Analyses of Hydrogen Storage Materials and On-Board Systems

Hydrogen Delivery Analysis Meeting

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Timeline

- Start date: June 2004
- End date: Sept 2009
- 41% Complete

Barriers

- Barriers addressed
  - B. Cost
  - C. Efficiency
  - K. System Life Cycle Assessments

Budget

- Total project funding
  - DOE share = $1.5M
  - No cost share
- FY06 = $275k
- FY07 = $300k (plan)

Collaboration

- Argonne and other National Labs
- Centers of Excellence and other developers
- Tech Teams and other stakeholders

Objectives

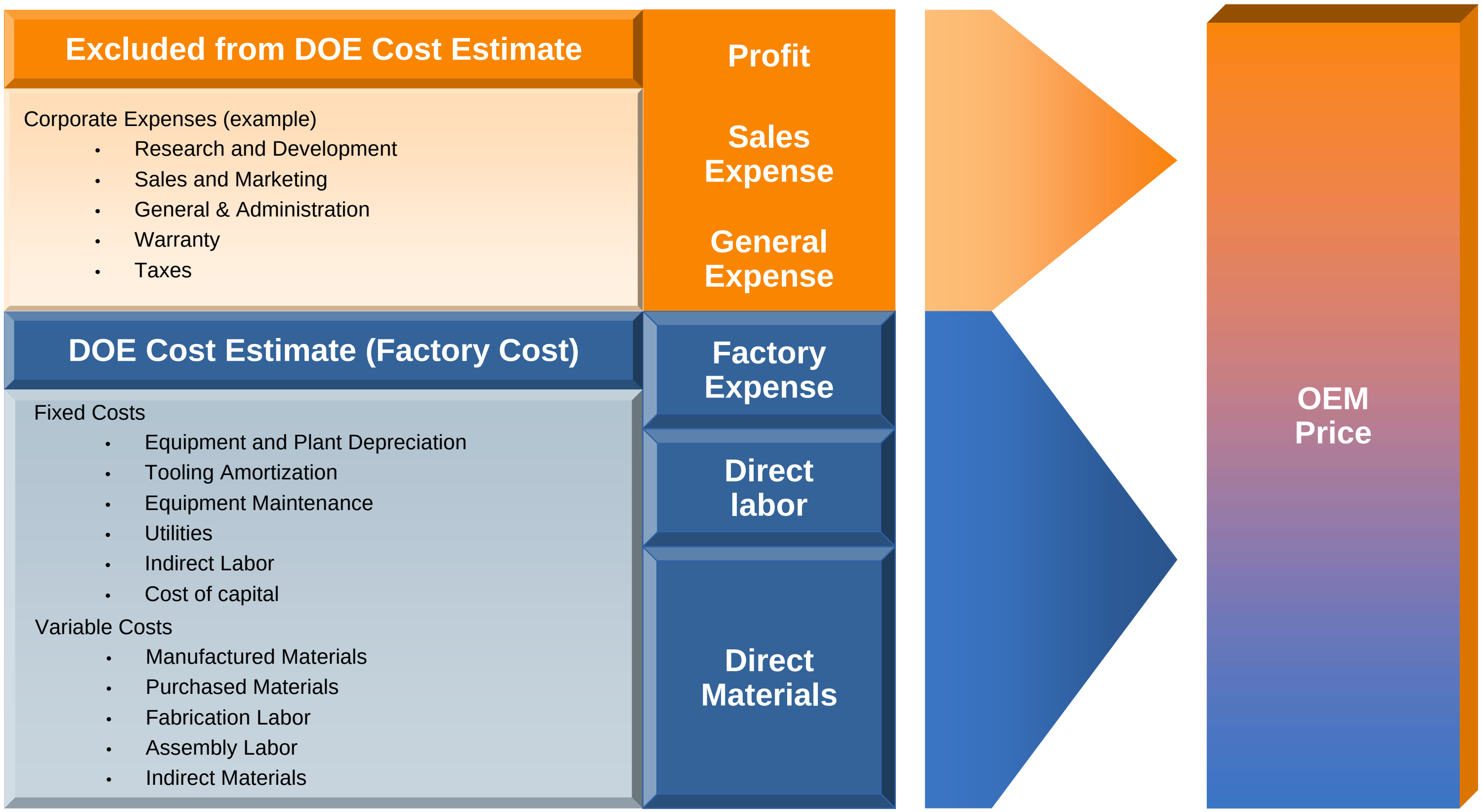
This project provides an independent cost assessment of the hydrogen storage technologies being developed for the DOE Grand Challenge.

Objective	Description	Technology Focus		
		2005	2006	2007
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 Assessment	Evaluate or develop system-level designs to estimate weight, volume, and bottom-up factory cost for the on-board storage system	• Sodium Alanate	• SBH	• Compressed H_2 (update) • Liquid HC*
On-Board Cost Estimate	Estimate Bill-of-Material factory costs for the on-board storage system		• Cryo-compressed	• Liquid H_2 • AC
Off-Board Assessment	Evaluate or develop designs and cost inputs to estimate refueling cost and Well-to-Tank energy use and GHG emissions for the fuel chain		• Liquid H_2 (includes Cryo-compressed) • Compressed H_2	• SBH • Liquid HC* • AC* • Sodium Alanate*

* Results have not been generated to date. Note that previously analyzed systems will continually be updated based on feedback and new information.

SBH = Sodium Borohydride, HC = Hydrocarbon, AC = Activated Carbon

We estimate an OEM factory cost, excluding OEM corporate charges for profit, sales and G&A expenses.



- We assume a vertically integrated process for the manufacture of the tank, so no mark-up is included on those components
- Raw materials and BOP components are assumed to be purchased by the OEM and therefore include supplier mark-ups

OEM – Original Equipment Manufacturer
G&A – General and Administration Expense

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

Technology Assessment

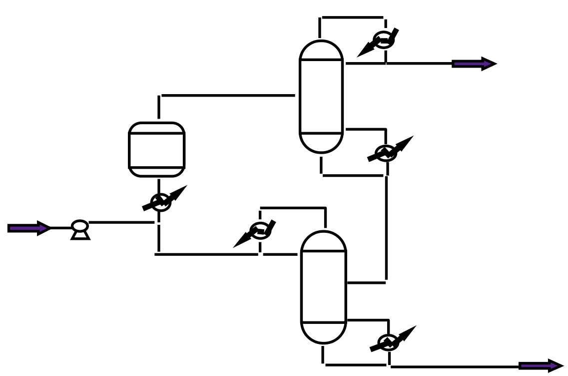
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Design Assumptions
- Obtain Developer Input

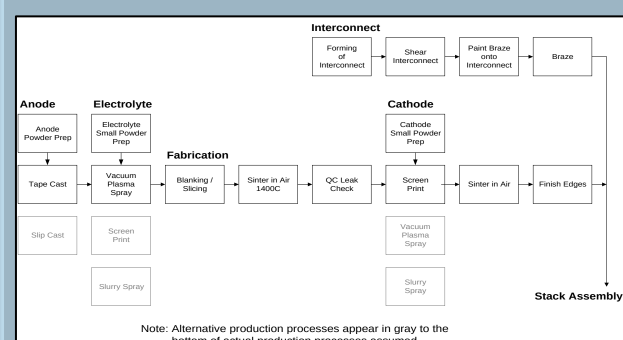
Cost Model and Estimates

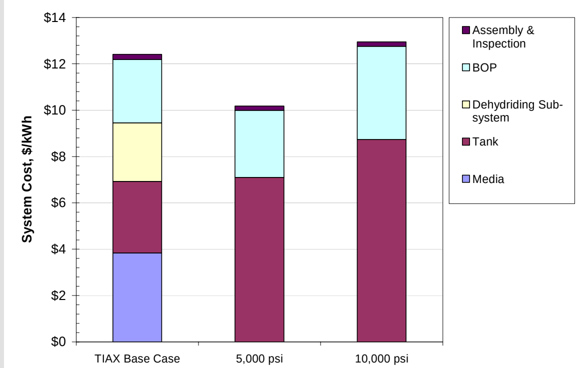
- Develop BOM
- Specify Manufacturing Processes and Equipment
- Determine Material and Processing Costs
- Develop Bulk Cost Assumptions

