has the highest hydrogen capacity for truck delivery at 3,600 kg. The remaining three options include CH_2, SBH, and MgH_2. MgH_2's capacity is almost 1,500 kg, which is double the capacity of CH_2. There seems to be a negligible difference in the storing capacity between SBH and MgH_2. However, when comparing costs of SBH and MgH_2, in terms of $/kg, SBH is significantly higher, indicating that MgH_2 would be the more economical choice.

Table 45. Hydrogen Electrolysis Specifications

Hydrogen Production/Delivery Method	Electrolysis Specifications				
	Uninstalled Cost	Power	Overall Hydrogen Production	Amount of Material Electrolyzed	Installation Factor
Water Electrolysis at Forecourt	\$605/kW	3,254 kW	1.5 ton/day	13.5 ton, H_2O/day	1.10
Water Electrolysis at Wind Central Plant	\$665/kW	278 MW	50 ton/day	450 ton, H_2O/day	1.20
$NaBH_4$ Chemical Hydride Transport	\$300/kW	110 MW	125 ton/day	2,510 ton, Na/day	1.92
MgH_2 Chemical Hydride Transport	\$62/kW	831 MW	332 ton/day	2,002 ton, Mg/day	1.77

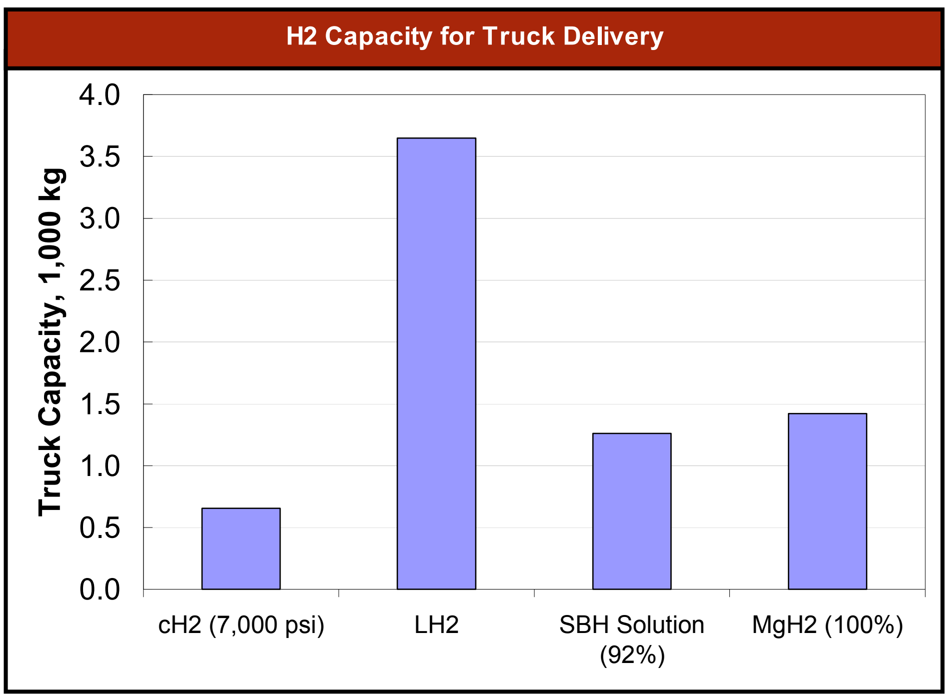
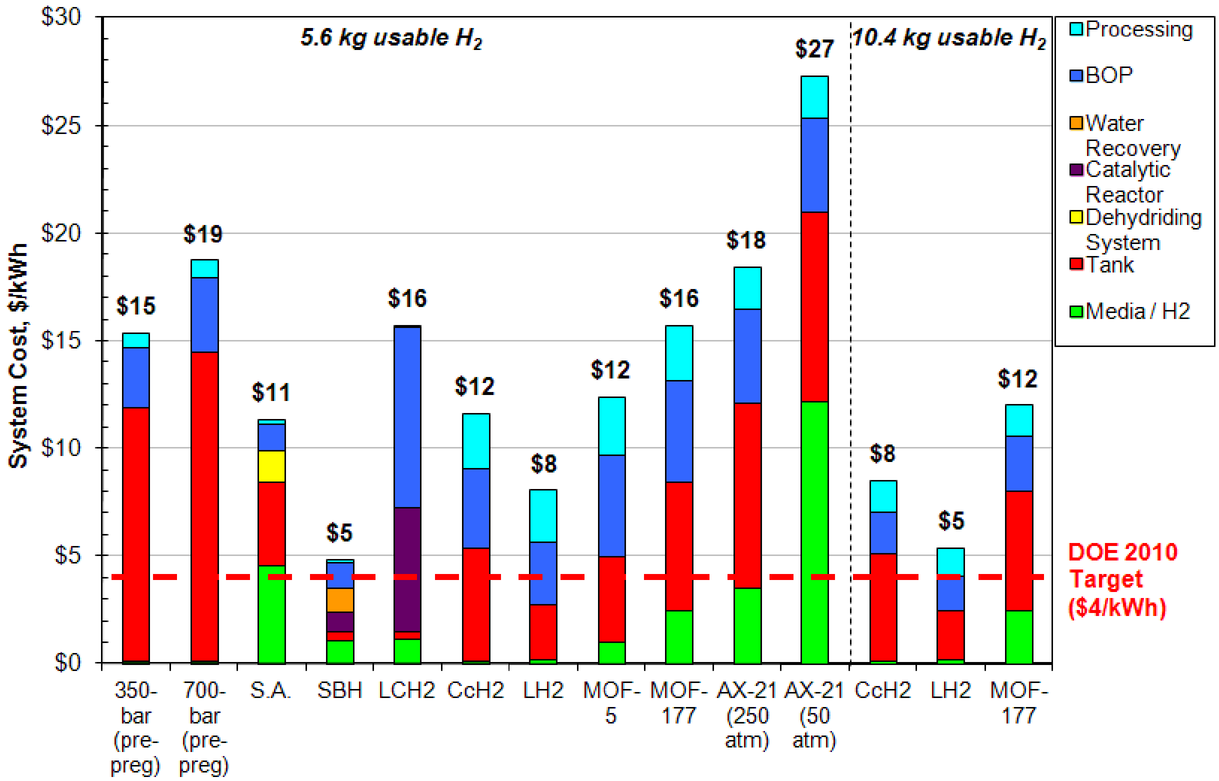


