Analyses of Hydrogen Storage Materials and On-Board Systems

Project ID # st_12_lasher

Compressed and Liquid Hydrogen Carrier System Cost Assessments

DOE Merit Review
May 19, 2009

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Reference: D0268

Timeline

- Start date: June 2004
- End date: June 2009
- 80% Complete

Barriers

- A. System Weight and Volume
- B. System Cost
- K. System Life Cycle Assessments

Budget

- Total project funding
  - DOE share = $1.5M
  - No cost share
- FY08 = $350k
- FY09 = $261k (plan)

Collaboration

- Design and performance assessment: Argonne and other National Labs
- Technical input: Centers of Excellence and other developers
- Review: Tech Teams and other stakeholders

This project provides an independent cost assessment of the hydrogen storage technologies being developed for the DOE Grand Challenge.

Objective	Description
Overall	Help guide DOE and developers toward promising R&D and commercialization pathways by evaluating the status of the various on-board hydrogen storage technologies on a consistent basis
On-Board Storage System Assessment	Evaluate or develop system-level designs for the on-board storage system to project: 1) Bottom-up factory cost 2) Weight and volume (ANL lead)
Off-Board Fuel Cycle Assessment	Evaluate or develop designs and cost inputs for the fuel cycle to project: 1) Refueling cost 2) Well-to-Tank energy use and GHG emissions (ANL lead)

Last year's objective was to evaluate a liquid hydrogen carrier (LCH_2) and update our compressed hydrogen storage assessments.

The on-board cost and performance assessments are based on detailed technology assessment and bottom-up cost modeling.

Technology Assessment

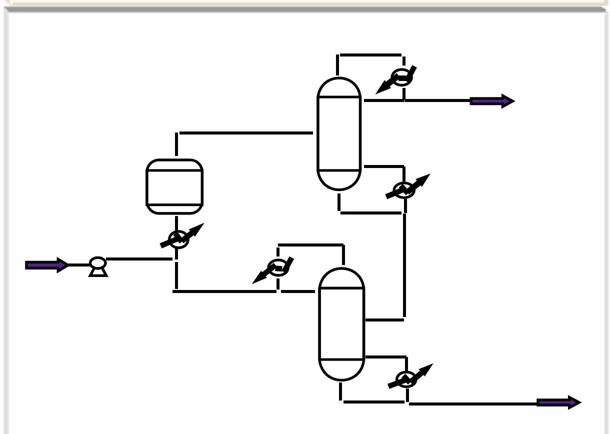
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Design Assumptions
- Obtain Developer Input

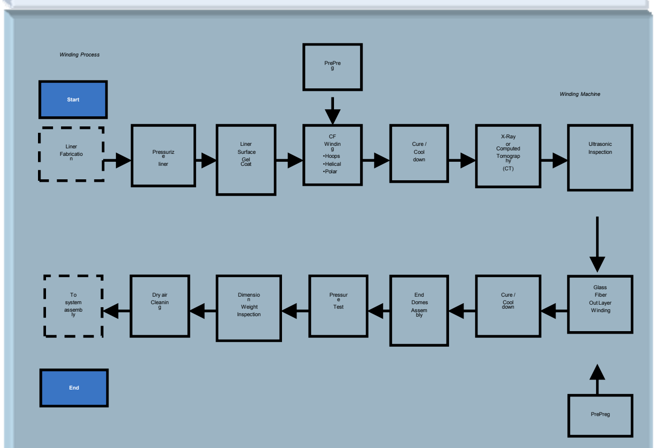
Cost Model and Estimates

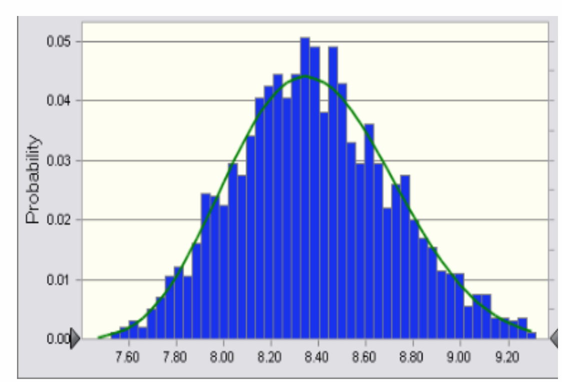
- Develop BOM
- Specify Manufacturing Processes and Equipment
- Determine Material and Processing Costs
- Develop Bulk Cost Assumptions

Overall Model Refinement

- Obtain Developer and Industry Feedback
- Revise Assumptions and Model Inputs
- Perform Sensitivity Analyses (single and multi-variable)



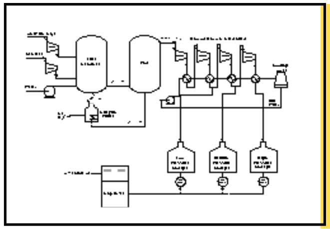




BOM = Bill of Materials

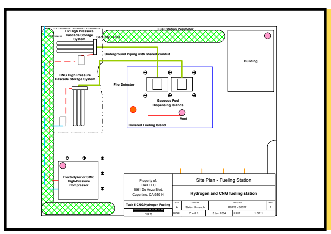
The off-board assessment makes use of existing models to calculate cost and performance for each technology on a consistent basis.

Conceptual Design



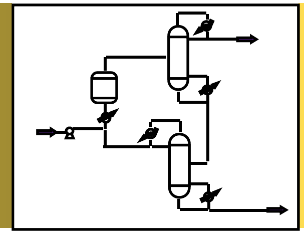
- System layout and requirements

Site Plans



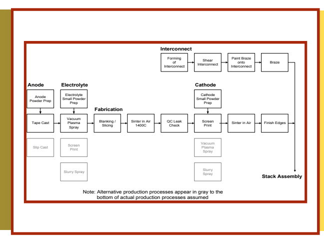
- Safety equipment, site prep, labor and land costs

Process Simulation



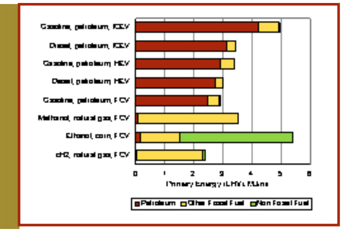
- Energy requirements
- Equipment size/specs

Capital Cost Estimates



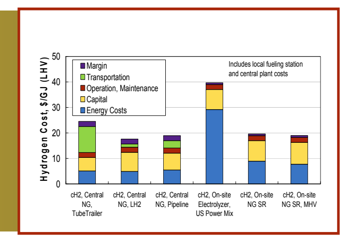
- High and low volume equipment costs

ANL/GREET Model



- WTT energy use
- WTT GHG

TIAX/H2A Model



- Equivalent hydrogen selling price

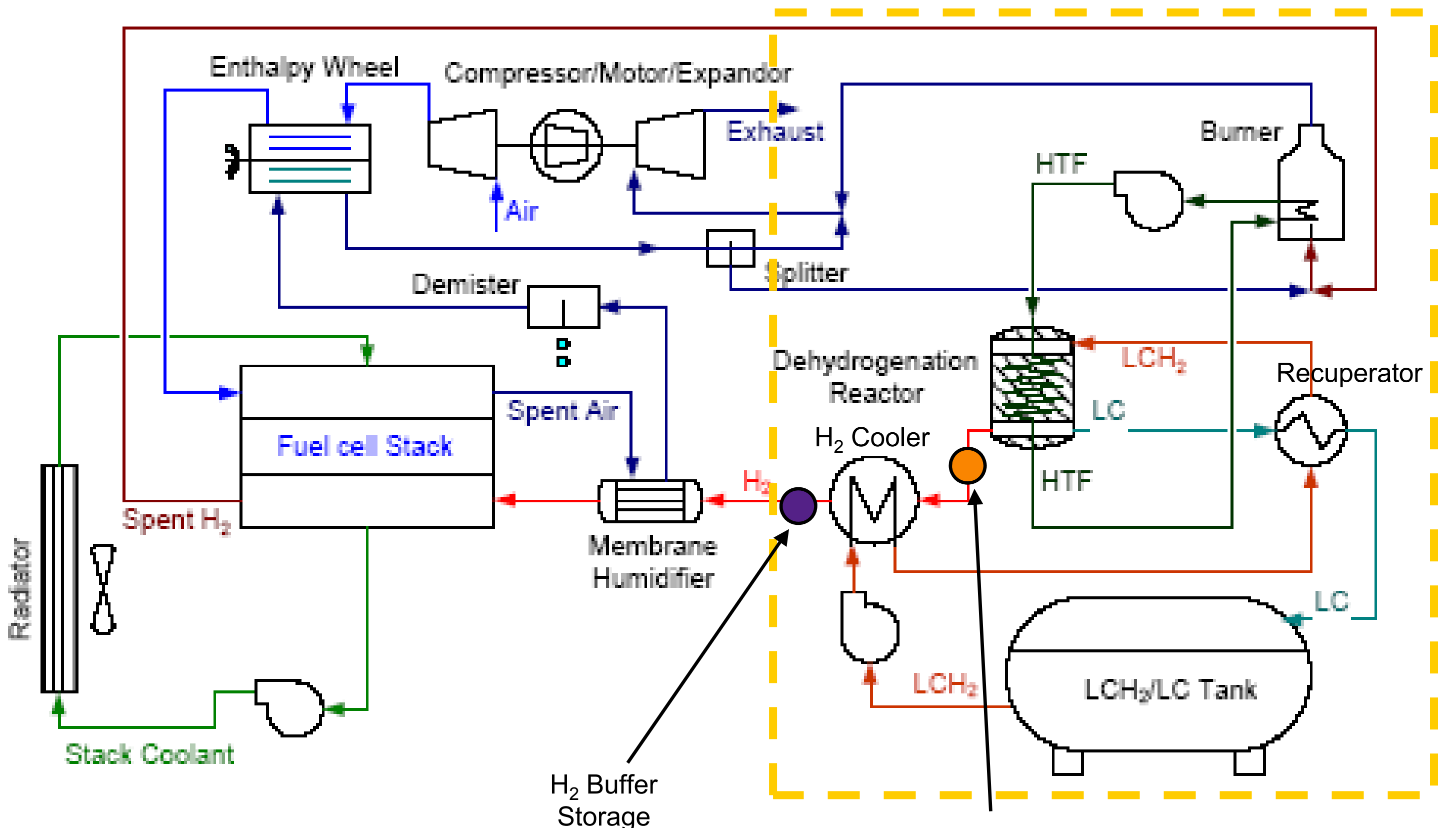
We completed on-board and off-board assessments of LCH_2 and updated our compressed H_2 assessment since the last Review.

- Completed liquid hydrogen carrier (LCH_2) system cost assessments
  - Based on ANL's performance assessment of Air Products and Chemicals Inc. (APCI) regenerable organic liquid carrier (n-ethylcarbazole-like material[1])
  - High-volume (500,000 units/yr) on-board system factory cost projection = $15.4/kWh useable H_2
  - On-board system weight estimate = 2.2 wt.%; volume estimate = 19 g H_2/L
  - Mature market (i.e., 250 TPD H_2 eq.) refueling cost projection = $4.74/kg H_2 eq.
- Updated 5 and 10-ksi compressed hydrogen on-board system factory cost assessment
  - Made slight adjustments to the tank safety factor and carbon fiber requirements to be consistent with ANL's updated analysis assumptions and results
  - Applied tank safety factor to nominal pressure (i.e., 5 and 10 ksi) rather than max filling over pressure (i.e., 6.25 and 12.5 ksi)
  - High-volume projection = $15.6 and $23/kWh useable H_2 for 5 and 10-ksi, respectively
  - On-board system weight estimates = 5.9 and 4.6 wt.%; volume estimates = 18 and 25 g H_2/L for 5 and 10-ksi, respectively
- Completed review of Rohm & Haas (R&H)'s Ammonia Borate (AB) regen. and 1st fill cost projections
  - Based on R&H plant configuration and performance assessments
  - Mature market (i.e., 100 TPD H_2 eq.) AB regeneration cost projection = $8/kg H_2 eq.
  - Mature market (i.e., 10,000 TPY AB) AB 1st fill cost projection = $9/kg AB

[1] N-ethylcarbazole is toxic and has a low weight % making it relatively inappropriate for an actual on-board storage medium, however it is being used as a representative material for expected carriers to be developed and allows analysis regarding the system, and delivery to be completed.

We used the on-board system definition and design developed by APCI[1] and ANL[2] as the basis of our LCH$_2$ factory cost assessment.

On-Board Storage System to be Evaluated (yellow dashed box)



Source: ANL (2007)

[1] "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez, G., 2007 DOE H$_2$ Program Review

[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE H$_2$ Program Review, May 2007

Media and storage tank assumptions and specifications were based on previous TIAX analyses and discussions with APCI and ANL[1,2].