Overall Model Refinement

- Obtain Developer and Industry Feedback
- Revise Assumptions and Model Inputs
- Perform Sensitivity Analyses ("Best" and "Worst" cases)







BOM = Bill of Materials

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

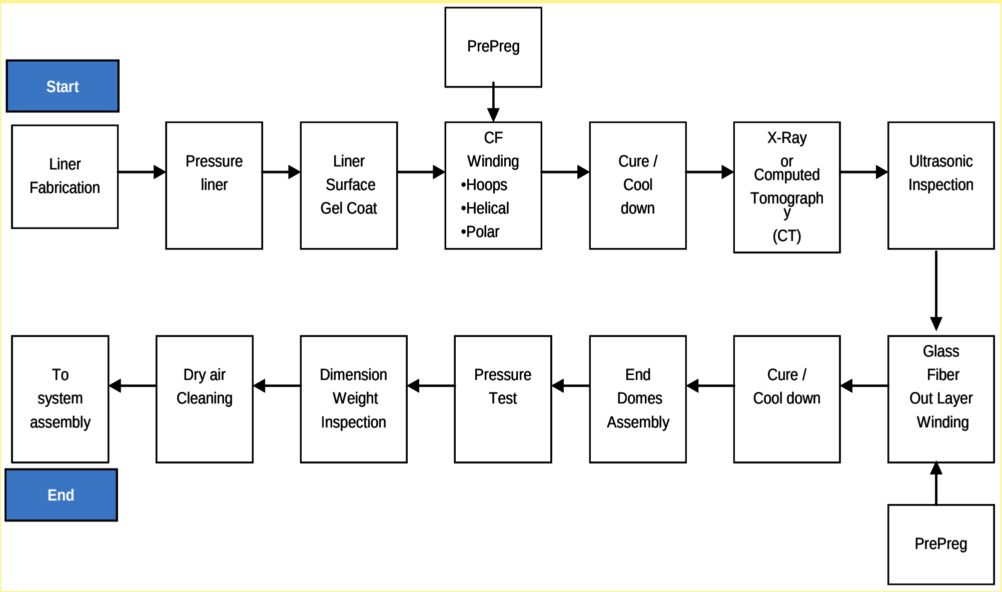
Cost of Non-Operating Capital:

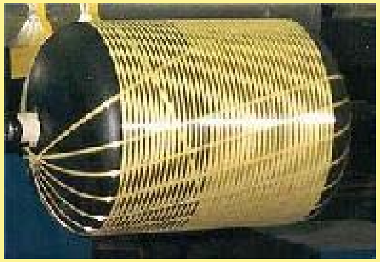
- Equipment
- Building

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

Processing and assembly/inspection costs are derived from an understanding of the detailed process steps and their requirements.

Example: Processing Steps for Compressed Tanks

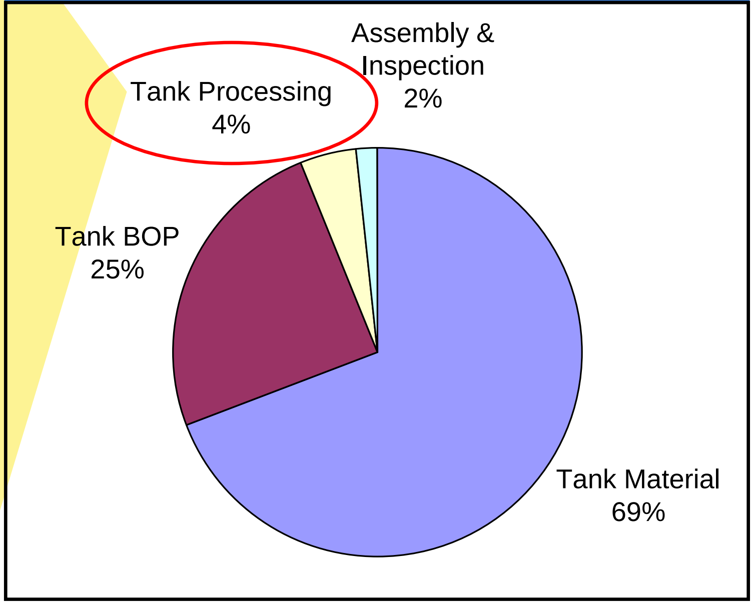




Winding Process

Winding Machine

5,000 psi Storage System Factory Cost Breakout



The on-board cost estimates are simply based on Bill of Material (BOM) costs plus an assumed processing cost.

Review of Designs/ Component Specs

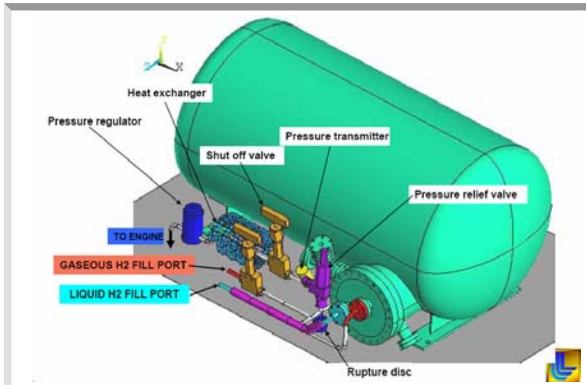
- Perform Literature Search
- Understand System Requirements and Design Assumptions
- Obtain Developer Input

BOM and Cost Estimates

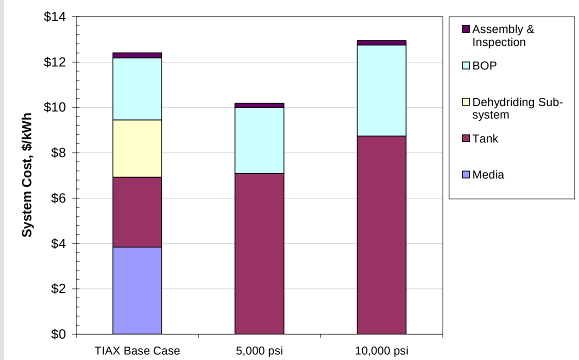
- Develop BOM
- Determine Material and Component Costs
- Develop Bulk Cost Assumptions

BOM and Estimate Refinement

- Obtain Developer and Industry Feedback
- Revise BOM Assumptions
- Perform Sensitivity Analyses