Figure 57. Hydrogen Capacity for Truck Delivery

5 Conclusion

Across the various hydrogen storage systems, according to the designs and assumptions described in the previous sections, on-board high-volume factory costs are projected as shown in Figure 58.



Note: System cost estimates assume use of pre-preg carbon fiber, except where noted for the 350- and 700-bar compressed systems. Additional assumptions, technology maturity, and uncertainty level vary by system; systems may not be directly comparable.

Figure 58. Summary of On-Board Hydrogen Storage System Costs

Reductions in the key cost drivers may bring hydrogen storage system costs closer to the DOE target of $4/kWh. In general, tanks costs are the largest component of system cost, responsible for at least 30 percent of total system cost, in all but the SBH and LCH_2 systems. Purchased BOP cost also drives system cost, accounting for 10 to 50 percent of total system cost across the various storage systems. Potential improvements in these cost drivers for all storage systems may come from new manufacturing processes and higher production volumes for BOP components. In addition, advances in the production of storage media may help drive down overall costs for the sodium alanate, SBH, LCH_2, MOF, and AX-21 systems. Table 46 summarizes the key cost drivers for the on-board hydrogen storage systems analyzed in this project.

Table 46. Summary of On-Board Hydrogen Storage System Key Cost Drivers

	Hydrogen Storage System	Key Cost Driver(s)
4.1.1	**Compressed Hydrogen Storage**	
	Type IV, 1 tank, 350-bar	Carbon fiber
	Type IV, 1 tank, 700-bar	Carbon fiber
	Type IV, 2 tank, 350-bar	Carbon fiber
	Type IV, 2 tank, 700-bar	Carbon fiber
	Type III, 1 tank, 350-bar	Carbon fiber, liner
	Type III, 1 tank, 700-bar	Carbon fiber, liner
	Type III, 2 tank, 350-bar	Carbon fiber, liner
	Type III, 2 tank, 700-bar	Carbon fiber, liner
4.1.2	**Liquid Hydrogen Storage**	
	5.6 kg	Other BOP, assembly and inspection
	10.4 kg	MLVI, other BOP
4.1.3	**Cryo-Compressed Hydrogen Storage**	
	5.6 kg	Carbon fiber, liner and fittings
	10.4 kg	Carbon fiber, liner and fittings
4.1.4	**Sodium Alanate Hydrogen Storage**	Catalyzed media, dehydriding accessories
4.1.5	**MOF-177 Hydrogen Storage**	
	5.6 kg	Carbon fiber, MOF-177 media
	10.4 kg	Carbon fiber, MOF-177 media
4.1.6	**MOF-5 Hydrogen Storage**	
	5.6 kg	Carbon fiber, assembly and inspection
4.1.7	**AX-21 Hydrogen Storage**	
	250-atm	Carbon fiber, AX-21 media
	50-atm	AX-21 media

6 References

[1] U.S. Department of Energy (DOE), Hydrogen Production Model (H2A),

http://www.hydrogen.energy.gov/h2a_production.html, 2009.

[2] Abdallah, M., "Low Cost Carbon Fiber (LCCF) Development Program," Hexcel, Phase I Final Report to DOE ORNL, August 2004.

[3] Du Vall, F., "Cost Comparisons of Wet Filament Winding Versus Prepreg Filament Winding for Type II and Type IV CNG Cylinders," SAMPE Journal, Vol. 37, No. 1, p.39-42, January/February 2001.

[4] U.S. Department of Energy (DOE): Hydrogen Delivery Scenario Analysis Model (HDSAM), http://www.hydrogen.energy.gov/h2a_delivery.html, 2009.

7 Appendix

The following final system reports, DOE Annual Merit Review presentations, SSAWG presentations, and Tech Team presentations are included in a separate CD accompanying this summary report.