System Element	Design Parameter	Value	Basis/Comment
Media/System	Media/material (prototypical)	N-ethylcarbazole[3]	ANL[2], APCI[1]
	Material H_2 storage capacity	5.8 wt%[3]	ANL[2], APCI[1]
	Storage system efficiency	67.7%	ANL[2]; includes H_2 utilized to fire burner only (does not include 95% reactor conversion efficiency)
	LCH$_2$ solution density	1200 kg/m^3	ANL[2]
	LC solution density	950 kg/m^3	ANL[2]
LCH$_2$/LC Storage Tank	Usable H_2 capacity	5.6 kg	Design basis; note: ANL[2] analysis done for 6.4 kg usable H_2
	Stored H_2 capacity	8.7 kg	Calculated based on 95% conversion efficiency and 67.7% storage efficiency; note: ANL[2] analysis done for 10 kg stored H_2
	Tank material of construction	HDPE	ANL[2]
	% excess tank volume	10%	Over fuel volume, to account for sloshing
	Bladder/separator?	Yes	Single tank design; needed to separate LCH$_2$ from LC
	Temperature	70 ^{o}C	Needed to prevent solidification

[1] "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez, G., 2007 DOE Hydrogen Program Review

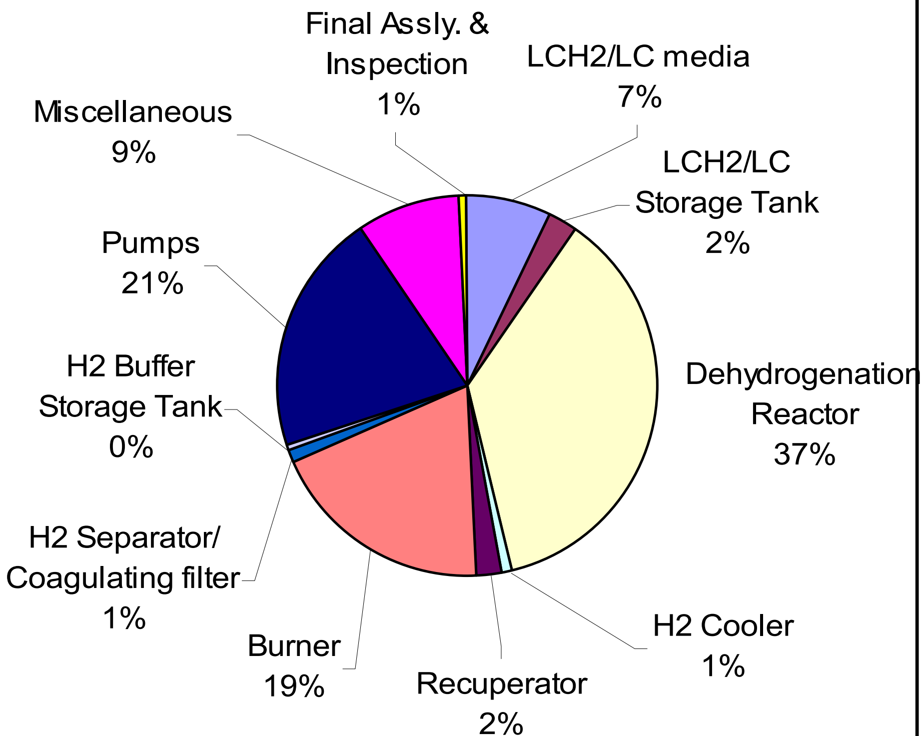
[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

[1] N-ethylcarbazole is toxic and has a low weight % making it relatively inappropriate for an actual on-board storage medium, however it is being used as a representative material for expected carriers to be developed and allows analysis regarding the system, and delivery to be completed.

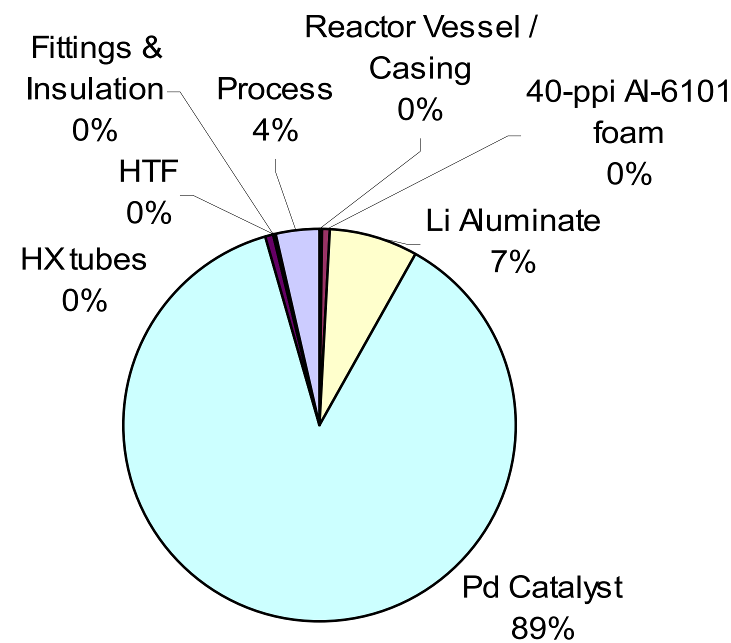
Other component design assumptions are presented in the Appendix.

We estimate the high-volume factory cost[1] of the system to be about \$15.4/kWh, of which ~32% is due to the cost of the Pd catalyst.

LCH$_2$ System Factory Cost[1] = \$2,870
\$15.4/kWh based on 5.6 kg usable H$_2$ (8.7 kg stored H$_2$)



LCH$_2$ Dehydrogenation Reactor Factory Cost[1] = \$1,045

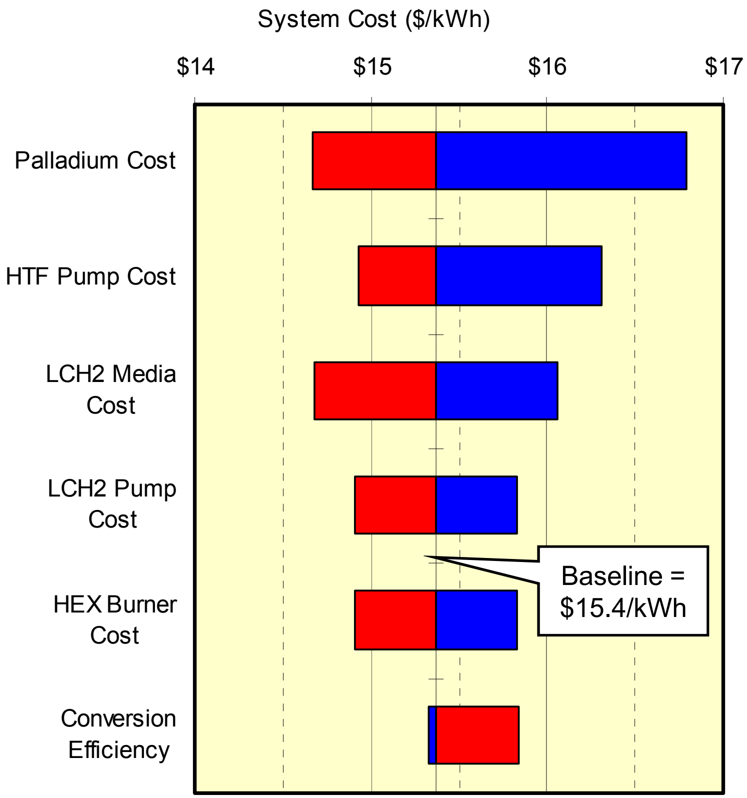


Note: A trade-off study was not performed on the size/cost of the pumps versus size/cost of the reactor sub-system and burner.

[1] Cost includes deflation by 9.27% to Year 2005 USD.

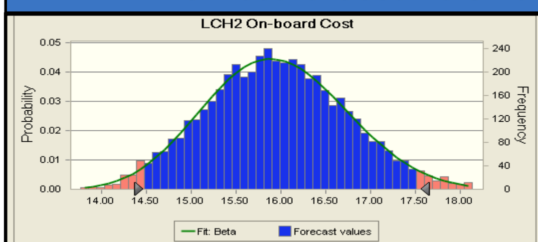
Uncertainty in the catalyst, carrier media, and purchased component prices significantly affect the projected cost of the liquid carrier system.

On-board Cost Sensitivity – Liquid Hydrogen Carrier (5.6 kg H$_2$), \$/kWh



Key Sensitivity Parameters	On-board Cost Sensitivity – LCH$_2$			
	Base-line	Min	Max	Basis/Comment
Conversion Efficiency	95%	65%	100 %	◆ Baseline from ANL 2007 DOE AMR[1], min from APCI 2008 DOE AMR[2]
Palladium Cost (\$/troy oz.)	436	360	580	◆ Baseline from metalprices.com average ◆ Min and Max estimates from min and max LME values over the past year
HTF Pump Cost	\$400	\$300	\$600	◆ Baseline from catalog prices discounted by ~60%
LCH$_2$ Media Cost (per gal)	\$7	\$2	\$12	◆ Discussion with APCI
LCH$_2$ Pump Cost	\$200	\$100	\$300	◆ Baseline from catalog prices discounted by ~60%
HEX Burner Cost	\$400	\$300	\$500	◆ Baseline from catalog prices for natural gas burners discounted by ~60%.

On-board Cost Multi-variable Sensitivity – LCH$_2$



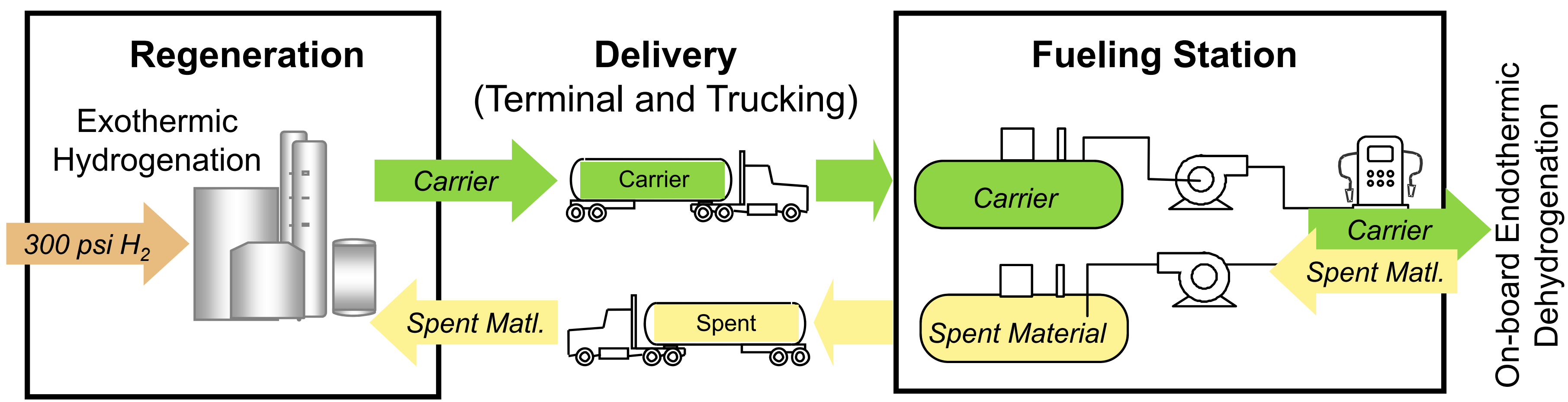
System Cost	\$/kWh
Mean	16
Std. Dev.	0.8
Baseline	15.4

[1] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

[2] "Reversible Liquid Carriers for an Integrated Production, Storage and Delivery of Hydrogen", Toseland, B. and Pez, G., 2008 DOE H$_2$ Program Review

An H2A Carrier model was developed to evaluate the off-board refueling cost for LCH$_2$ and allow for direct comparison to other H$_2$ options.

- Most financial assumptions are maintained from the original H2A Delivery Components Model
- New calculation tabs were added as part of the DOE Delivery Project for novel carriers, resulting in the H2A Delivery Components Carrier Model v34
- These new calculation tabs were populated with inputs based on industry and developer feedback specifically for LCH$_2$ and SBH



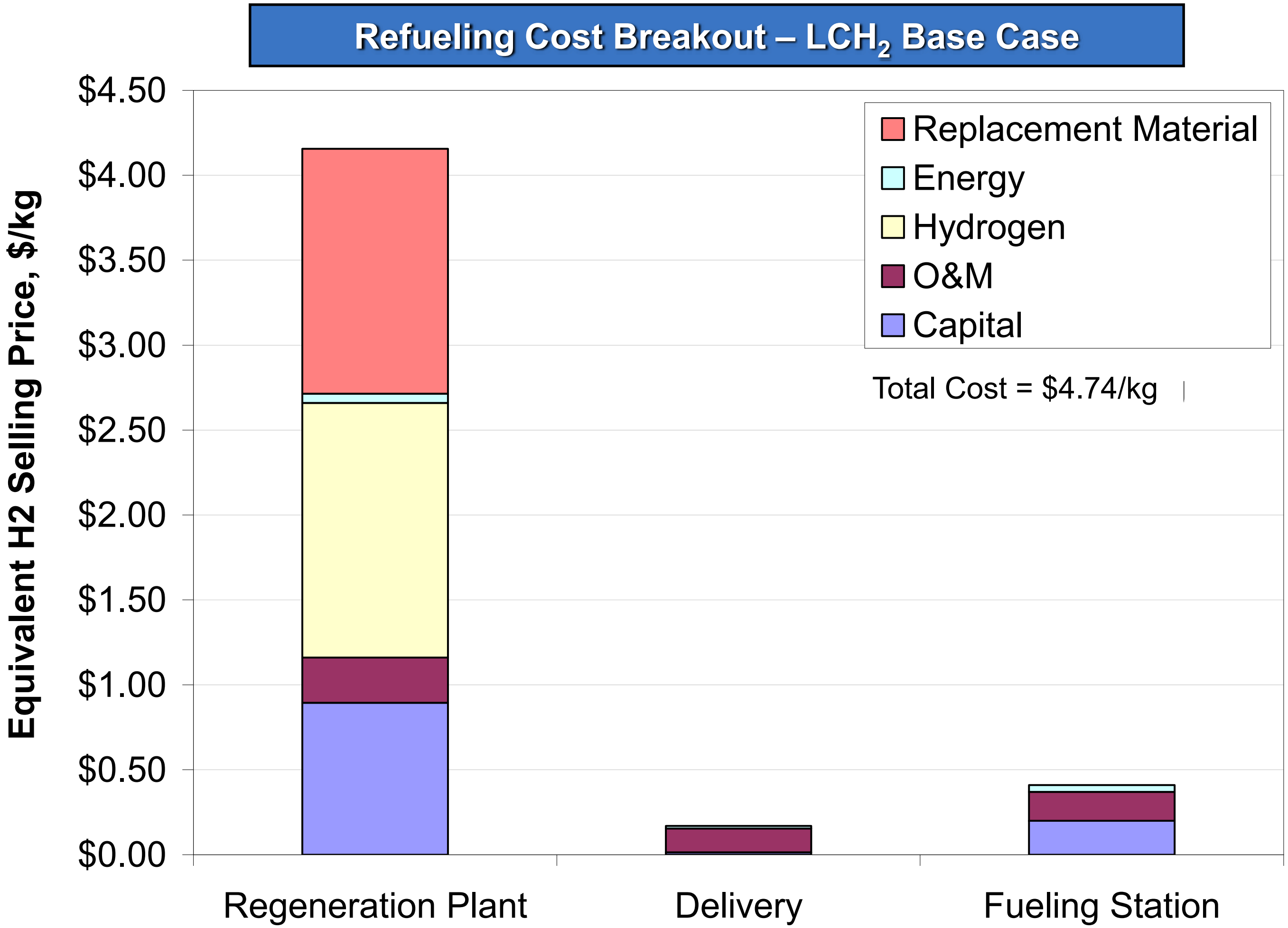
The off-board assessment for novel carriers requires evaluation of regeneration, delivery and forecourt technologies.