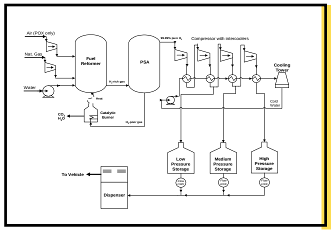
Cryo-compressed System Components - 2nd Generation Design	Estimated Weight (kg)	Reference	TIAX Assumptions				
			Quantity	Unit Cost ($/kg)	Unit Cost ($/unit)	Component Cost ($)	Source/Comments
Hydrogen	11	LLNL	1	3.00		32	DOE H2 Cost Target
Internal Pressure Vessel	44	LLNL					
- Al Liner	12	ANL	1	2.5		31	TIAX 2003 cH2 Storage System Cost Assessment
- Carbon Fiber Composite	32	TIAX	1	32		1,024	Safety factor = 2.25; Translation strength = 81.5%; T700S PrePreg CF = $20/kg (2005)
- SS304 Support	8	ANL/TIAX	3	4.40		35	Estimated based on ANL Tank Schematic; assumes SS304 = $2.87/kg (2005)
Insulation and Vacuum Shell	56	LLNL					
- SS304 Shell	54	ANL	1	2.9		156	Assumes SS304 = $2.87/kg (2005)
- Insulation	2	LLNL/TIAX	1	50		103	40 layers aluminized Mylar w/ spacer; $0.15/feet^2 based on quote from MPI (2005)
Total Vessel & Vac. Shell	***119***	LLNL				***1,382***	
In-Tank Heater	0	LLNL	1		10	10	TIAX 2005 NaBH4 H2 Storage System Cost Assessment
Level Sensor Box	0	LLNL	1		10	10	TIAX 2005 assumption
Valve Box	17	LLNL	1	2.9		49	Assumes SS304 = $2.87/kg (2005)
Pressure Transmitters	0	LLNL	2		23	46	TIAX 2003 cH2 Storage System Cost Assessment
Pressure Gauges	3	LLNL	2		10	20	TIAX 2005 assumption
Pressure Regulator	1	LLNL	1		171	171	TIAX 2003 cH2 Storage System Cost Assessment
ASME Relief Valve	1	LLNL	1		20	20	TIAX 2003 cH2 Storage System Cost Assessment
Circle Seal Cryogenic Valves	2	LLNL	2		20	40	Assumes similar price as the relief valve
Nupro Relief Valves	0	LLNL	2		5	10	TIAX 2005 NaAlH4 H2 Storage System Cost Assessment
Vent and Fill Valve	2	LLNL	2		91	182	TIAX 2003 cH2 Storage System Cost Assessment
Rupture Disc	0	LLNL	2		5	10	TIAX 2005 NaAlH4 H2 Storage System Cost Assessment
LH2 Fill Hose	1	LLNL	1	2.9		3	Assumes SS304 = $2.87/kg (2005)
Tank Frame	7	LLNL	1	2.9		20	Assumes SS304 = $2.87/kg (2005)
Heat Exchanger	3	LLNL	1		50	50	TIAX 2005 NaBH4 H2 Storage Cost Study; assumes spiral gas/gas HX
Non EP Conduit	1	LLNL	1		18	18	1" conduit coupling quote from Conduit Pipe Products, Co. (2005)
Tubing	7	LLNL	1	2.9		20	Assumes SS304 = $2.87/kg (2005)
Aluminum Plate	2	LLNL	1	2.5		4	Assumes Al = $2.21/kg, TIAX 2003 cH2 Storage System Cost Assessment
Wire	5	LLNL	1	8		36	Assumes $8/kg for wire plus insulation; current LME copper price = $7.39/kg
Grounding Lugs	0	LLNL	1	2.9		0	Assumes SS304 = $2.87/kg (2005)
Misc Nuts and Bolts	1	LLNL	1	2.9		3	Assumes SS304 = $2.87/kg (2005)
Misc Fittings	2	LLNL	1	2.9		5	Assumes SS304 = $2.87/kg (2005)
Total For Accessories	***55***	***LLNL***				***726***	Does not include computer, computer stand, electronic boards
Total	**174**					**2,108**	($/system)
						6.29	($/kWh) w/o processing cost (based on 10.1 kg usable H2
					Total	**8.35**	($/kWh) w/ 50% processing markup on tank costs



Processing and assembly/inspection costs are not determined for the cost estimates, so we must rely on developer feedback.

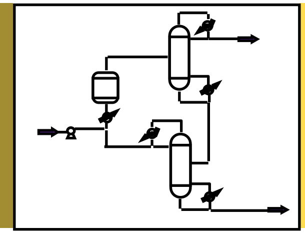
The off-board assessment makes use of existing models to calculate cost and performance for each technology on a consistent basis.

Conceptual Design



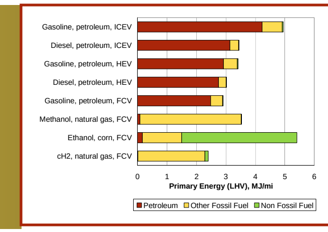
- System layout and equipment requirements

Process Simulation



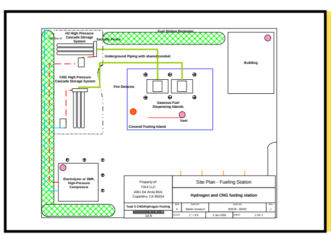
- Energy requirements
- Equipment size/ specs

GREET Model



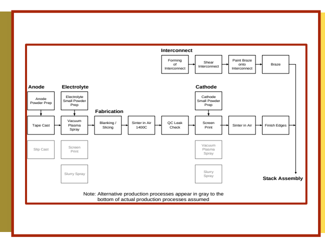
- WTT energy use
- WTT GHG

Site Plans



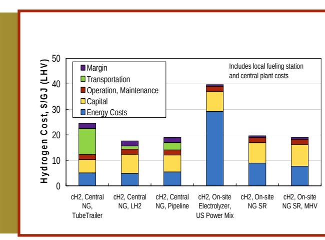
- Safety equipment, site prep, land costs

Capital Cost Estimates



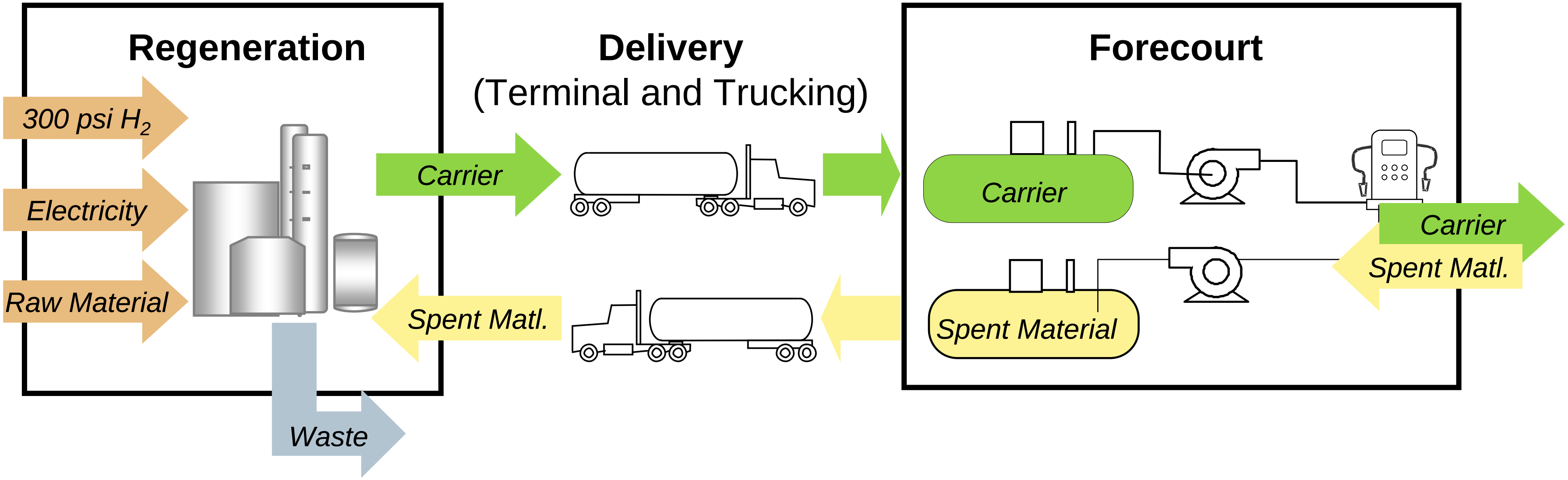
- High and low volume equipment costs

H2A Model



- Equivalent hydrogen selling price

The off-board assessment for Sodium Borohydride (SBH) requires evaluation of regeneration, delivery and forecourt technologies.



- 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

Fundamental system requirements and basic schematics were acquired from literature, industry and National Labs.