Title	Date	File Name
Final System Reports		
H_2 Storage using Compressed Gas: On-board System and Ownership Cost Update for 350 and 700-bar	December 23, 2011	TIAX On-Board Comp Cost – Updated March 2012.pdf
H_2 Storage using Cryogenic Liquid: On-board System and Ownership Cost Assessment	April 30, 2010	TIAX On-Board Liquid Cost Update_final2.pdf
H_2 Storage using Cryo-compressed: On-board System and Ownership Cost Assessment for Gen 3 Tank	November 30, 2009	TIAX On-Board Cryo-comp Cost Update_final6.pdf
Sodium Alanate Storage System Cost Estimate	March 31, 2007	NaAl4_On-Board Cost_final1.pdf
H_2 Storage using Carbon Sorbents: On-board System Cost Assessment	March 20, 2012	TIAX Sorbent Report – Revised Mar 2012_v2.pdf
H_2 Storage using a Liquid Carrier: Off-board and On-board System Cost Assessments	September 14, 2010	TIAX Off-board and On-board LCH2 Cost - Sept 2010 - v3.pdf
SBH Review Meeting – TIAX On-Board Assessment	September 10, 2007	TIAX_H2 Storage Cost_SBH Review Mtg_final1.pdf
SBH Review Meeting – TIAX Off-Board Assessment	September 11, 2007	TIAX_H2 Storage Cost_SBH Review Mtg_final1.pdf
Review of Cost Assessment for Ammonia Borane 1st Fill and Regeneration Processes	August 25, 2010	TIAX Memo PNNL-1st Fill & LANL-Regen - Final - v2.pdf
Chemical Hydride Off-Board Assessment—Preliminary Results for DOE and Developer Review	June 7, 2006	Chemical Hydrides_Off-Board Assessment_v2.pdf
Annual Merit Review Presentations		
Analyses of Hydrogen Storage Materials and On-Board Systems—DOE Merit Review	May 25, 2005	st19_lasher.pdf
Analyses of Hydrogen Storage Materials and On-Board Systems—DOE Merit Review	May 17, 2006	ST20_Lasher_H2 Storage_final.pdf
Analyses of Hydrogen Storage Materials and On-Board Systems—DOE Merit Review	May 17, 2007	ST32_Lasher_H2 Storage_v1.pdf
Analyses of Hydrogen Storage Materials and On-Board Systems: Cryo-compressed and Liquid Hydrogen System Cost Assessments—DOE Merit Review	June 10, 2008	ST1_Lasher_H2 Storage_v4.pdf

Title	Date	File Name
Analyses of Hydrogen Storage Materials and On-Board Systems: Compressed and Liquid Hydrogen Carrier System Cost Assessments—DOE Merit Review	May 19, 2009	st_12_lasher.pdf
Analyses of Hydrogen Storage Materials and On-Board Systems: Updated Cryogenic and Compressed Hydrogen Storage System Cost Assessments—DOE Annual Merit Review	June 7-11, 2010	ST002_Lasher_H2 Storage.pdf
Analyses of Hydrogen Storage Materials and On-Board Systems: Updated Hydrogen Storage System Cost Assessments—DOE Annual Merit Review	May 11, 2011	st002_law_2011_o.pdf
SSAWG Presentations		
SBH Off-Board Assessment – Preliminary Results for Hydrogen Storage Systems Analysis Working Group Meeting	May 19, 2006	Chemical Hydrides_NaBH4 Off-Board_draft5.pdf
Gen 3 Cryo-compressed Hydrogen System Cost Assessment – Preliminary Results for Discussion	June 30, 2009	Cryocompressed preliminary cost 073009_2.pdf
Overview of Approach and FY 2011 Activities – Hydrogen Storage Systems Analysis Working Group	January 12, 2011	TIAX – SSAWG Update – Jan 2010 – v3.pdf
H_2 Storage Using Carbon Sorbents: On-Board System Cost Assessment	February 22, 2012	TIAX Sorbent Report – SSAWG Feb 2012_v3.pdf
Hydrogen Storage Technical Team Presentations		
SBH Off-Board Assessment – Preliminary Results	June 22, 2006	TIAX Tech Team 22 June 06.pdf
Cryo-tank and Sodium Borohydride System Cost Updates	September 27, 2007	Tech Team_Cryotank and SBH Update_Sept 07_final2.pdf
Cryo-compressed and Liquid Hydrogen System Cost Updates	April 17, 2008	TIAX Cryocompressed Onboard Cost v1.pdf
Liquid Hydrogen Carrier On-Board and Off-Board H_2 Storage System Cost Assessment	June 18, 2009	TT Mtg_TIAX_LCH2 Assessment_final.pdf
Updated Cryogenic and Compressed Hydrogen Storage System Cost Assessments	May 20, 2010	Tech Team_Lasher_H2 Storage_final1.pdf
Updated Hydrogen Storage System Cost Assessments	April 28, 2011	Tech_Team_Law_H2_Storage_v2.pdf
Updated Hydrogen Storage System Cost Assessments	March 15, 2012	Tech_Team_Law_H2_Storage_Mar2012_v2.pdf