The LCH$_2$ regeneration facility assumptions were based on previous H2A assessments and discussions and information provided by APCI.

Regeneration Plant Component	Assumptions
Hydrogen	Hydrogen is purchased as a pure gas at 20 bar for $1.50/kg No losses are assumed
Material Storage Tanks	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 est.) 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 est.) Catalyst lifetime based on material processed: 350,000-1,000,000 kg_m/kg_c; 500,000 baseline (industry est.)

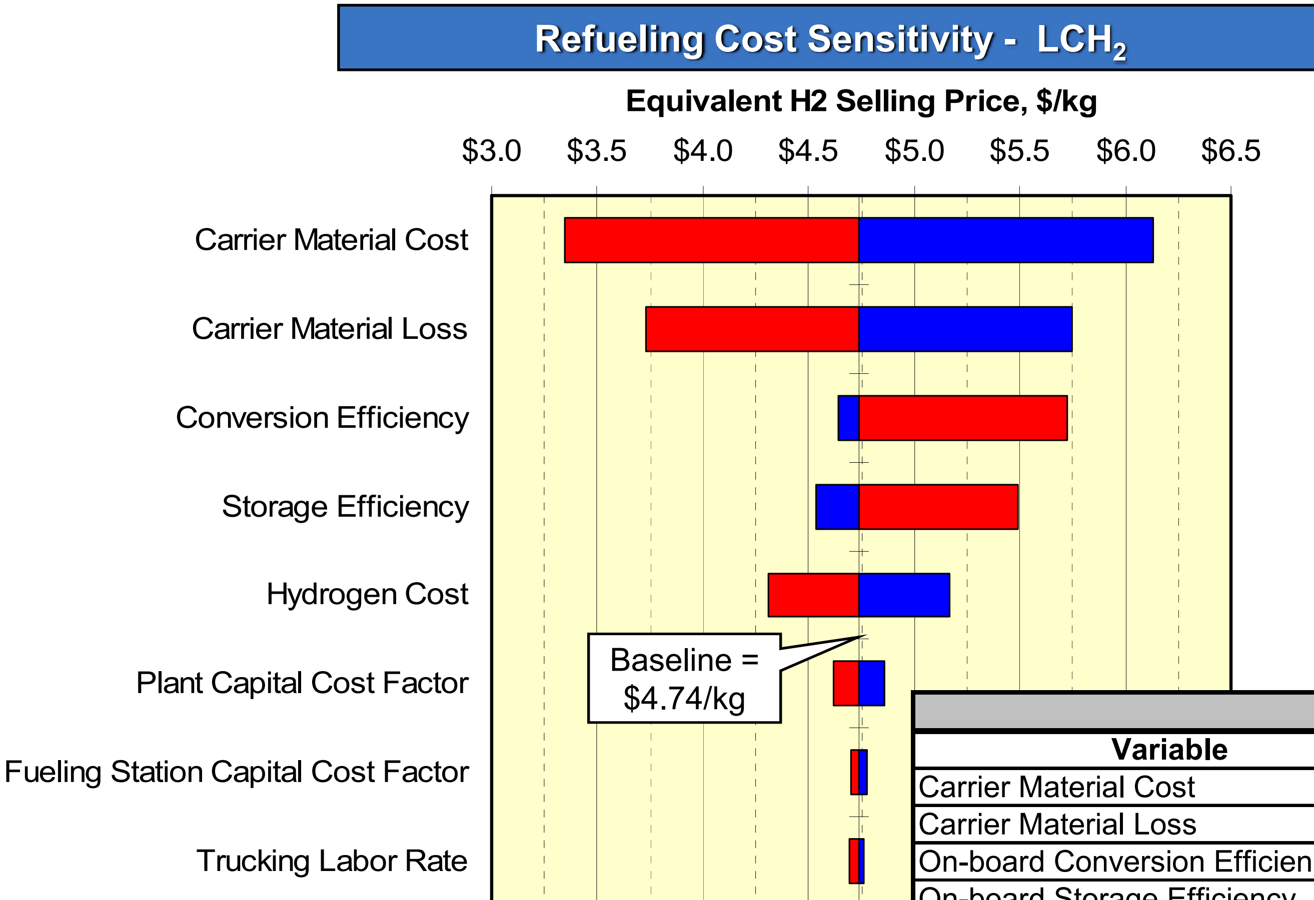
Delivery and Fueling Station design assumptions are presented in the Appendix.

Off-board cost results indicate that the major non-H_2 costs include capital costs at the regeneration plant and carrier material replacement.



Note: Detailed assumptions are presented in the Appendix. If the carrier is used as an off-board transportation media only (i.e., fueling station dehydrogenation), the H_2 selling price would increase to about $5.90/kg.

Factors effecting the initial and replacement costs of carrier material have the greatest affect on the hydrogen selling price sensitivity.



		Values		
Variable	**Units**	**Min**	**Baseline**	**Max**
Carrier Material Cost	$/gal	$2	$7	$12
Carrier Material Loss	%	0.5%	2.75%	5%
On-board Conversion Efficiency	%	65%	95%	100%
On-board Storage Efficiency	%	50%	67.7%	75%
Hydrogen Cost	$/kg	$1	$1.5	$2
Plant Capital Cost Factor	%	50%	100%	150%
Fueling Station Capital Cost Factor	%	50%	100%	150%
Trucking Labor Rate	$/hr	$25	$40	$50

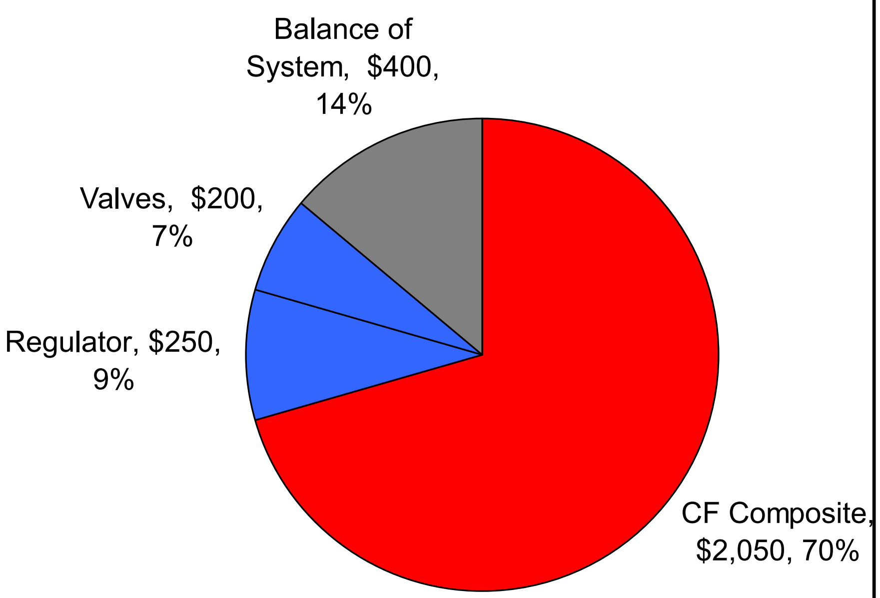
We reviewed and updated our previous compressed tank design assumptions with DOE, Quantum, SCI, Toray and ANL.

Design Parameter	Base Case Value	Basis/Comment
Usable H_2 storage capacity	5.6 kg	Design assumption based on ANL drive-cycle modeling for 350 mile range assuming a mid-sized, hydrogen fuel cell vehicle
Tank size (water capacity)	261 L (5-ksi) 150 L (10-ksi)	Required for 5.6 kg useable H_2 capacity (6.0 and 5.8 kg total H_2 capacity for 5-ksi and 10-ksi tanks, respectively)
Carbon fiber type	Toray T700S	Consistent with industry use and other H_2 storage analyses
Safety factor	2.35	EIHP Rev 12b design criteria applied to nominal storage pressure (i.e., 5 ksi and 10 ksi)
Composite tensile strength	2,550 MPa	Toray material data sheet for 60% fiber by volume
Translation strength factors	82.5% (5-ksi) 63% (10-ksi)	Quantum, 2004
L/D Ratio	3	Discussions with Quantum, 2008; based on the outside of the CF wrapped tank
“Empty” pressure	290 psi	Discussions with Quantum, 2008
Max filling over pressure	25% design pressure	Required for fast fills to prevent under-filling
Tank liner	5 mm HDPE	Discussions with Quantum, 2008; typical for 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

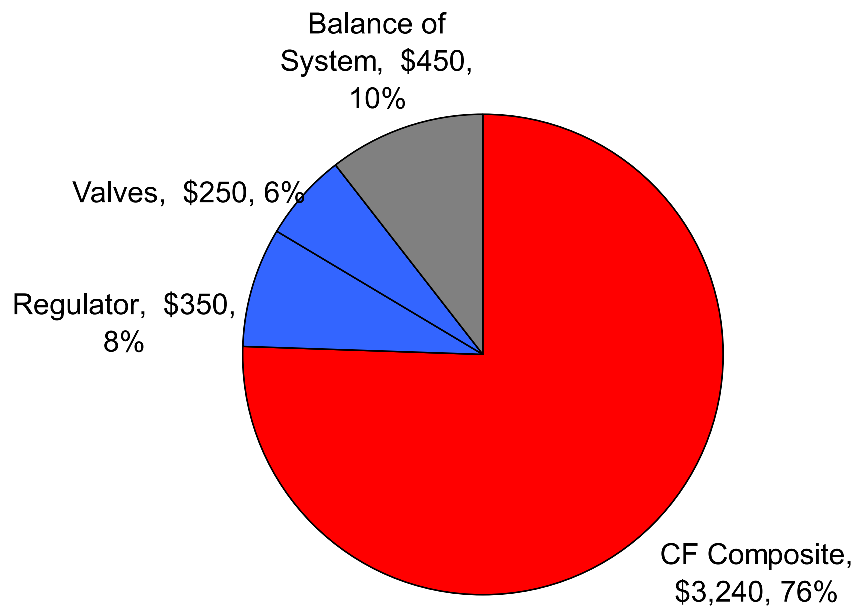
= updated design parameter in 2008/2009

Updated results show carbon fiber (CF) composite accounts for ~70% and 75% of the base case 5-ksi and 10-ksi system costs, respectively.

5,000-psi System Factory Cost[1] = $2,900
$15.6/kWh based on 5.6 kg usable H_2 (6 kg stored H_2)



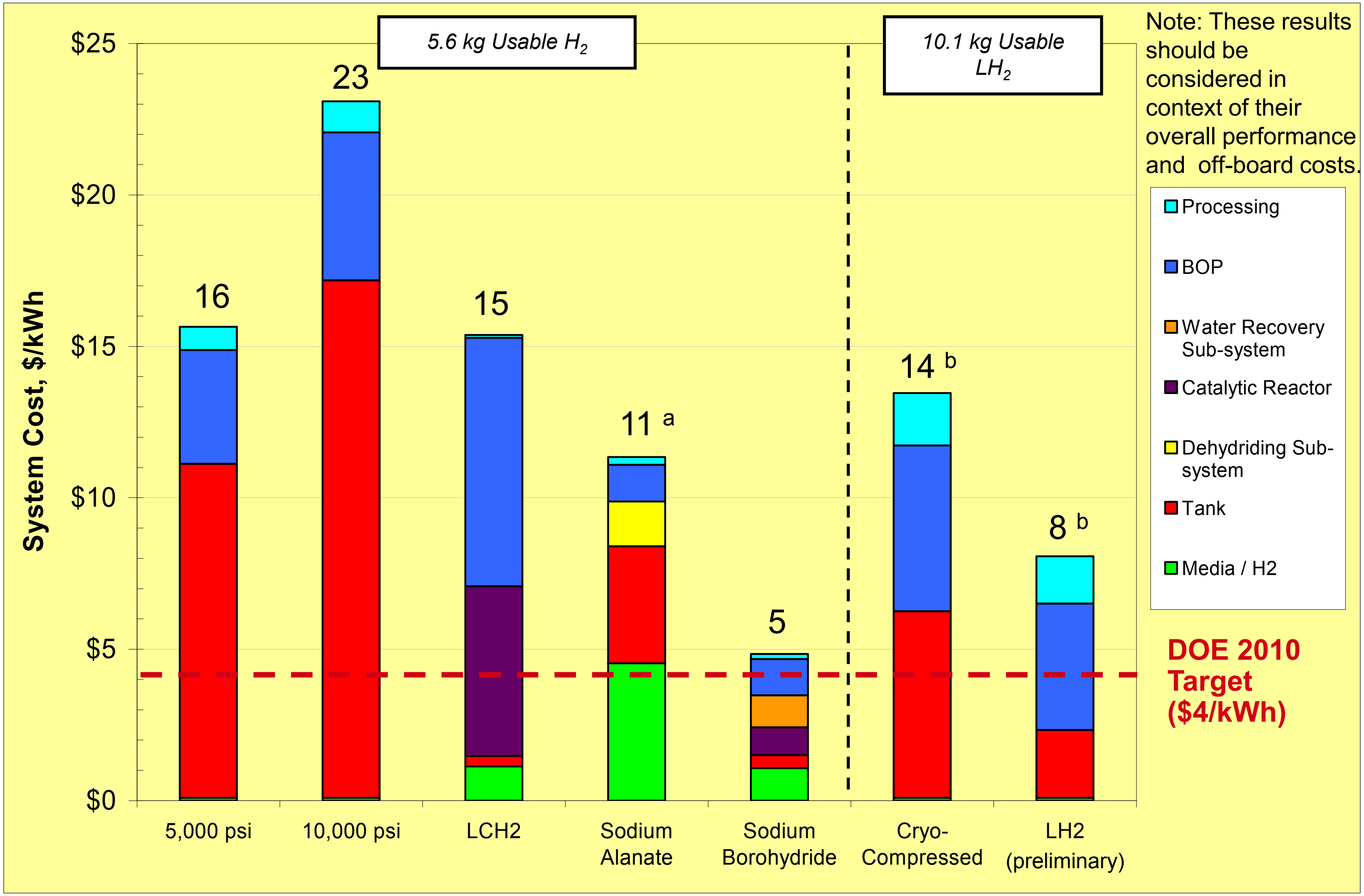
10,000-psi System Factory Cost[1] = $4,300
$23.1/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



[1] Cost estimate in 2005 USD. Includes processing costs.