Liquid H_2

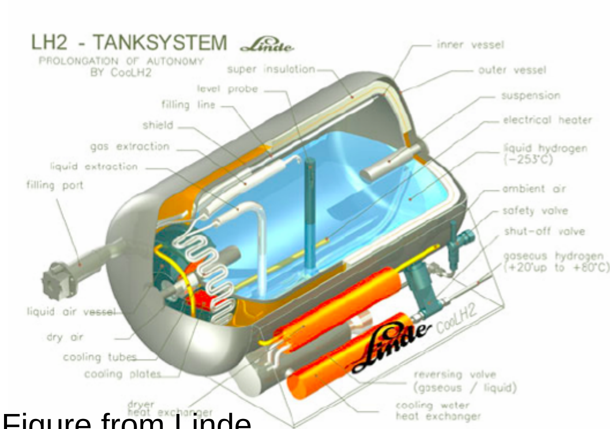


Figure from Linde

Cryo-compressed

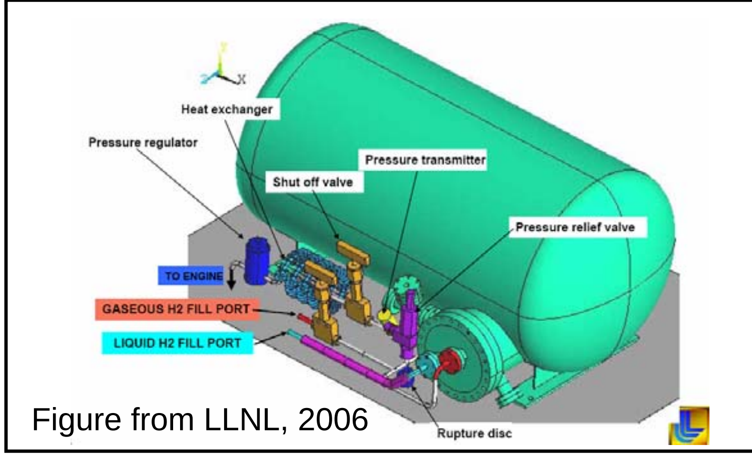


Figure from LLNL, 2006

Activated Carbon (AX-21)

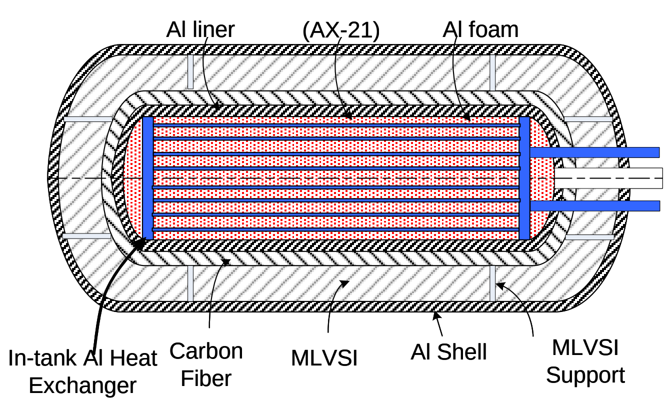


Figure from ANL, 2006

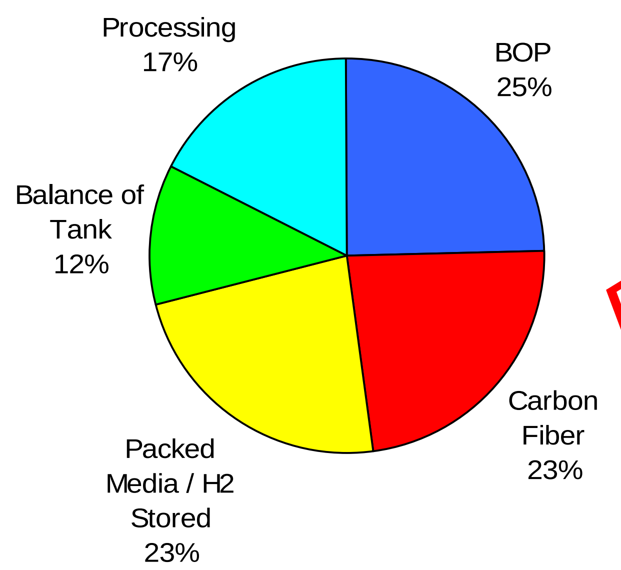
For each cost estimate, we relied on system-level design assumptions from literature and discussions with National Labs and developers.

Sub-System	Parts List	Specifications	Basis/Comments
Media	Hydrogen	5.6 kg usable	ANL drive-cycle modeling
	Activated Carbon (AX-21)	42 kg usable H_2/ m^3, 300 kg/m^3 bulk dens, 2800 m^2/g, 0.1 W/m-K	ANL AC modeling for 200 bar, 100 K, and 50 K temp. swing
	Al foam	2 wt% Al-2024 foam, 2.4 W/m-K	
Tank	In-tank LN_2 Heat Exchanger	Al-2024, 9.5 mm OD, 1.2 mm thick tubes, 0.9 mm thick tube sheets, 107 tubes	ANL AC tank design; similar in style to $NaAlH_4$ in–tank heat exchanger, but functionally used to cool the tank with LN_2 during refueling
	SS Filters	Sintered SS	Not mentioned by ANL, assumed necessary (similar to $NaAlH_4$)
	Al liner	2 mm Al alloy	ANL AC tank design
	CF Composite	T700S, 60% fiber by vol, 1600 kg/m^3, 2.25 SF	TIAX assumptions based on previous high-pressure tank designs
	CF Composite Layer Thickness	7 mm	TIAX netting analysis for 175L, 200 bar, 82% translation strength
	MLVSI	10^{-5} torr vacuum, 1 W heat transfer rate through insulation (~5 W total)	ANL AC tank design (same as cryo-compressed tank)
	MLVSI Layers	35	Preliminary TIAX estimate based on cryo-compressed tank, adjusted for new tank surface area and temperatures
	MLVSI support	Composite material	Low thermal conductivity material required
	Al outer shell	3 mm Al alloy	ANL AC tank design
BOP	Regulators, valves, fill port, etc	200 bar pressure	Assumed same as for cryo-compressed tank, although pressure is 40% lower

* Part lists for other systems shown in backup slides

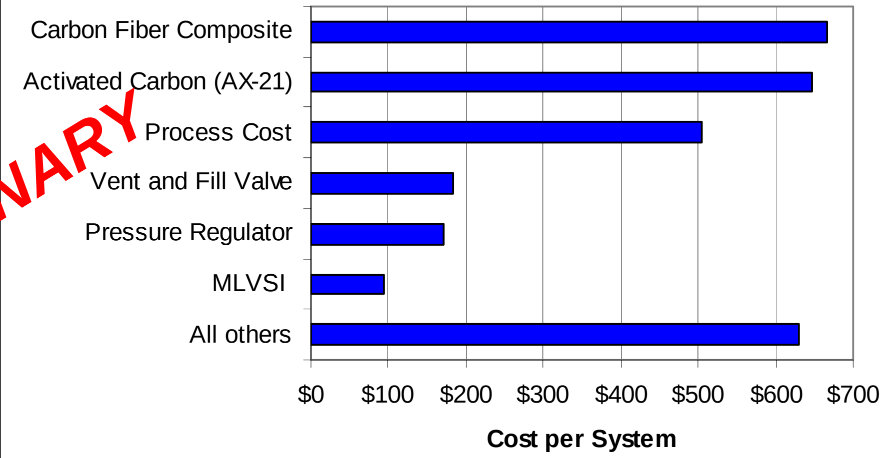
From BOM cost estimates, we calculated total system costs and identified key sub-systems and cost drivers.

