PEM Fuel Cell System Manufacturing Cost Analysis for Automotive Applications

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President

November 12, 2014

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Conduct a bottom-up manufacturing cost analysis of a 80kW light-duty vehicle fuel cell power system which includes a fuel cell system, a hydrogen storage tank , and a hybrid Li-ion battery pack.

- **Executive decision making**
  - Our manufacturing cost analysis focuses on helping manufacturers make strategic design, sourcing and investment decisions based on the analysis of current and potential manufacturing costs.
- **Direct research and inspire innovation**
  - Help identify the factors with significant impact on technology system costs
  - Help identify the areas where more research could lead to significant reductions in system costs.
- **Design and manufacturing cost reduction**
  - Understand the costs of each design feature and part as well as the system costs at the design stage.
  - Reduce the manufacturing cost via “true value mapping” which virtualizes the costs in every manufacturing step.
- **Facilitate future government agency and investor funding application**

Approach Manufacturing Cost Modeling Methodology

This approach has been used successfully for estimating the cost of various technologies for commercial clients and the DOE.

Technology Assessment

- Literature research
- Definition of system and component diagrams
- Size components
- Develop bill-of-materials (BOM)

Manufacturing Cost Model

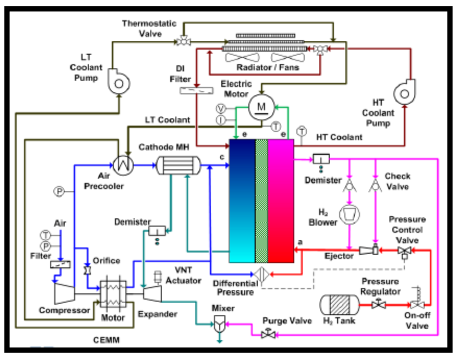
- Define system value chain
- Quote off-shelve parts and materials
- Select materials
- Develop processes
- Assembly bottom-up cost model
- Develop baseline costs

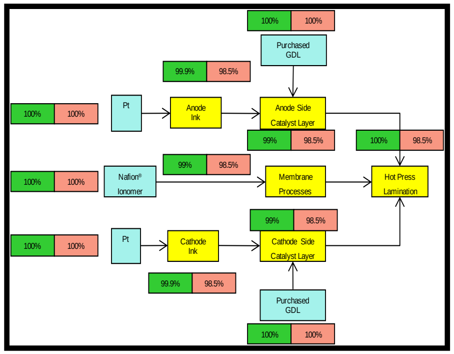
Scenario Analyses

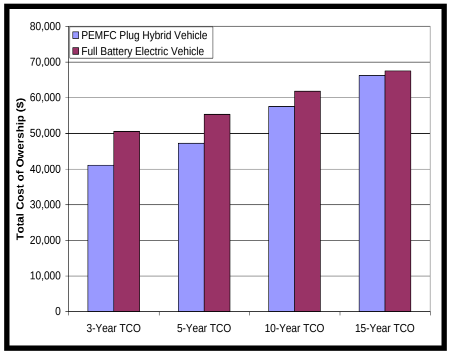
- Technology scenarios
- Sensitivity analysis
- Economies of Scale
- Supply chain & manufacturing system optimization
- Life cycle cost analysis

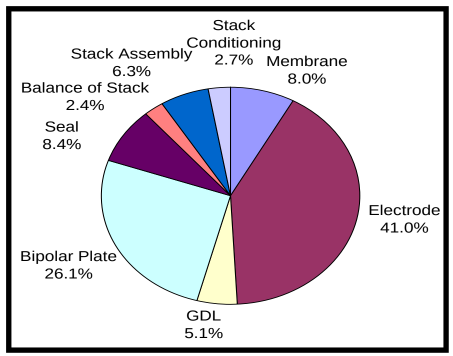
Verification & Validation

- Cost model internal verification reviews
- Discussion with technical developers
- Presentations to project and industrial partners
- Audition by independent reviewers



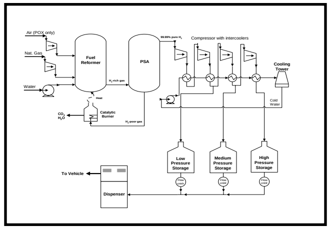






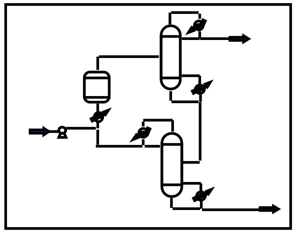
Combining performance and cost model will easily generate cost results, even when varying the design inputs.