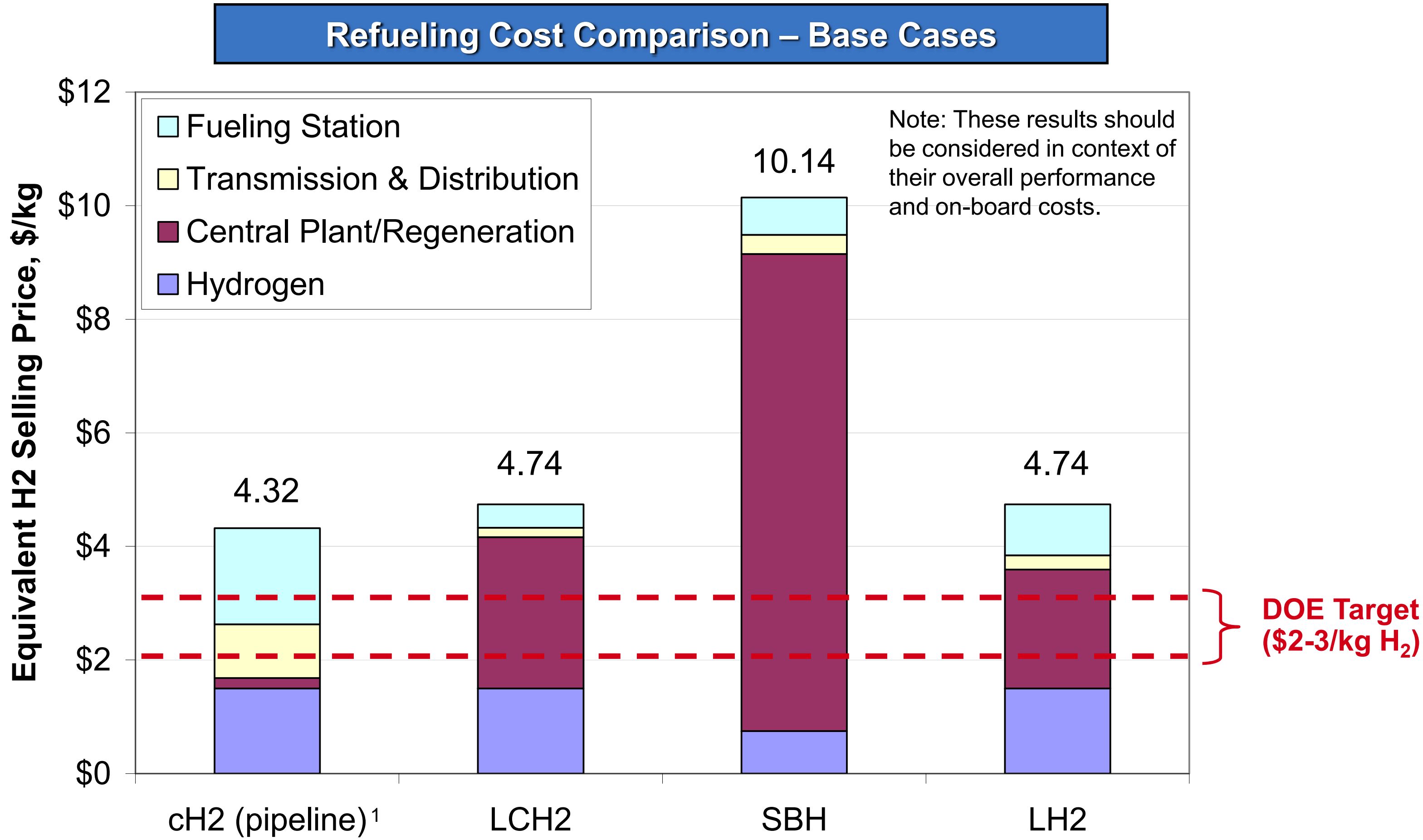
Processing costs account for approximately 5% of the total cost, and are included above. Sensitivity results are presented in the Appendix.

5-ksi, 10-ksi, and LCH_2 on-board storage system costs are projected to be 4 - 6 times higher than the 2010 target, using base case assumptions.



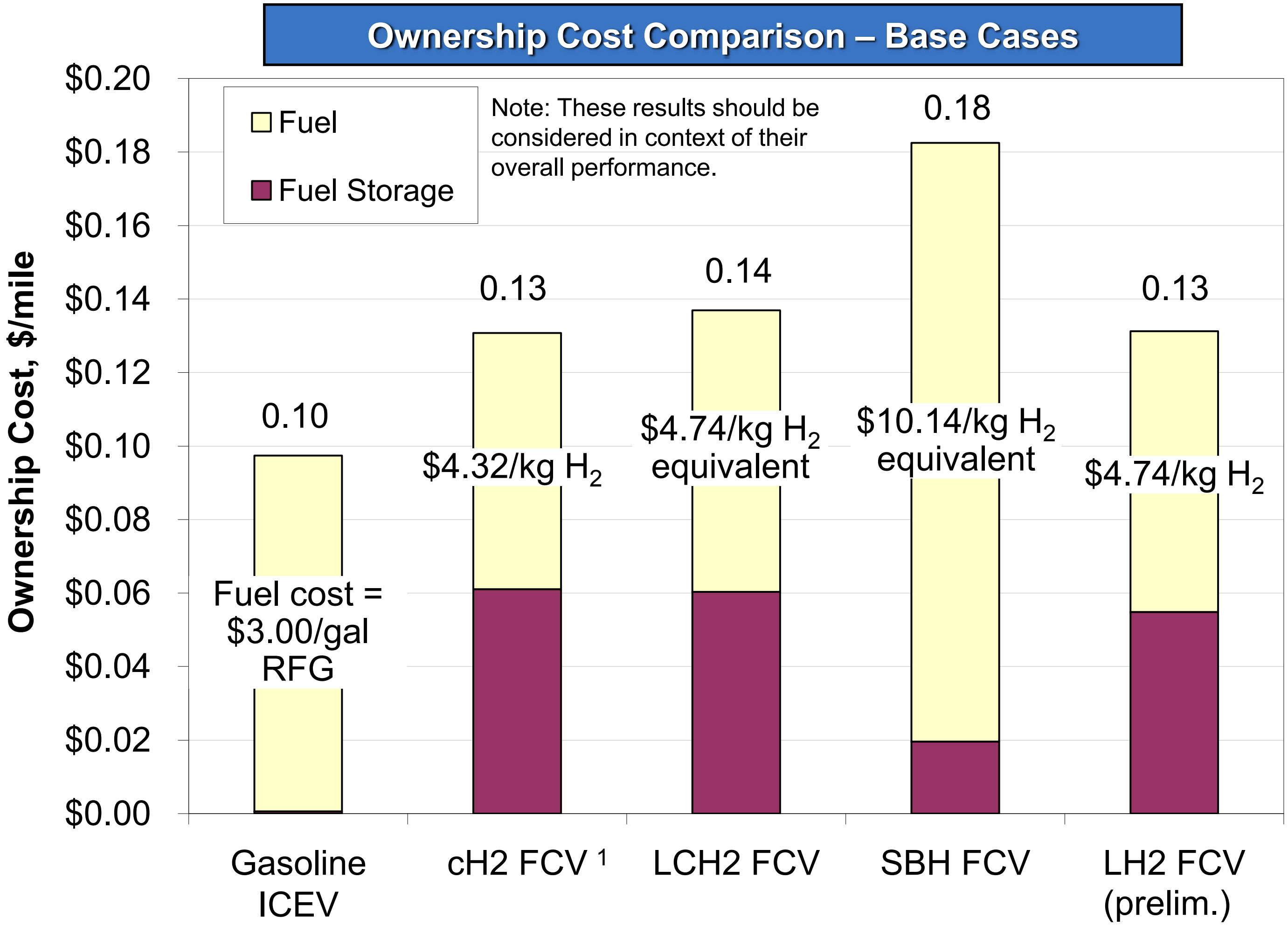
[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.
[b] Normalizing the cryo-compressed and liquid H_2 systems for 5.6 kg of usable hydrogen results in system costs of ~\$20/kWh and ~\$14/kWh, respectively.

Both compressed hydrogen (cH_2) and LCH_2 refueling costs are projected to be 1.5-2.5 times more expensive than the DOE target range.



[1] cH_2 option assumes compressed hydrogen pipeline delivery with 6,250 psi dispensing and 5,000-psi on-board storage system.
Note: cH_2 and LH_2 results were calculated using the baseline delivery scenarios in HDSAM v2.06. LCH_2 and SBH results were calculated using a modified H2A Delivery Components Carrier Model v34. Detailed assumptions are presented in the Appendix.

Fuel system ownership costs for the 5-ksi and LCH_2 systems are projected to be 35-40% more expensive than gasoline at $3/gal.



[1] cH_2 FCV option assumes compressed hydrogen pipeline delivery with 6,250 psi dispensing and 5,000-psi on-board storage system.
Note: Detailed assumptions are presented in the Appendix.

Last year, we collaborated closely with ANL and numerous developers and other stakeholders participating in the DOE Grand Challenge.

- Argonne National Laboratory (ANL) - frequent email exchanges and monthly conference calls with DOE
  - LCH_2 and cH_2 on-board system design
  - LCH_2 and cH_2 on-board and off-board performance assessment
- H_2 Storage Centers of Excellence (SNL, LANL, PNNL, NREL, LLNL, SRNL) - participated in SSAWG and Novel Carrier meetings and some monthly conference calls as necessary
  - Reviewed assumptions and results for various technologies
- Independent projects and developers (APCI, R&H) - frequent email exchanges and regular conference calls throughout the cost assessment
  - LCH_2 on-board and off-board system designs
  - LCH_2 and AB off-board systems cost inputs
  - Reviewed assumptions and results for LCH_2 and AB results
- Stakeholders (Tech Teams, Quantum, SCI, Toray) – H_2 Delivery Tech Team meeting and frequent email exchanges and regular conference calls throughout the cost assessment
  - cH_2 on-board system cost inputs
  - Reviewed assumptions and results for updated cH_2 results
  - Tech Team reviewed R&H's AB off-board system cost inputs and results

We have completed certain aspects of on-board and off-board evaluations and updates for nine hydrogen storage technologies.

Analysis To Date		cH_2	Alanate	MgH_2	SBH	Cryo-comp	LH_2	AC	LCH_2	AB
On-Board	Review developer estimates	√	√		√	√	√	√	√	
	Develop process flow diagrams and system energy balances	√	√		√	√	√		√	
	Independent performance assessment (wt, vol)	√	√		√	√	√ *		√	
	Independent cost assessment	√	√		√	√	√ *	WIP	√	
Off-Board	Review developer estimates	√		√	√	√	√		√	√
	Develop process flow diagrams and system energy balances	√		√	√				√	√
	Independent performance assessment (energy, GHG)[a]	√			√				√	
	Independent cost assessment	√			√		√		√	
Overall	Ownership cost projection	√			√		√		√	
	Solicit input on TIAX analysis	√	√		√	√ *	√ *	WIP	√	
	Analysis update	√			√	WIP	WIP			

* Preliminary results under review.
[a] Work with ANL and H2A participants on separate WTT analysis tools.

(grey box) = Not part of current SOW
WIP = Work in progress

For the remainder of the contract, we will focus on incorporating stakeholder feedback and submitting final reports for each technology.

- Complete on-board cost assessments of liquid, cryo-compressed and AC options
  - Update previous results based on input from developers
  - Use latest compressed tank design and cost assumptions for cryo-compressed and AC
- Complete off-board cost assessment as requested by DOE and integrate with overall performance and on-board cost results
- Conduct cost assessment for new technologies (if any) selected by DOE with input from the Centers of Excellence and other developers after ANL performance assessment
  - Some technologies don't pass the performance filter and need additional R&D before a cost assessment makes sense
  - Those that pass the performance filter will be evaluated for on-board and off-board costs
- Continue to work with DOE, H2A, other analysis projects, developers, National Labs, and Tech Teams to revise and improve past system models
- Complete final reports with ANL for each detailed assessment to date
  - Draft final reports are already being written and/or reviewed for 5-ksi, 10-ksi and SBH
  - Start and complete reports for Sodium Alanate, Cryo-compressed, LH_2, AC and LCH_2
  - To the extent possible, well-to-wheel performance and lifecycle cost results will be presented in the final reports for each technology

Thank You

Questions?

Last year's objective was to evaluate a liquid hydrogen carrier (LCH_2) and update our compressed hydrogen storage assessments.

Objective	Technology Focus			
	2004-2006	2007	2008	2009
On-Board Storage System Assessment	• Sodium Alanate • SBH	• Liquid H_2 • Cryo-compressed H_2	• LCH_2 • Compressed H_2 (5 and 10-ksi updates)	• AC • Liquid H_2 (update) • Cryo-compressed H_2 (update)
Off-Board Fuel Cycle Assessment	• Liquid H_2 • Compressed H_2 (5 and 10-ksi)	• SBH	• LCH_2	• Ammonia Borane • Compressed H_2 (5 and 10-ksi updates) • Liquid H_2 (update)

Note: Previously analyzed systems will continually be updated based on feedback and new information.

SBH = Sodium Borohydride, LCH_2 = Liquid Hydrogen Carrier, AC = Activated Carbon

In addition, TIAX completed a high-level review of Rohm and Hass (R&H)'s cost assessment of ammonia borane (AB) regeneration and 1st fill production.

- The goals of the review were as follows:
  - Validate R&H's implementation of the H2A Delivery Components Carrier Model for calculating the hydrogen equivalent cost for the AB regeneration and 1st fill production plants
  - Verify the underlying assumptions and cost inputs into the model
  - Check the energy and mass flows in the regeneration and 1st fill processes (to the extent possible)
- We reviewed two AB reports generated by R&H in February as well as other relevant reports
  - Evaluated all the process equipment and assumptions in addition to the implementation of these assumptions into the H2A Delivery Components Model supplied by R&H
  - The review was partially based on proprietary information received from R&H via the aforementioned reports as well as several conference calls
- R&H incorporated our feedback into their analysis and TIAX wrote a memo summarizing final comments and conclusions

The cost of capital equipment, buildings, labor, utilities, etc. are included in our processing cost assessments.