Activated Carbon System Cost, 5.6 kg H_2 - $2,900



PRELIMINARY

Activated Carbon Cost Components Pareto, 5.6 kg H_2



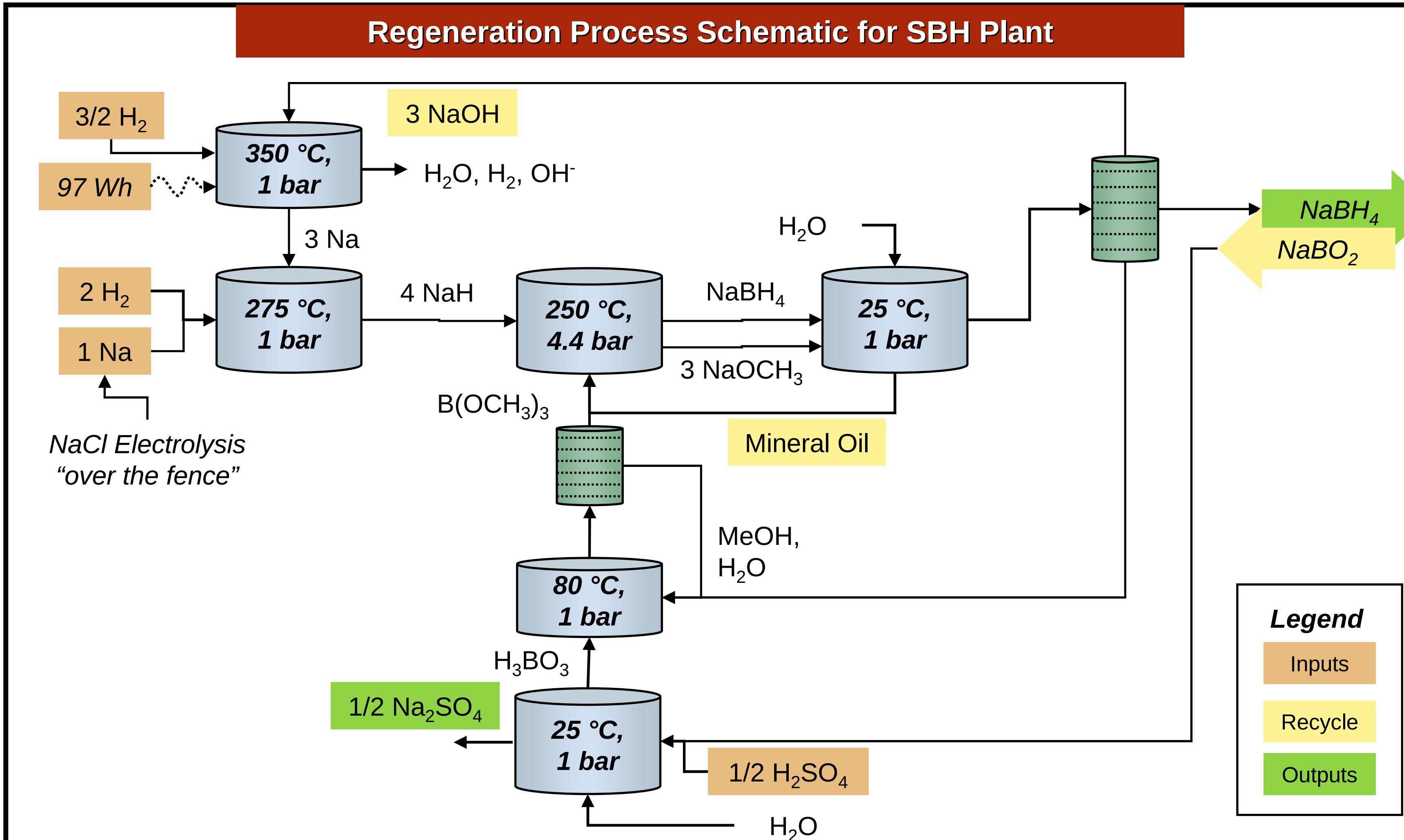
Note: It is not clear what processing cost to use for carbon fiber tanks with MLVSI (e.g., cryo-compressed and activated carbon) but developers comments indicate that processing costs could be somewhere between 10-100% of the tank material costs. We chose 50% for now, but we will be refining this based on further developer discussions.

Critical cost drivers such as carbon fiber, activated carbon, and processing cost will be evaluated in more detail for the AC system.

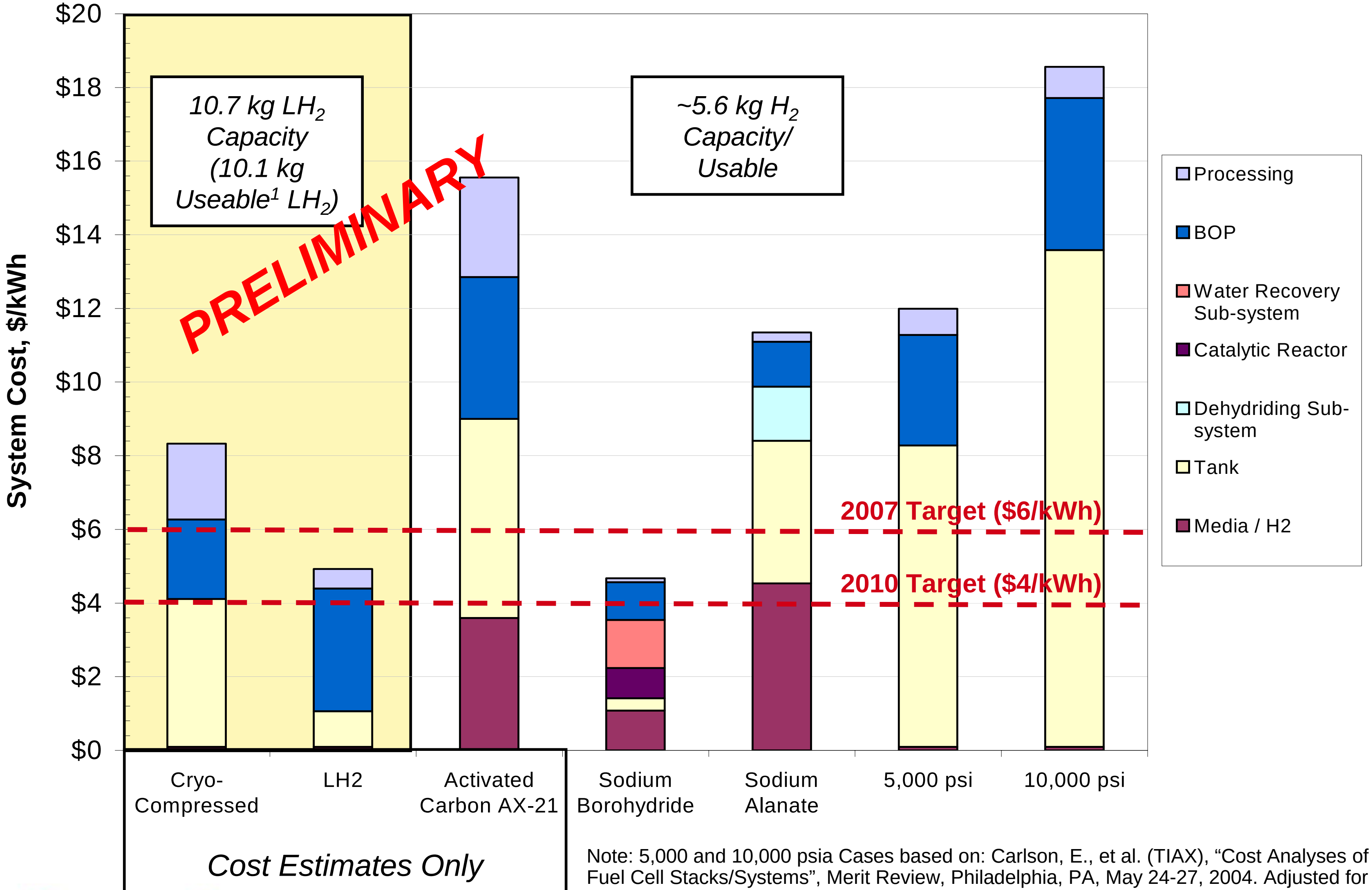
The H2A Carrier model was used to allow for direct cost comparison to compressed and liquid H_2 fuel options.

- Most financial assumptions are maintained from the original H2A Model
- New calculation tabs were added as part of the DOE Delivery Project
  - Regeneration – calculates material regeneration costs based on capital and operating costs of a central plant
  - Trucking – calculates trucking costs for all novel carriers
  - Storage Terminal – calculates required storage for fresh and spent materials
  - Forecourt – calculates forecourt station costs for fueling vehicles with novel carrier storage
- Calculation tabs were populated with inputs based on industry and developer feedback
  - TIAX made initial estimates consistent with H2A methodology
  - Model and estimates were reviewed with developers
  - Model inputs and results were updated

We evaluated a regeneration process for SBH that reflects existing technology but is not currently being used at the industrial-scale.