- Variable Cost Elements
  - Material
  - Direct Labor
  - Utility
- Operating Fixed Costs
  - Tooling & Fixtures
  - Maintenance
  - Overhead Labor
  - Cost of Operating Capital →
- Non-Operating Fixed Costs
  - Equipment
  - Building
  - Cost of Non-Operating Capital →

Cost of Operating Capital:

- Working Capital
  - Including materials, labor, utility, tooling and maintenance cost
  - Working capital period: 3 months

Cost of Non-Operating Capital:

- Equipment
- Building

We assume 100% debt financed with an annual interest rate of 15%, 10-year equipment life, and 25-year building life.

The dehydrogenation reactor design was also based on information from APCI and ANL[1,2].

System Element	Design Parameter	Base Case Value	Basis/Comment
Dehydrogenation Reactor	Type	Vertical, tubular trickle bed reactor	ANL[2]
	Heat of dehydrogenation	+51 kJ/mol H_2	APCI[1], ANL[2]; =25 MJ/kg H_2
	Catalyst	Pd on Li Aluminate	Dispersed wash-coat (thin-film) catalyst, 50 micron, 363 mm active length
	Catalyst concentration	4% wt. of substrate	
	Catalyst substrate	40-ppi Al-6101 foam	92% porosity, 224 kg/m^3 bulk density
	Conversion efficiency	95%	ANL[2]
	Liquid Hourly Space Velocity (LHSV)	20 h^{-1}	ANL[2]; H_2 volumetric flow rate/liter reactor volume
	Peak operating temp.	240-270 ^{o}C	ANL[2]
	Max. operating pressure	8 bar (116 psi)	ANL[2]
	HX tube material	Al-2219-T81	ANL[2]; 40 tubes (11.1 mm OD, 0.8 mm wall, 400 mm length)
	Reactor vessel material	Al-2219-T81	ANL[2]; 182 mm OD, 0.8 mm wall, 460 mm total length, 2.25 safety factor

[1] "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez., G, 2007 DOE Hydrogen Program Review
[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

LCH$_2$ Design Assumptions Continued

System Element	Design Parameter	Base Case Value	Basis/Comment
H_2 Buffer Storage Tank	Material	Al-2219-T81	ANL[2]; (249 mm OD, 0.5 mm wall, 744 mm total length, 2.25 safety factor)
	Peak Operating Temp	80 °C	ANL[2]
	Max. Operating Pressure	8 bar (116 psi)	ANL[2]
	Tank capacity	20 g H_2	ANL[2]
HEX Burner	Burner type	H_2/air (non-catalytic)	ANL[2]; 5% excess O_2, 1100 °C combustion products' exit temperature
	Burner fuel	32.3% by weight of stored H_2	
	Burner firing rate	82 kW (280,000 Btu/h)	
	HX Type	Counterflow Microchannel	ANL[2]; HTF=XCelTherm® 600, 100 °C approach temp., 310 microchannels (14.1 mm x 0.9 mm x 363 mm)
	HX Material	Inconel 600	
H_2 Cooler	HX Type	Counterflow Microchannel	ANL[2]; T_{outlet} = 80 °C, 90 microchannels (10.6 mm x 1.4 mm x 165 mm)
	HX Material	SS316	
Recuperator	HX Type	Counterflow Microchannel	ANL[2]; T_{LCH2} = T_R-10 °C, 610 microchannels (10.1 mm x 0.6 mm x 263 mm)
	HX Material	SS316	

1 "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez., G, 2007 DOE Hydrogen Program Review
2 "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

LCH$_2$ Design Assumptions Continued

System Element	Design Parameter	Base Case Value	Basis
HTF Pump	Working fluid	XCelTherm® 600	ANL[2]
	Operating Temp	320 °C	
	Pressure Head	1 bar (15 psi)	
	Density	850 kg/m^3	
	Flow rate	458 Liter/min (6.5 kg/s)	
LCH$_2$ Pump	Working fluid	LCH$_2$	ANL[2]
	Operating Temp	70 °C	
	Pressure Head	8 bar (116 psi)	
	Density	1200 kg/m^3	
	Flow rate	2.65 Liter/min (0.053 kg/s)	

[1] "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez., G, 2007 DOE Hydrogen Program Review
[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

We used Year 2008 prices for the key raw materials, which are listed below. Subsequently, we deflated all material prices by 9.27% to Year 2005 USD.

System Element	Raw Material	Base Case Price (Year 2008 USD)	Basis/Comment
Media	N-ethylcarbazole	$7/gal	APCI; $2-12/gal range; consistent with TIAX off-board LCH$_2$ storage system assessment
LCH$_2$/LC Storage Tank	HDPE	$1.83/kg	Plastics Technology, May 2008, pg. 95
Dehydrogenation Reactor	Pd catalyst	$14/g ($436/tr.oz.)	www.metalprices.com; June, 2008
	Li Aluminate	$48/kg	https://www.sigmaaldrich.com/catalog/search/ProductDetail?ProdNo=336637&Brand=ALDRICH
	Al-6101	$2.8/kg	LME Al alloy, 15-month avg., June 2008
	Al-2219-T81	$3.7/kg	http://www.steelforge.com, June 2008
	HTF (XCelTherm® 600)	$8/gal	RadCo Industries, Inc., June 2008
HEX Burner	Inconel 600	$16.5/kg	www.metalprices.com; June, 2008
H$_2$ Cooler, Recuperator	SS316	$8/kg	www.metalprices.com; June, 2008, 1-year avg.

We based the cost of purchased components on vendor quotes/catalog prices, using our judgment to adjust for high-volume production.

Purchased Component	Weight (kg)	Volume (L)	Base Case 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	

[1] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

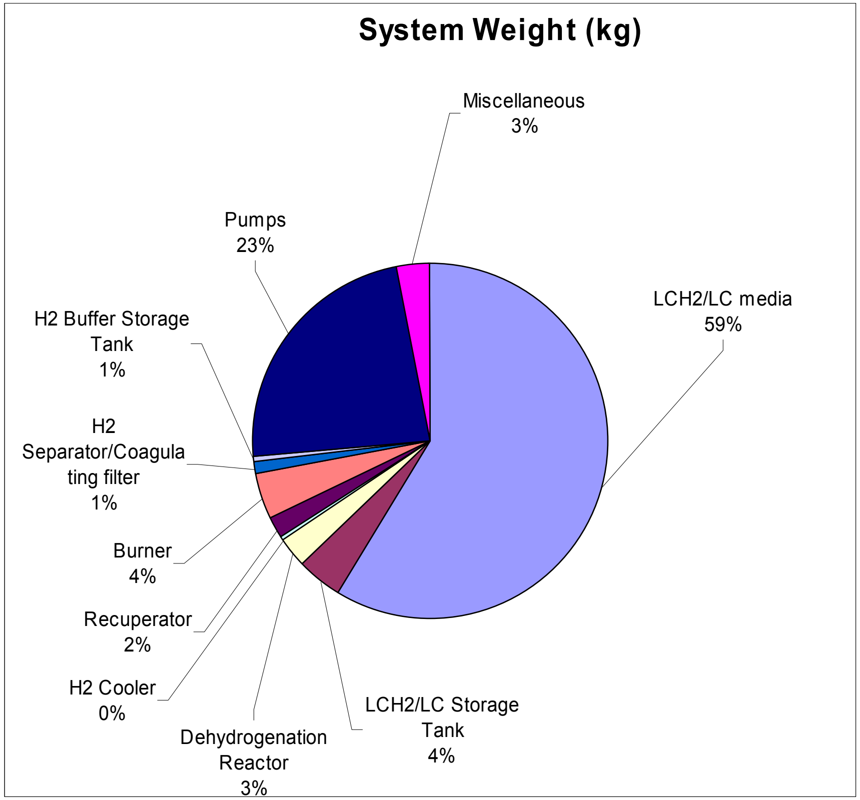
We performed bottom-up costing (i.e., raw materials, process flow charts) on all other components.

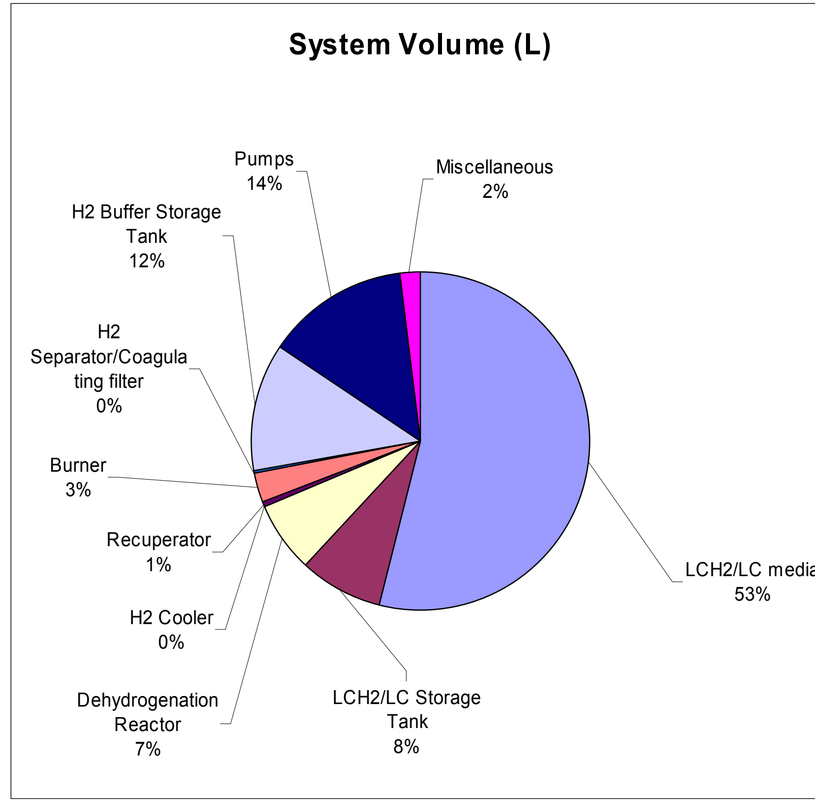
Processing cost makes up just ~5% of the total system cost due to the high production volume assumption and large fraction of purchased components.

On-board System Cost Breakout Liquid Hydrogen Carrier – 5.6 kg H_2	Material, $	Processing, $	Processing Fraction
LCH_2/LC Media[1]	**210**	**(purchased)**	**0.0%**
LCH_2/LC Storage Tank	**55**	**10**	**15.4%**
Dehydrogenation Reactor	**1,008**	**37**	**3.5%**
- Pd Catalyst	916	(purchased)	0.0%
- Li Aluminate	76	(purchased)	0.0%
- Al-6101 foam substrate	4	19	82.6%
- Reactor Vessel (Al-2219-T81)	3	2	40.0%
- HX tubes (Al-2219-T81)	4	16	80.0%
- Other (HTF, insulation, fittings)	5	(purchased)	0.0%
H_2 Cooler	**6**	**24**	**80%**
Recuperator	**36**	**24**	**40%**
Burner	**510**	**36**	**6.6%**
- Microchannel HX	92	36	28.1%
- H_2/air non-catalytic burner	400	(purchased)	0.0%
- H_2 blower	18	(purchased)	0.0%
H_2 Separator/Coagulating filter	**30**	**7**	**18.9%**
H_2 Buffer Storage Tank	**7**	**0.5**	**6.7%**
Pumps	**600**	**(purchased)**	**0.0%**
- HTF pump	400	(purchased)	0.0%
- LCH_2 pump	200	(purchased)	0.0%
Miscellaneous	**251**	**(purchased)**	**0.0%**
Final Assembly & Inspection	**0**	**17**	**100.0%**
Total Factory Cost	**2,713**	**156**	**5.4%**

[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.

We estimate the system weight to be 256 kg (2.2% wt.% H_2) and system volume to be 293 L (19 g H_2/L), primarily driven by the LCH$_2$ media.





System Weight = 256 kg

2.2 wt% based on 5.6 kg usable H_2 (8.7 kg stored H_2)

Compare to ANL estimate[1] = 2.8% wt.% H_2 for 10 kg stored H_2

System Volume = 293 L

19 g H_2/L based on 5.6 kg usable H_2 (8.7 kg stored H_2)

Compare to ANL estimate[1] = 23 g H_2/L for 10 kg stored H_2

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

[1] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

The chemical hydride (LCH$_2$ and SBH) off-board cost results were calculated using a modified version of the Delivery Components Carrier Model v34.

- Most financial assumptions are maintained from the original H2A Delivery Components Model
- New calculation tabs were added as part of the DOE Delivery Project for novel carriers, resulting in the H2A Deliver Components Carrier Model v34
  - Regeneration – calculates material regeneration costs based on capital and operating costs of a central plant and the storage capacity of the material
  - Storage Terminal – calculates required storage for fresh and spent materials
  - Trucking – calculates trucking costs for all novel carriers
  - Fueling Station – calculates fueling station costs for novel carrier storage and vehicle fueling
- These new calculation tabs were populated with inputs based on industry and developer feedback specifically for LCH$_2$ and SBH
  - TIAX made initial estimates consistent with H2A methodology
  - Model and estimates were reviewed with developers
  - Model inputs and results were updated

Capital cost estimates are derived from developer feedback and baseline H2A model assumptions.

Regeneration Plant Capital Equipment	Installed Cost ($millions)	Basis
Carrier Material	$285	Personal communication with APCI, 2008
Indirect Capital (permitting, project contingency, engineering, site prep, land)	$166	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	**$564**	

The ability of the liquid carrier to be transported in relatively standard, insulated tank trucks makes for cost efficient transportation.

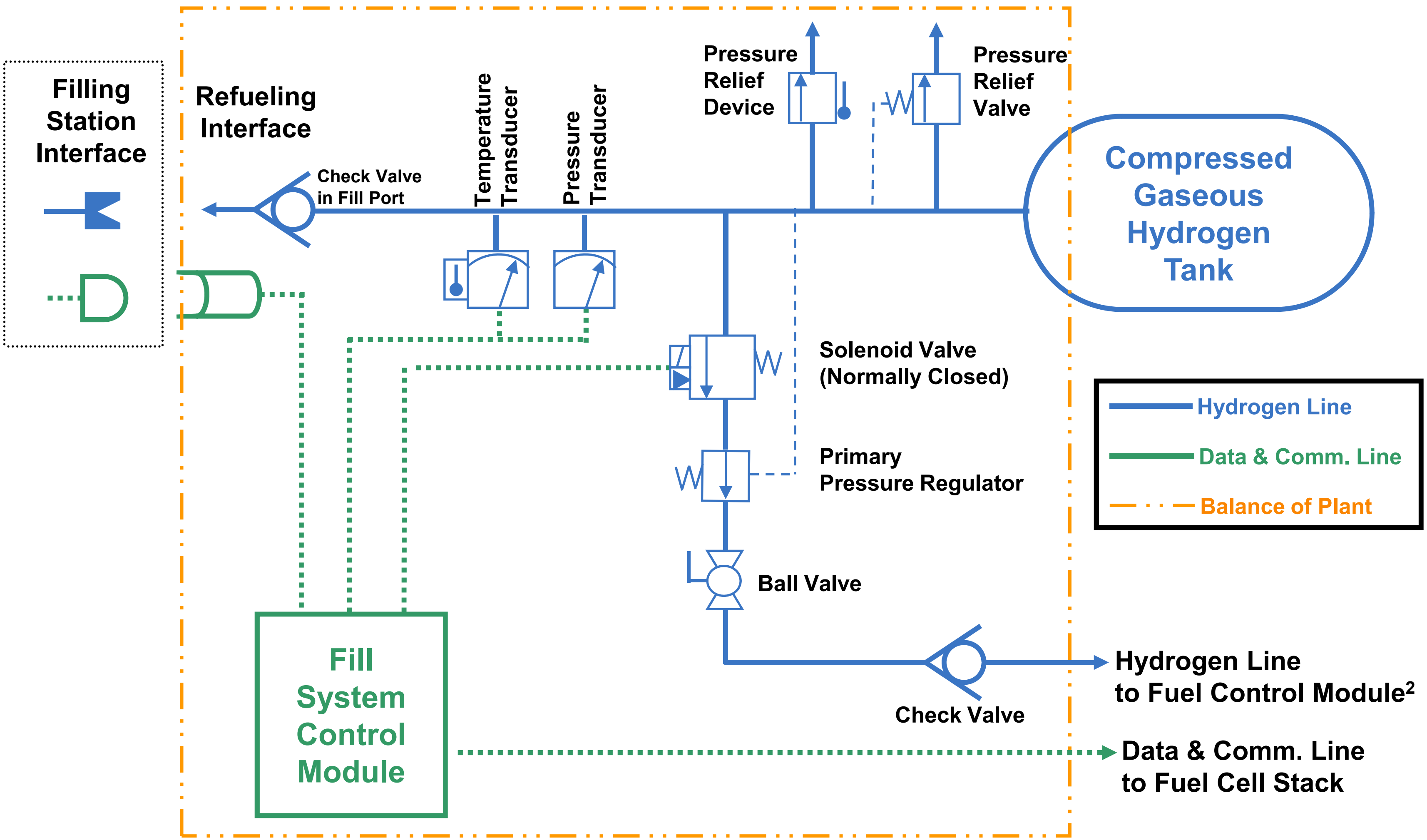
- Transport capacity: determined by the liquid carrier yield (3.7 wt% net) and the mass of material that can be transported within an insulated aluminum trailer (24,750 kg GVW)
- Insulation: will be able to maintain the temperature of the carrier for up to 1 day
- Trailer cost: $90,000 based on quotes from Heil and Polar trailer companies
- Loading/unloading time: 1.5 hrs combined (trailer unloads hydrogenated carrier and picks up dehydrogenated carrier)
- Baseline H2A assumptions include:

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

This analysis assumes the fueling station receives the liquid carrier via tanker trucks where the carrier is stored and dispensed to vehicles for on-board dehydrogenation.

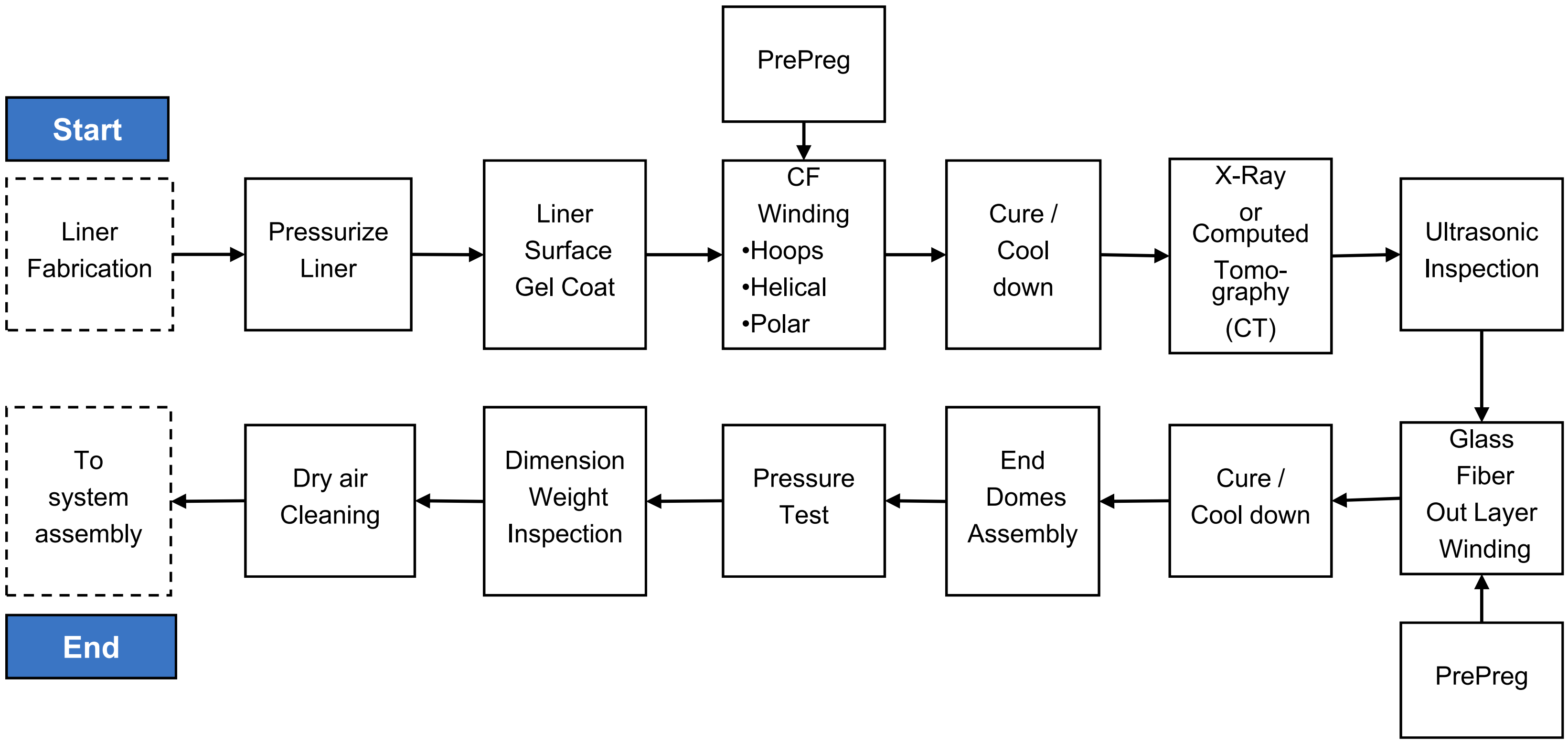
- All components (e.g., storage tanks, pumps, dispensers) are specified according to previously established methods for chemical hydrogen systems
- On-site storage in each of the hydrogenated and spent carrier tanks is equal to 1.5 truck deliveries
- Overall cost includes enough carrier material to fill 1/3 of the hydrogenated carrier tank and the full spent carrier tank
- Electricity consumption due to carrier pumping and other miscellaneous loads are the same as for sodium borohydride (SBH) = 0.50 kWh/kg
- A range of labor costs were used: $7.75/hr (minimum wage in CA) - $15/hr, with the baseline value of $10/hr

The system schematic[1] and bill of materials for the compressed systems were generated through discussions with tank developers.



[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.

The process for manufacturing wound composite tanks is well established from the Compressed Natural Gas Industry.



*Note that about 60 winding machines would be required for 500,000 5,000-psi tanks per year; about 100 machines would be required for 10,000-psi tanks.

We updated the carbon fiber composite calculations, which can significantly effect the overall weight and cost results.

- End dome shape and thickness modeled using composite pressure vessel algorithm[1]
  - Combination of hoop and helical windings assumed, with only helical windings on the end domes; ratio of hoop/helical windings equal to 1.8
  - Non-uniform end dome thickness; thickest at dome peak (exit hole)
  - Model yields carbon fiber weight calculations consistent with Quantum's models
- Carbon fiber composite requirement[2] for the rest of the tank also changed due to changes to the base case assumptions:
  - Safety factor changed to 2.35 from 2.25 and applied to nominal tank pressure (i.e., 5,000 and 10,000 psi) rather than max filling over pressure (i.e., 6,250 and 12,500 psi)
  - Carbon fiber composite tensile strength updated to 2,550 MPa from 2,940 MPa

2008 Updated Base Case Assumptions	5,000-psi	% Change '08/'06	10,000-psi	% Change '08/'06
Cylinder Composite Thickness, mm	14.3	19%	30.8	18%
Total Composite Weight, kg	51.7	8%	81.8	2%

[1] "Mechanics and Analysis of Composite Materials", Vasiliev and Morozov, New York: Elsevier Science, 2001.
[2] Other minor changes include assumptions for tank diameter and minimum tank pressure.

We based the cost of purchased BOP components on vendor quotes/catalog prices, using our judgment to adjust for high-volume production.

BOP Component	5,000-psi System			10,000-psi System		
	Weight (kg)	Volume (L)	Base Case Cost ($)	Weight (kg)	Volume (L)	Base Case Cost ($)
Regulator	2	1	250	3	1.3	350
Valves	2.5	1	200	3.5	1.5	250
Fittings, Bosses & Pipe	7	1	140	7	1	160
Fill Port	0.5	1	80	0.5	1	100
Miscellaneous	2	1	50	2	1	70
Total	14	5	720	16	6	930

We performed bottom-up costing (i.e., raw materials plus processing costs) on all other components.

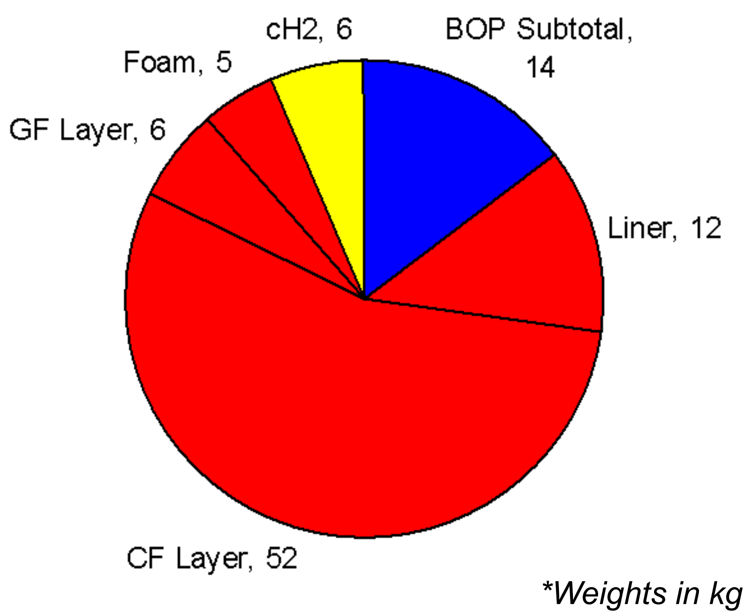
Raw Material	Base Case Price ($/kg)	Basis/Comment
Hydrogen	3.0	Consistent with DOE H_2 delivery target
T700S CF Prepreg	36.6	Discussion w/ Toray (2007) re: T700S fiber ($10-$16/lb, $13/lb base case) 1.27 prepreg/fiber ratio (DuVall 2001)
HDPE Liner	1.8	Plastics Technology, 2008
Glass Fiber Prepreg	5	Discussions with AGY, 2007 for non-structural fiber glass
Foam End Caps	7	Plastics Technology

Processing cost makes up just ~5% of the total system cost due to the high production volume assumption and large fraction of purchased components.

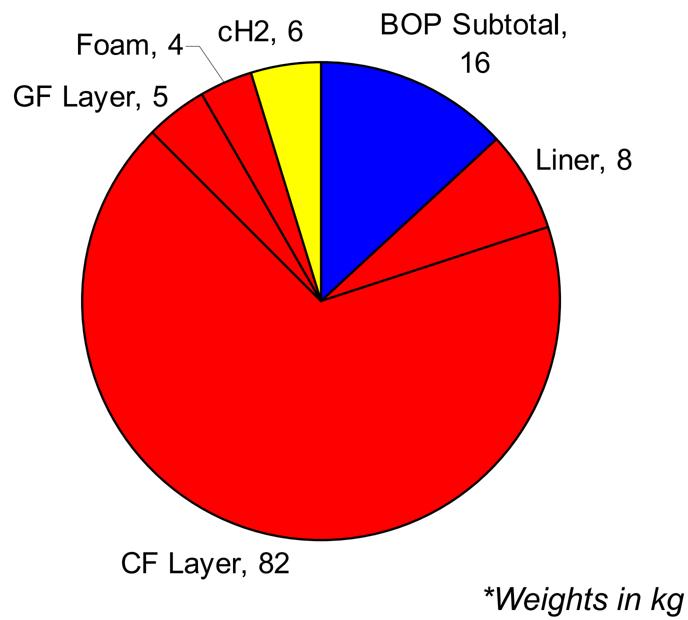
On-board System Cost Breakout Compressed Hydrogen Base Case – 5.6 kg H_2	5,000-psi			10,000-psi		
	Material, $	Processing, $	Processing Fraction	Material, $	Processing, $	Processing Fraction
Hydrogen	18	(purchased)	-	18	(purchased)	-
Pressure Vessel	2,056	98	5%	3,187	138	4%
- Liner	21	11	35%	14	10	41%
- Carbon Fiber Layer	1,972	78	4%	3,117	120	4%
- Glass Fiber Layer	32	7	18%	25	6	19%
- Foam	32	2	6%	30	2	6%
Regulator	250	(purchased)	-	350	(purchased)	-
Valves	200	(purchased)	-	250	(purchased)	-
Fittings, Bosses & Pipe	130	(purchased)	-	160	(purchased)	-
Fill Port	80	(purchased)	-	100	(purchased)	-
Miscellaneous	50	(purchased)	-	70	(purchased)	-
Final Assembly & Inspection	-	36	-	-	36	-
Total Factory Cost	2,784	134	5%	4,135	174	4%

For the baseline conditions, CF composite accounts for 55% of the total weight of the 5,000-psi system and about 70% of the 10,000-psi system.