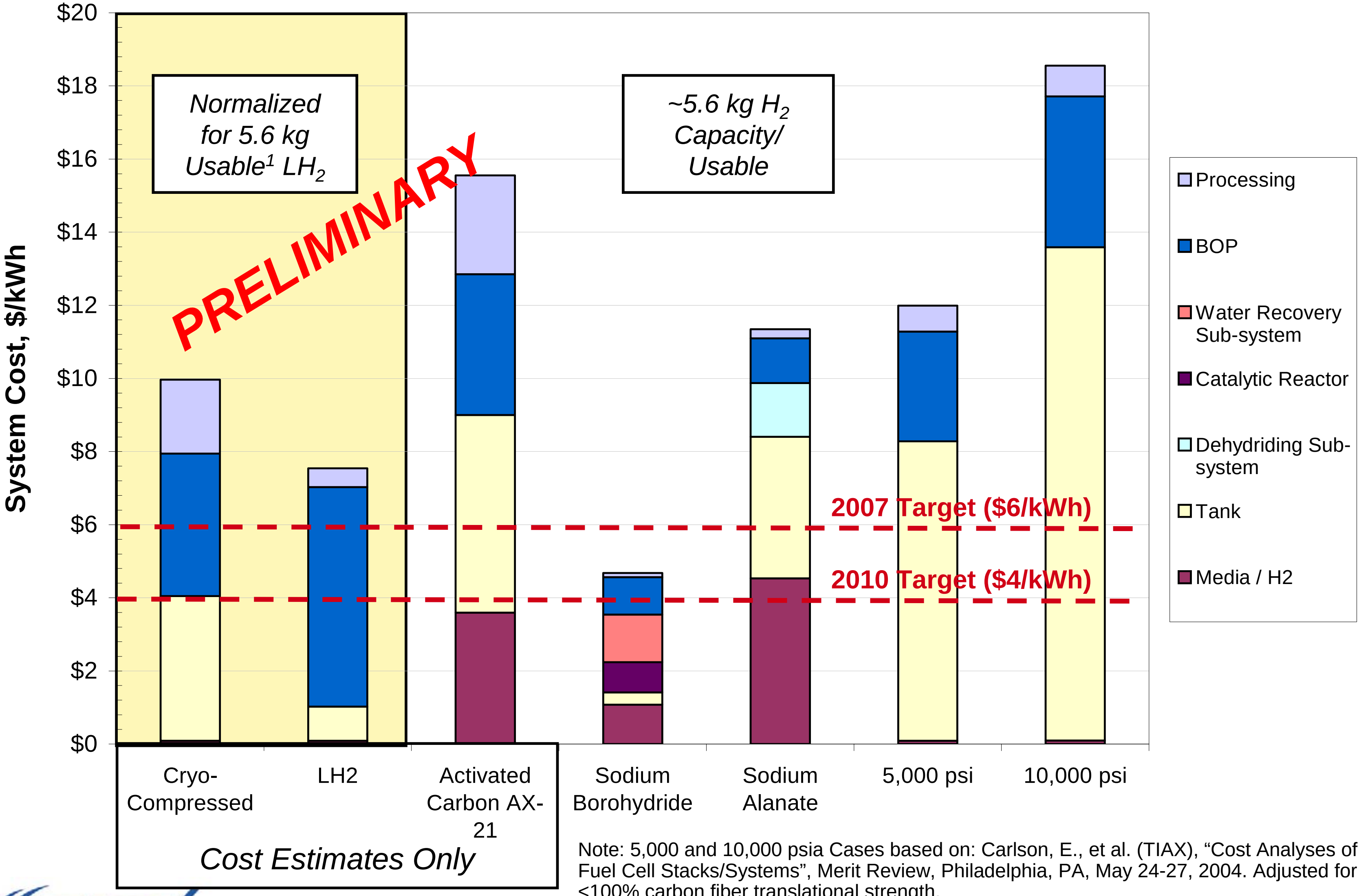


The cryo-compressed and LH_2 systems are projected to be cheaper than pressurized-only options; AC will have similar costs to pressurized-only.



Note: 5,000 and 10,000 psia Cases based on: Carlson, E., et al. (TIAX), "Cost Analyses of Fuel Cell Stacks/Systems", Merit Review, Philadelphia, PA, May 24-27, 2004. Adjusted for <100% carbon fiber translational strength.

However, the cryo-compressed system is estimated to be just 17% cheaper than a 5,000 psi tank system when normalized for 5.6 kg H_2.



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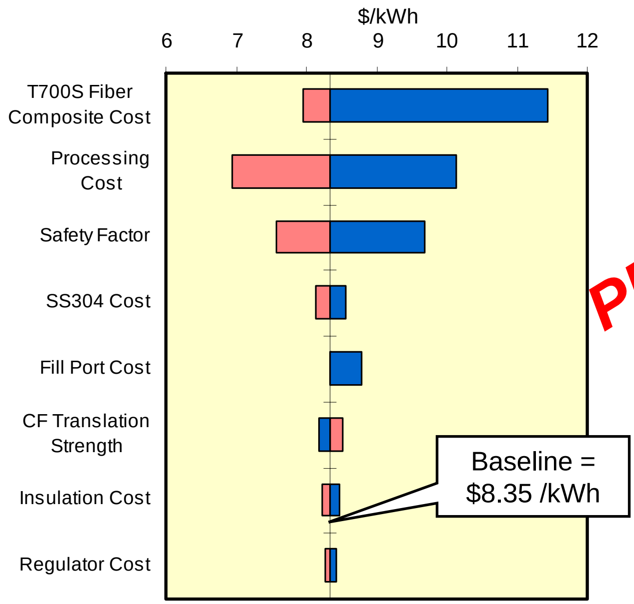
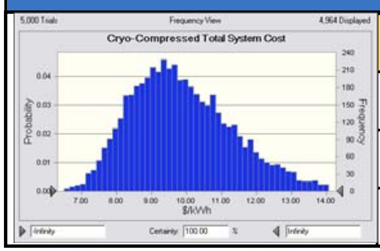
Single- and multi-variable sensitivity analyses are used to estimate the dependence and sensitivity of cost on/to the critical cost drivers.

Cryo-compressed System Single-variable Sensitivity Analysis (10.7 kg LH_2 Capacity)



PRELIMINARY

AC System Multi-variable Sensitivity Analysis



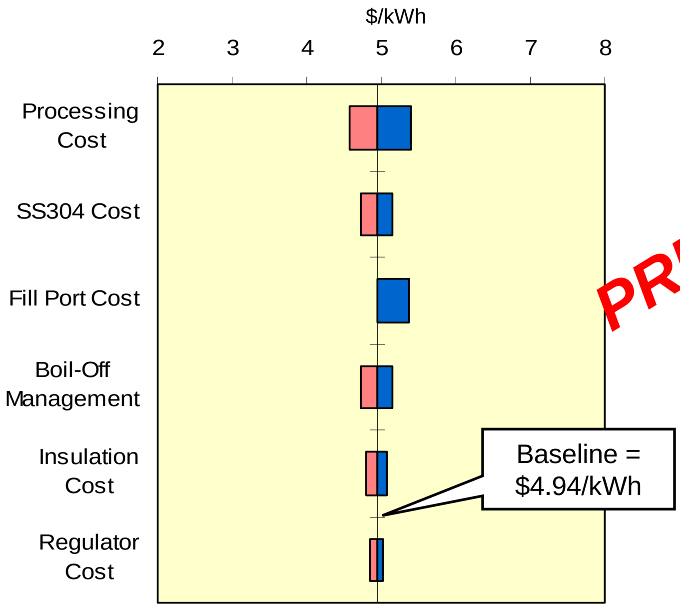
System Cost	$/kWh
Mean	9.9
Std. Dev.	1.5
TIAX Baseline	8.4