5,000-psi System Weight = 95 kg
5.9 wt% based on 5.6 kg usable H_2 (6 kg stored H_2)



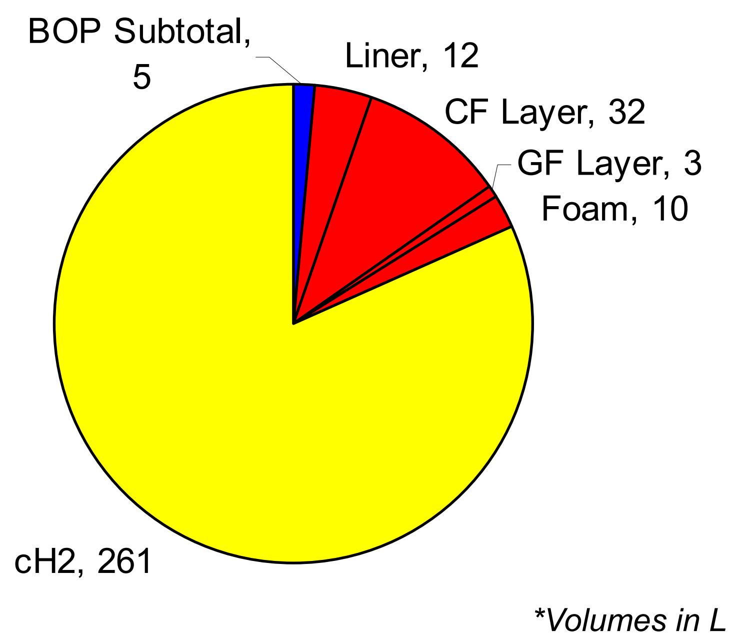
10,000-psi System Weight = 121 kg
4.6 wt% based on 5.6 kg usable H_2 (5.8 kg stored H_2)



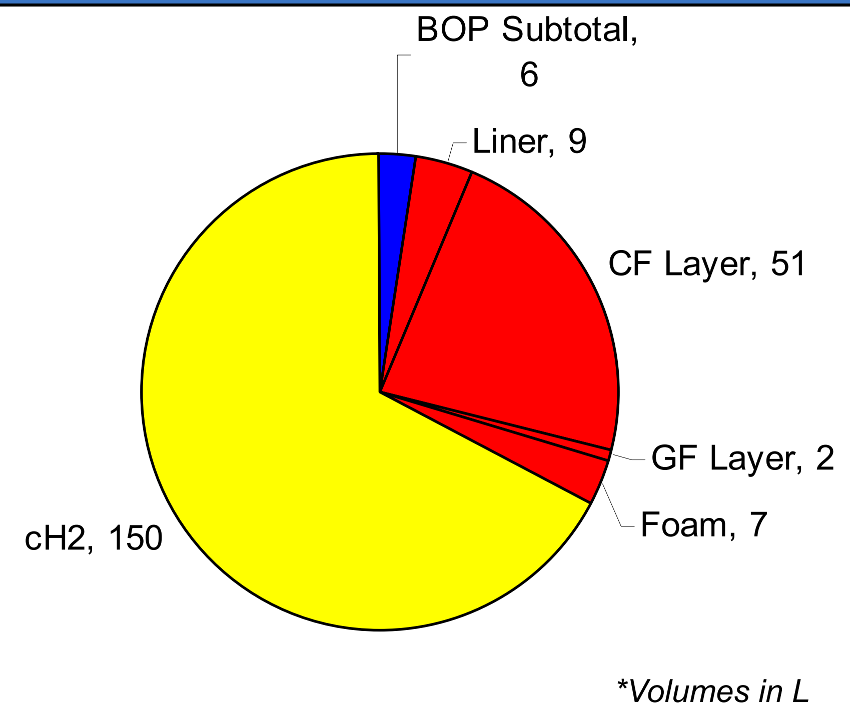
The gravimetric capacity of the 10,000-psi tank system is lower, despite the higher density of the stored H_2, due to the additional CF composite required.

For the baseline conditions, the stored hydrogen accounts for 80% of the total volume of the 5,000-psi system and about 70% of the 10,000-psi system.

5,000-psi cH_2 System Volume = 321 L
17.5 g H_2/L based on 5.6 kg usable H_2 (6 kg stored H_2)



10,000-psi cH_2 System Volume = 224 L
25 g H_2/L based on 5.6 kg usable H_2 (5.8 kg stored H_2)

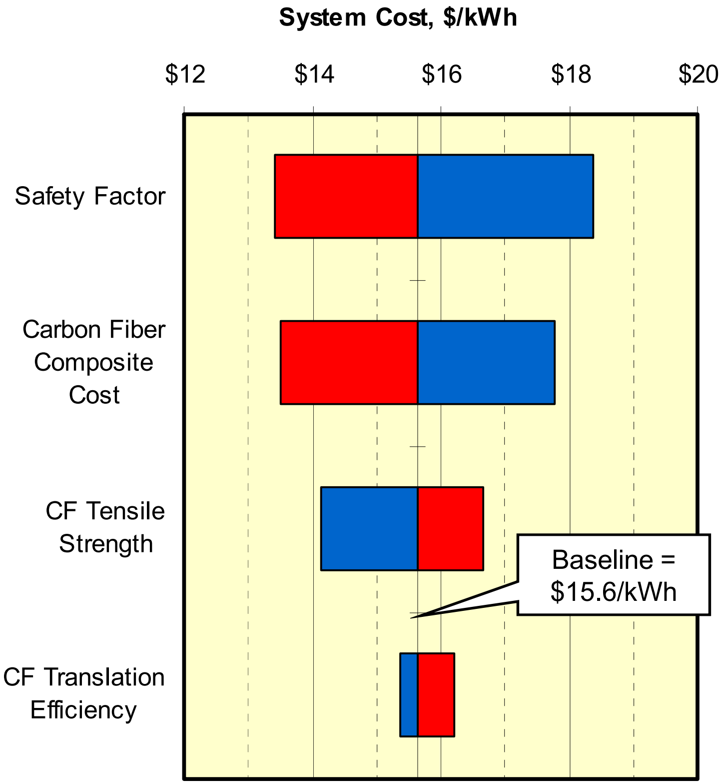


Note: Volume results do not include void spaces between components (i.e., no packing factor was applied).

The volume of the hydrogen alone fails to meet the 2010 targets of 45 g H_2/L (124 L for 5.6 kg H_2).

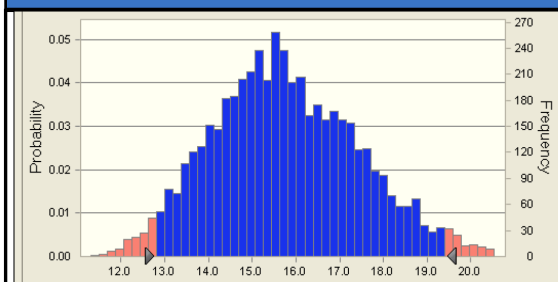
The range of uncertainty for the 5,000-psi tank's CF cost and safety factor have the biggest impact on the base case cost estimate (roughly 15-20% each).

On-board Cost Sensitivity – 5,000-psi (5.6 kg H_2), \$/kWh



Key Sensitivity Parameters	On-board Cost Sensitivity – 5,000-psi			
	Base	Min	Max	Basis/Comment
Safety Factor	2.35	1.80	3.0	◆ Base case is based on EIHP Rev 12b design criteria ◆ Min and Max based on discussions with Quantum and Dynatek (2005)
CF Prepreg (Fiber & Matrix) Cost (\$/lb)	16.6	12.8	20.4	◆ Based on discussion w/ Toray (2007) re: T700S fiber (\$10-\$16/lb, \$13/lb base case) ◆ 1.27 prepreg/fiber ratio (DuVall 2001)
CF Tensile Strength (MPa)	2,550	2,300	3,000	◆ Base case from Toray T700S data sheet (2007) ◆ Max calculated from fiber volume fraction (60%) and fiber strength (4,900 MPa) ◆ Min assumes 10% decrease from base case
CF Translation Strength (%)	81.5%	78%	85%	◆ Based on Quantum (2005) for 5,000-psi CF tanks

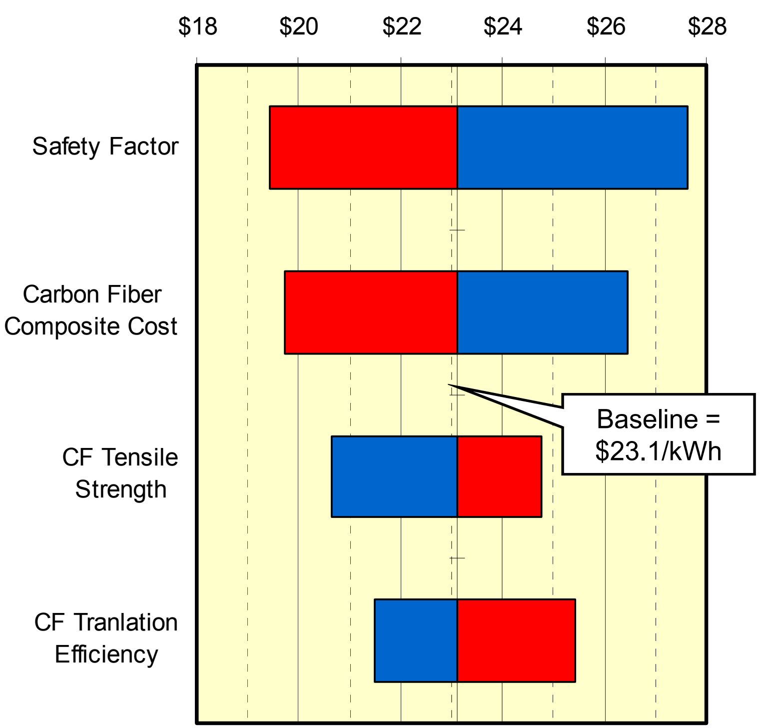
On-board Cost Multi-variable Sensitivity – 5,000-psi



System Cost	\$/kWh
Mean	15.8
Std. Dev.	1.7
Baseline	15.6

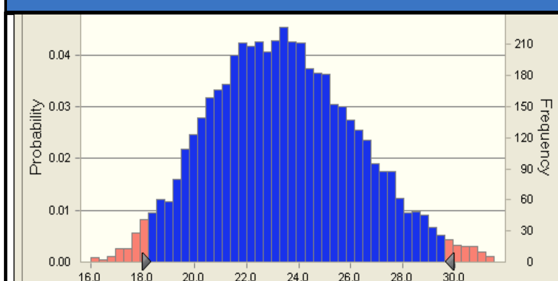
Likewise, variability in the parameters affecting CF requirements can significantly affect the overall cost of the 10,000-psi tank system.

On-board Cost Sensitivity – 10,000-psi (5.6 kg H_2), $/kWh



Key Sensitivity Parameters	On-board Cost Sensitivity - 10,000-psi			
	Base	Min	Max	Basis/Comment
Safety Factor	2.35	1.80	3.0	◆ Base case is based on EIHP Rev 12b design criteria ◆ Min and Max based on discussions with Quantum and Dynatek (2005)
CF Prepreg (Fiber & Matrix) Cost ($/lb)	16.6	12.8	20.4	◆ Based on discussion w/ Toray (2007) re: T700S fiber ($10-$16/lb, $13/lb base case) ◆ 1.27 prepreg/fiber ratio (DuVall 2001)
CF Translation Strength (%)	63%	55%	70%	◆ Based on Quantum (2005) for 10,000-psi CF tanks
CF Tensile Strength (MPa)	2,550	2,300	3,000	◆ Base case from Toray T700S data sheet (2007) ◆ Max calculated from fiber volume fraction (60%) and fiber strength (4,900 MPa) ◆ Min assumes 10% decrease from base case

On-board Cost Multi-variable Sensitivity – 10,000-psi



System Cost	$/kWh
Mean	23.5
Std. Dev.	2.9
Baseline	23.1

5,000 and 10,000-psi system cost, weight and volume decreased (grav. and vol. capacities increased) due to revised assumptions from the last Merit Review.