Key Sensitivity Parameters	Cryo-Compressed Key Variable Assumptions			
	Base-line	Min	Max	Comments/Source
CF Composite Cost ($/lb)	14.6	12.8	25.5	◆ Includes Epoxy (1.27x CF) ◆ Baseline from TIAX (2003) inflated to 2005$ ◆ Min and max based on developer input
Processing Markup (%)[2]	50%	10%	100%	◆ Min equivalent to compressed-only tanks; max based on cryo-tank developer comments
Safety Factor	2.25	1.80	3.00	◆ Baseline assumes a typical industry factor ◆ Min and max based on Quantum and Dynatek, respectively
CF Translation Strength (%)	81.5%	78%	85%	◆ Estimates reported by Quantum for 5,000 psi tanks
Fill Port Cost ($)	90	90	170	◆ Industry interviews (2003), inflated to 2005$ ◆ Need to develop bottom up cost for min
SS304 Cost ($/kg)	2.7	2.1	3.1	◆ Baseline from TIAX (2003) inflated to 2005$
Regulator Cost ($)	170	140	200	◆ Industry interviews (2003), inflated to 2005$

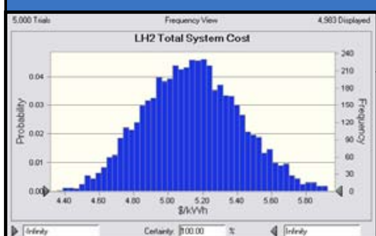
[1]The processing cost markup is applied to the tank cost.

The processing cost markup uncertainty has the most significant impact on the liquid hydrogen system cost.

LH_2 System Single-variable Sensitivity Analysis (10.7 kg H_2 Capacity)



AC System Multi-variable Sensitivity Analysis



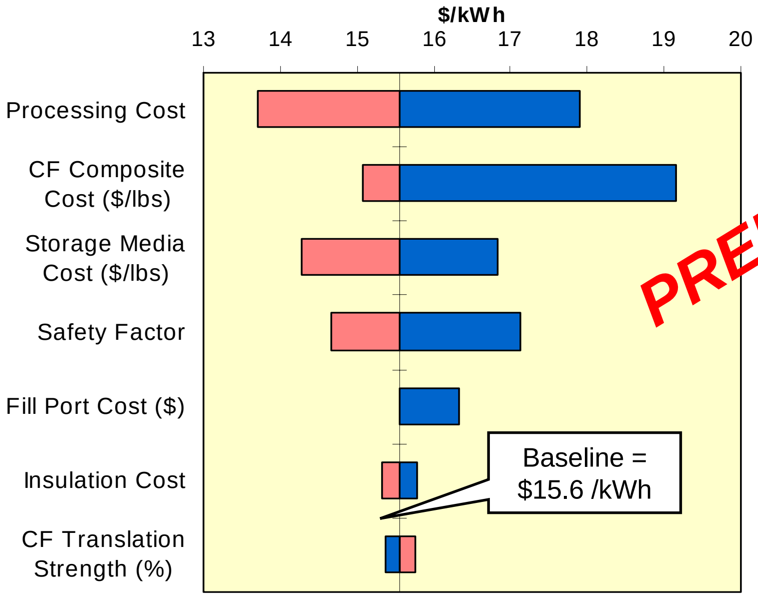
System Cost	$/kWh
Mean	5.1
Std. Dev.	0.3
TIAX Baseline	4.9

Key Sensitivity Parameters	Liquid H_2 Storage Key Variable Assumptions			
	Base-line	Min	Max	Comments
Processing Markup (%)[2]	50%	10%	100%	◆ Min equivalent to compressed-only tanks; max based on cryo-tank developer comments
Fill Port Cost ($)	90	90	170	◆ Industry interviews (2003), inflated to 2005$ ◆ Need to develop bottom up cost for min
SS304 Cost ($/kg)	2.7	2.1	3.1	◆ Baseline from TIAX (2003) inflated to 2005$
Regulator Cost ($)	170	140	200	◆ Industry interviews (2003), inflated to 2005$
Boil-off Management	320	240	400	◆ TIAX estimate; need to obtain more specific material types/weights from Linde or BMW for bottom up analysis

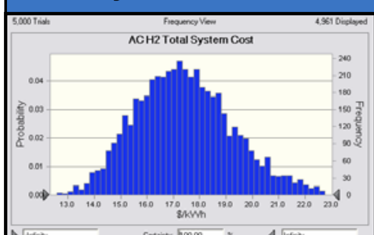
[1] Costs per kWh are based on a projected 336 kWh (10.1 kg) "usable" hydrogen assuming 94% drive cycle utilization (ANL). A drive cycle utilization calculation should be performed specifically for the LH_2 system.
[2] The processing cost markup is applied to the tank cost.

The AC storage media, carbon fiber and processing cost assumptions show the most significant variability in overall cost.

AC System Single-variable Sensitivity Analysis (5.6 kg H_2 Capacity)



AC System Multi-variable Sensitivity Analysis

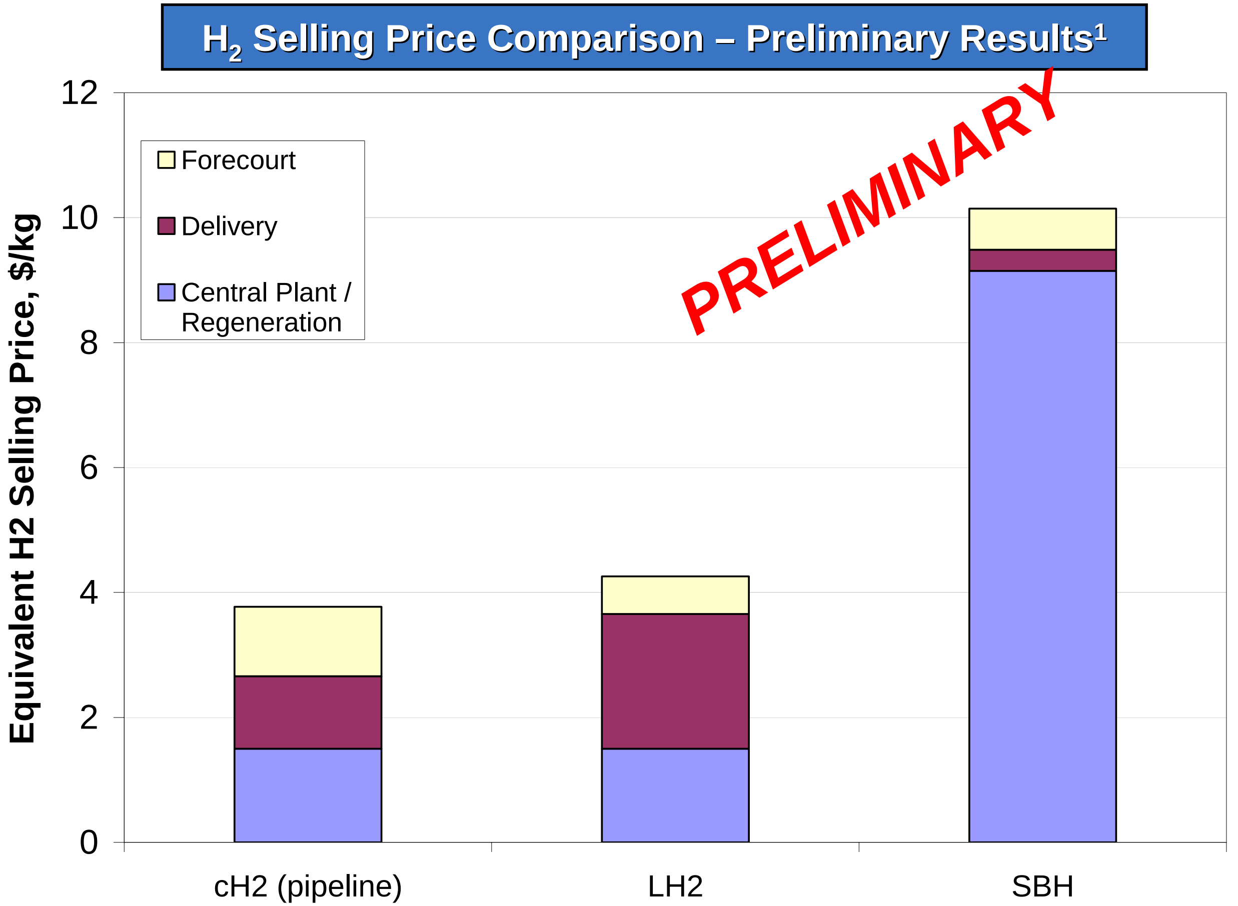


System Cost	$/kWh
Mean	17.3
Std. Dev.	1.9
TIAX Baseline	15.6

Key Sensitivity Parameters	AC H_2 Storage Key Variable Assumptions			
	Base-line	Min	Max	Comments
Processing Markup (%)[1]	50%	10%	100%	◆ Min equivalent to compressed-only tanks; max based on cryo-tank developer comments
CF Composite Cost ($/lb)	14.6	12.8	25.5	◆ Includes Epoxy (1.27x CF) ◆ Baseline from TIAX (2003) inflated to 2005$ ◆ Min and max based on developer input
AC Media Cost ($/lbs)	7	4	10	◆ Cost estimate from Kansai Coke and Chemical Co DTI (1996), projected for high volume and 2005$
Safety Factor	2.25	1.80	3.0	◆ Baseline assumes a typical industry factor ◆ Min and max based on Quantum and Dynatek, respectively
Fill Port Cost ($)	90	90	170	◆ Industry interviews (2003), inflated to 2005$ ◆ Need to develop bottom up cost for min
CF Translation Strength (%)	81.5%	78%	85%	◆ Estimates reported by Quantum for 5,000 psi tanks

[1]The processing cost markup is applied to the tank cost.

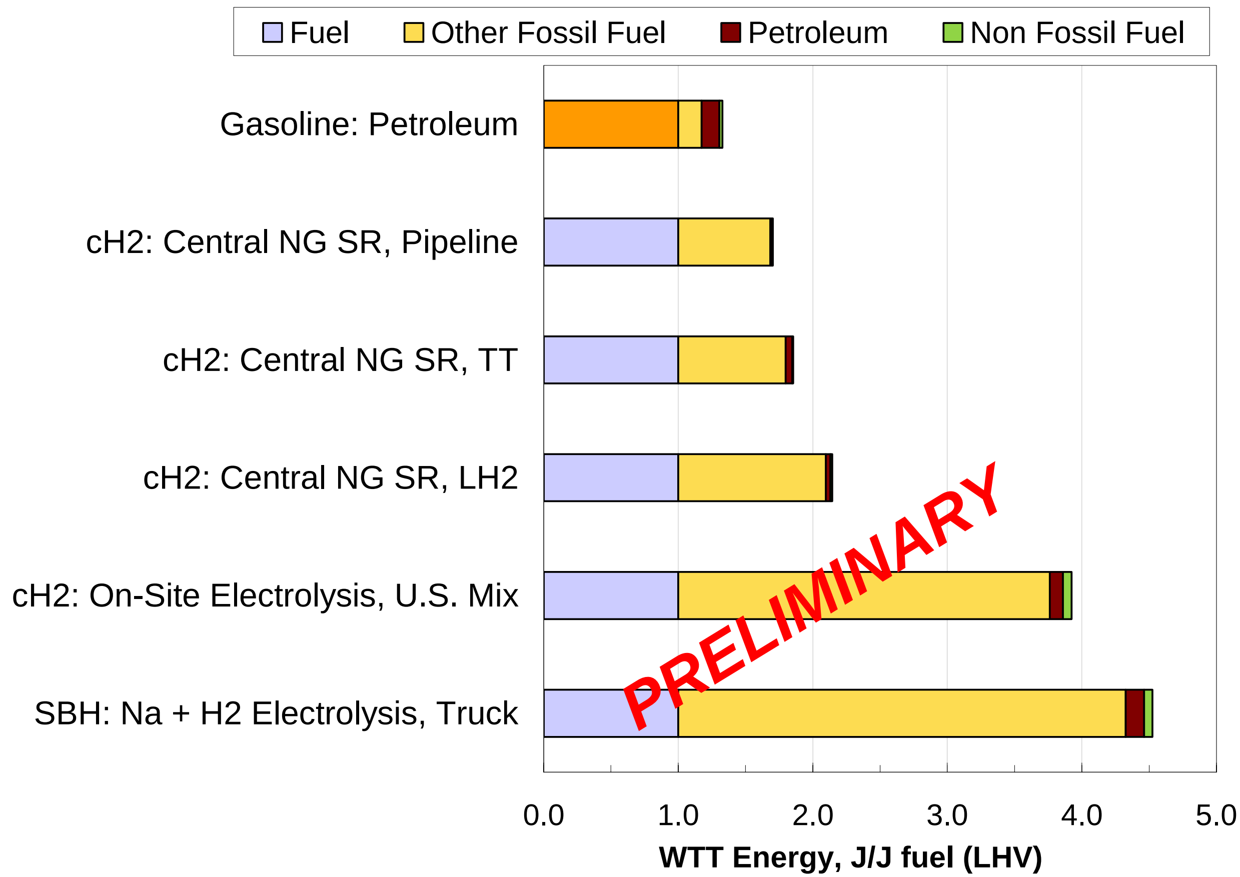
Preliminary results indicate that the equivalent H_2 price for SBH will be ~2.5 times more expensive than liquid or compressed hydrogen.



[1] These results are based on natural gas steam reforming as the sources for the hydrogen. Production and delivery efficiency (LHV) assumptions include: steam reformer = 74%, pipeline power = 3 kWh/kg, liquefier power = 8.6 kWh/kg. Cost assumptions include: 100 km truck delivery from a central plant to the forecourt designed for 1500 kg/day H_2, SBH plant = 470 TPD (100 TPD H_2 equivalent), Hydrogen plant = 300 TPD.

WTT primary energy inputs for SBH based on "current technology" are even more energy intensive than electrolysis pathways.

WTT Energy Comparison – Preliminary Results[1]



"Efficiency"
75%
58%
54%
47%
27%
22%

[1] These results are based on natural gas steam reforming or water electrolysis with grid power as the sources for the hydrogen. Production and delivery efficiency (LHV) assumptions include: steam reformer = 74%, electrolyzer = 70%, pipeline power = 3 kWh/kg, liquefier power = 8.6 kWh/kg.

Future Work FY07

We are in the process of finalizing the AC, cryo-compressed, and LH_2 on-board results and conducting the off-board assessment.

- Finalize results for the on-board cryo-compressed, liquid H_2 and AC systems, including:
  - Solicit additional developer feedback, especially regarding processing costs
  - Develop more detailed cost estimates for key cost variables
  - Evaluate and compare system weight breakout to ANL and developers estimates
- Finalize results for LH_2 and SBH and start off-board analyses for liquid HC, alanate and AC systems
  - Determine WTT energy use and GHG emissions for each fuel chain
  - Estimate “refueling cost” and storage system “ownership cost”
  - Consider vehicle integration impacts
- Continue to work with DOE, H2A, other analysis projects, developers, National Labs, and Tech Teams to revise and improve past system models

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

Analysis To Date		cH_2	Alanate	SBH	Cryo-comp	LH_2	AC	MgH_2	Liquid HC
On-Board	Review developer estimates	√	√	√	√	√	√		WIP
	Develop process flow diagrams and system energy balances	√	√	√					
	Independent performance assessment (wt, vol)	√	√	√					
	Independent cost assessment	√	√	√	√ *	√ *	√ *		
Off-Board	Review developer estimates	√		√	√			√	WIP
	Develop process flow diagrams and system energy balances	√		√	√			√	
	Independent performance assessment (energy, GHG)	√		√ *	√ *				
	Independent cost assessment	√		√ *	√ *				
Overall	WTT analysis tool[1]	√							
	Solicit input on TIAX analysis	√	√	WIP	WIP	WIP			
	Interim report	WIP	WIP						

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

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

Acknowledgement

Thank You

Questions?