- The key change resulting in the decreases was that the tank safety factor was applied to the *nominal* tank pressure (i.e., 5,000 and 10,000 psi) rather than *max. filling* over pressure (i.e., 6,250 and 12,500 psi) based on new/contradictory information from industry
- Changing the tank end dome shape based on ANL's latest performance analysis, which uses a composite pressure vessel algorithm[1], also resulting in decreases
- Changing the carbon fiber composite tensile strength from 2,940 to 2,550 MPa to be consistent with ANL's latest performance analysis partially offset the above adjustments
- There were several other less significant changes that were made based on the latest industry feedback[2] or to match the latest ANL assumptions

2009 Updated Results and % Change '09/'08 AMR	5,000 psi System		10,000 psi System	
	Base Case	% Change	Base Case	% Change
System Cost, $/kWh	15.6	-9%	23.1	-13%
Gravimetric Capacity, wt%	5.9	11%	4.7	18%
Volumetric Capacity, g H_2/L	17.5	3%	25.0	9%

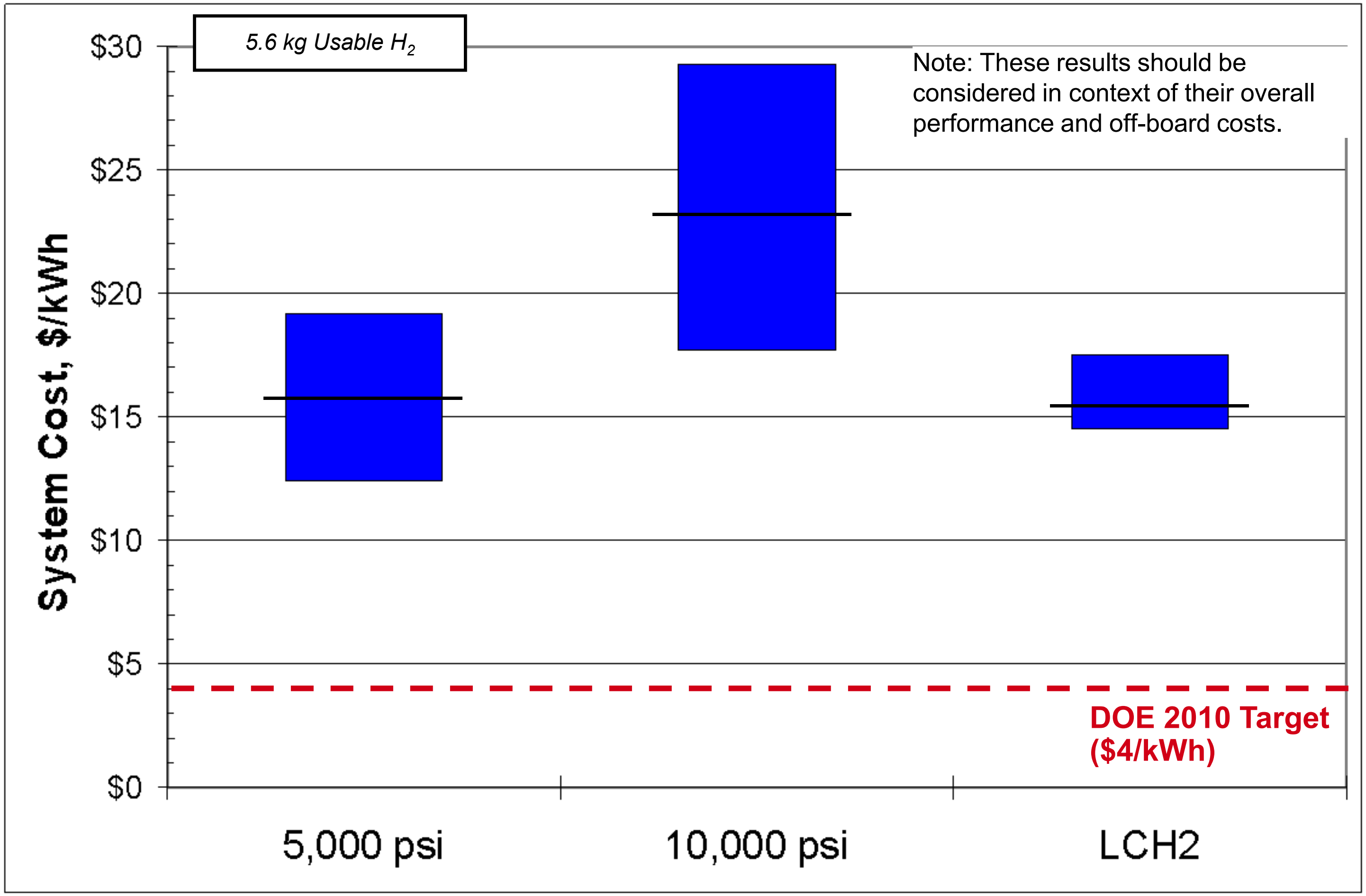
[1] "Mechanics and Analysis of Composite Materials", Vasiliev and Morozov, New York: Elsevier Science, 2001

[2] For example, the tank empty pressure assumption changed from 400 psi for 5,000-psi tanks and 200 psi for 10,000-psi tanks to 290 psi for both.

The compressed (cH_2) and liquid hydrogen (LH_2) off-board cost results were calculated using the baseline delivery scenarios in HDSAM v2.06.

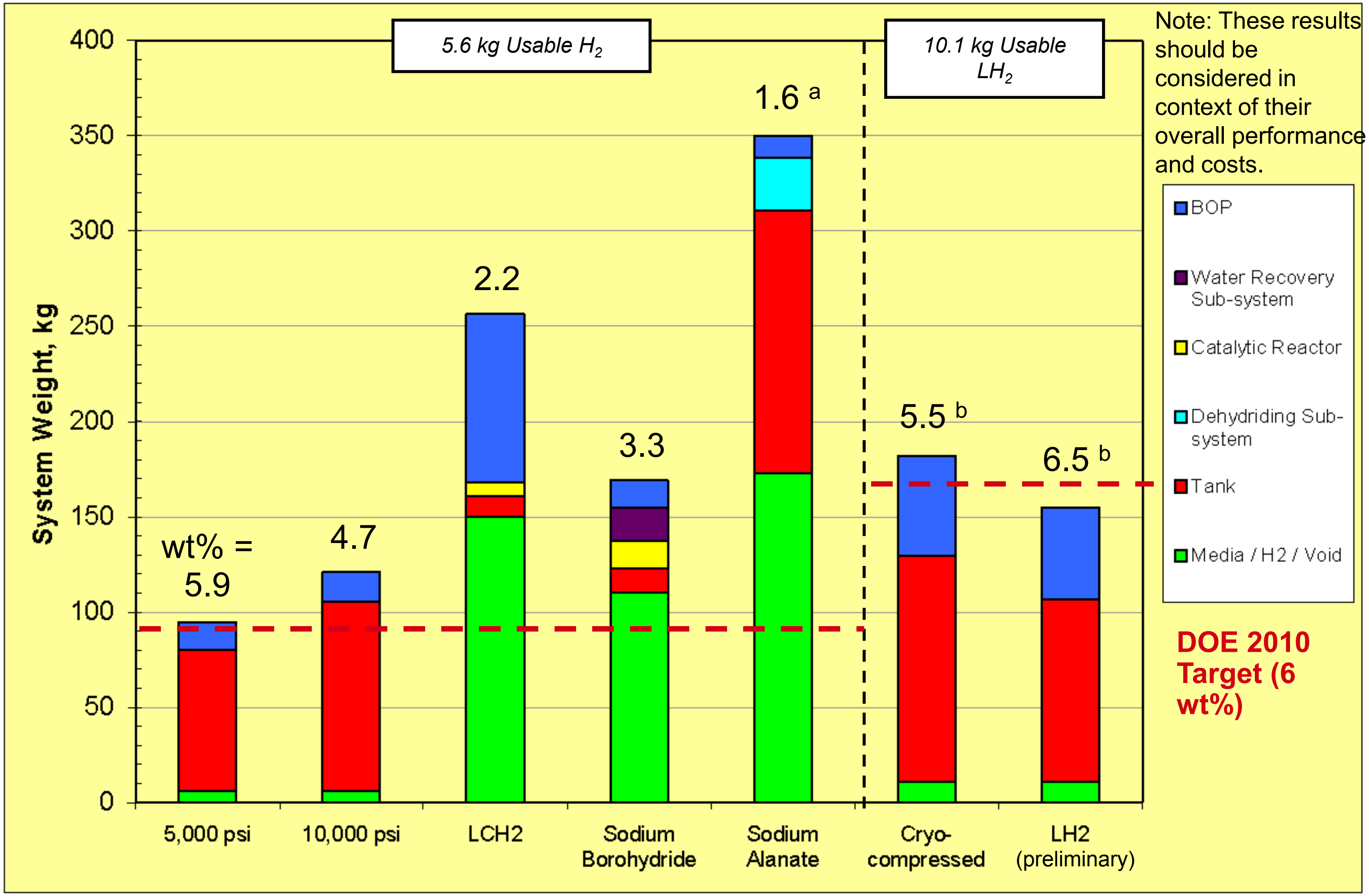
HDSAM Delivery Scenario Assumptions	cH_2	LH_2
Hydrogen Market	Urban	Urban
Market Penetration	30%	30%
City Selection	Indianapolis, IN (~1.2M people)	Indianapolis, IN (~1.2M people)
Transmission/Distribution Mode	Compressed gas pipeline	Cryogenic liquid trucks
Plant Outage and Summer Peak Storage	Geologic	Cryogenic liquid tanks
Refueling Station Size	1,000 kg/day	1,000 kg/day
Assumed On-board Storage System	5,000 psi compressed	Cryogenic liquid

None of the on-board system designs evaluated last year are expected to meet the DOE 2010 cost target based on the sensitivity analyses[1].



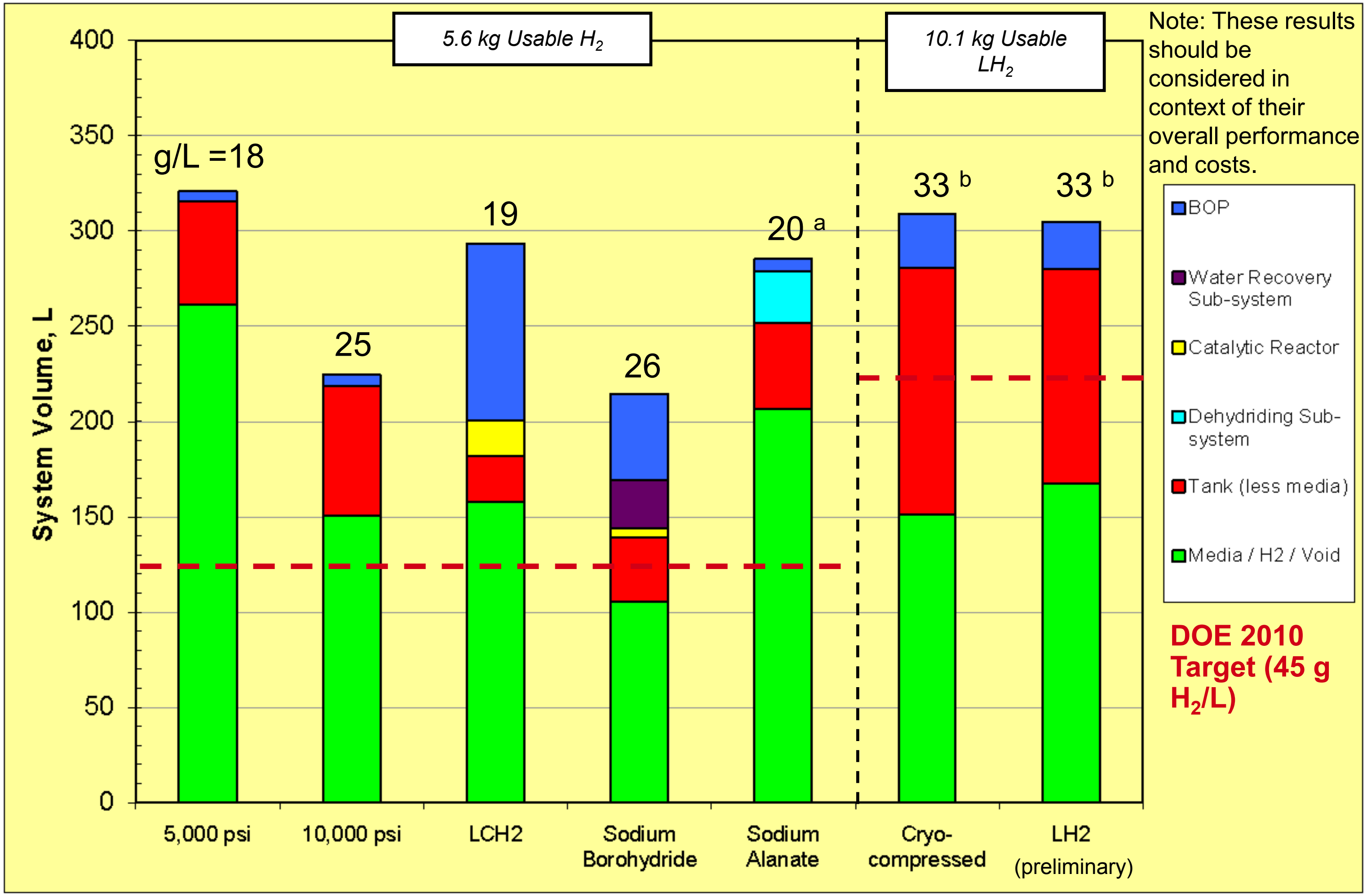
[1] Based on the range of likely cost and performance values. Range is defined here as the mean plus/minus two standard deviations (~95% confidence).

The 5,000-psi tank system may just meet the DOE 2010 gravimetric target of 6 wt%, but the 10,000-psi tank system is about 20% lower than the 2010 target.



[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.
[b] Normalizing the cryo-compressed and liquid H_2 systems for 5.6 kg of usable H_2 results in gravimetric capacities of ~4.0 wt% and ~4.4 wt%, respectively.

The volumetric capacities of both compressed tank systems are 40-60% lower than the DOE 2010 target of 45 g H_2/liter.



[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.
[b] Normalizing the cryo-compressed and liquid H_2 systems for 5.6 kg of usable hydrogen results in volumetric capacities of ~28 g H_2/L system volume each.

"Ownership cost" provides a useful comparison metric that includes both on-board and off-board (i.e., refueling) costs on equal footing.

Fuel System Ownership Cost Assumptions	Gasoline ICEV	cH_2 FCV[1]	LCH_2 FCV	SBH FCV	LH_2 FCV	Basis/Comment
Annual Discount Factor on Capital	15%	15%	15%	15%	15%	Input assumption
Manufacturer + Dealer Markup	1.74	1.74	1.74	1.74	1.74	Assumed mark-up from factory cost estimates[2]
Annual Mileage (mi/yr)	12,427	12,427	12,427	12,427	12,427	Car vehicle miles traveled divided by total registrations for 2006[3]
Vehicle Energy Efficiency Ratio	1.0	2.0	2.0	2.0	2.0	Based on ANL drive-cycle modeling
Fuel Economy (mpgge)	31	62	62	62	62	ICEV: Car combined CAFE sales weighted FE estimate for MY 2007[3]
H_2 Storage Requirement (kg H_2)	NA	5.6	5.6	5.6	5.6	Design assumption based on ANL drive-cycle modeling
Fuel Price ($/eq. gal)	3.00	4.32	4.74	10.14	4.74	FCVs: Equivalent H_2 price from Off-board Assessment Base Cases
H_2 Storage System Factory Cost ($/kWh)	NA	15.6	15.4	5.0	14.00 (prelim.)	H_2 storage cost from On-board Cost Assessment of 5.6 kg usable H_2

[1] cH_2 FCV option assumes pipeline delivery with 6,250 psi dispensing and 5,000-psi on-board storage system.
[2] Source: DOE, "Effects of a Transition to a Hydrogen Economy on Employment in the United States", Report to Congress, July 2008
[3] Source: U.S. Department of Transportation, NHTSA, "Summary of Fuel Economy Performance," Washington, DC, March 2007

The implicit assumption in this ownership cost assessment is that each fuel system and vehicle perform equally well and have the same operating lifetime.