Conceptual Design



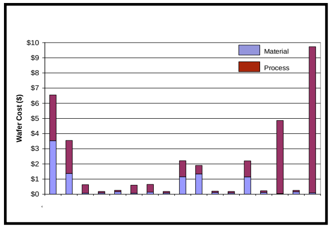
- System layout and equipment requirements

Process Simulation



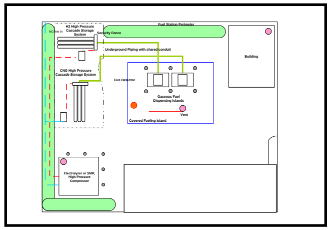
- Energy requirements
- Equipment size/ specs

Process Cost Calcs



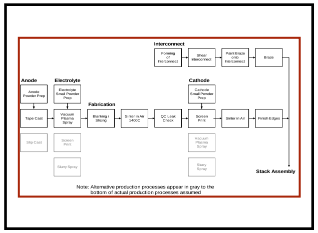
- Process cost
- Material cost

Site Plans



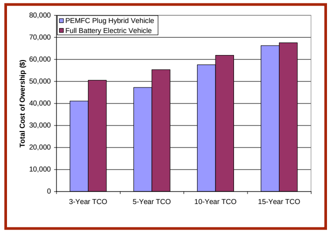
- Safety equipment, site prep, land costs

Capital Cost Estimates



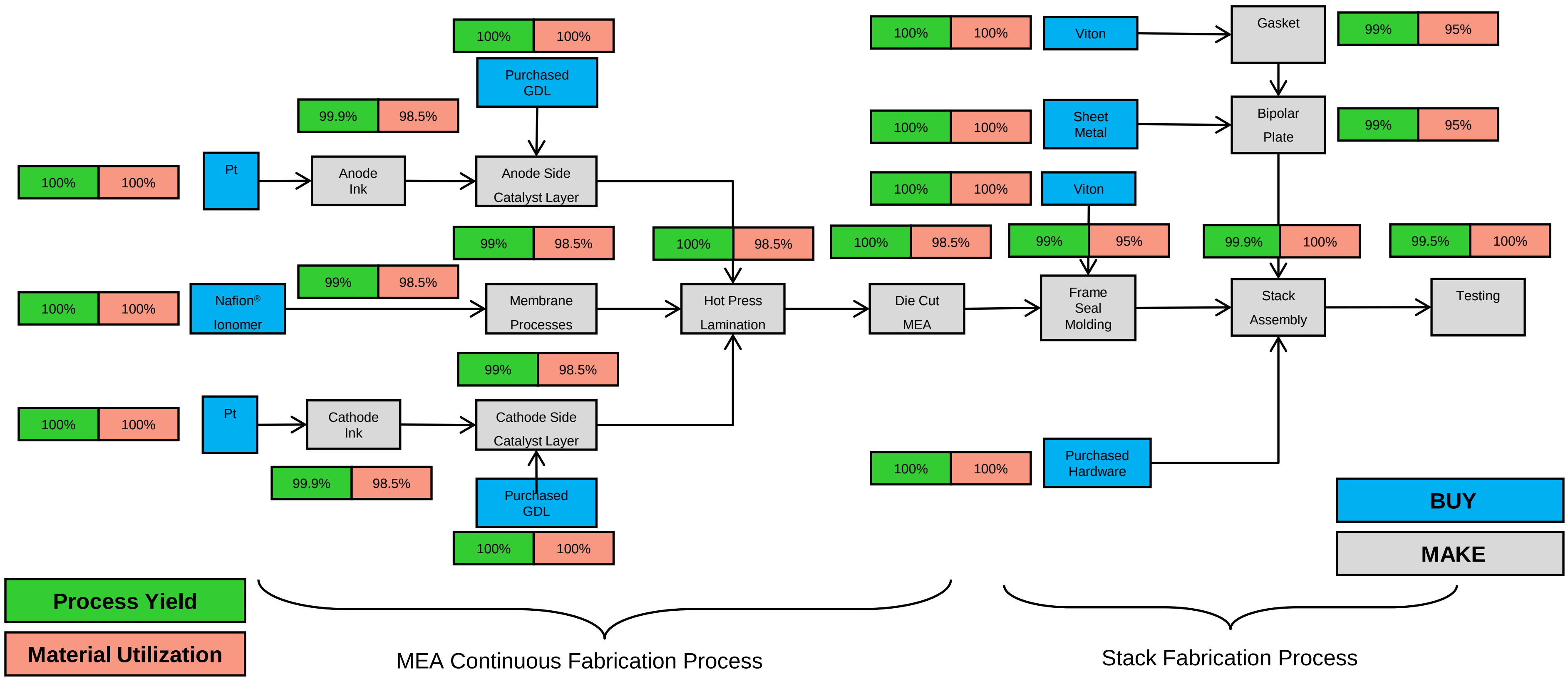
- High and low volume equipment costs

Product Costs



- Product cost (capital, O&M, etc.)

The bottom-up cost approach will be used to capture accurately the manufacturing costs for each fabrication step.



True-value-mapping analysis virtualizes costs in each fabrication step, which breaks down costs into materials, labor, capex, utility, maintenance, etc.

Austin Power Engineering's manufacturing cost models can be used to determine a fully loaded selling price to consumers at high or low volumes.

Consumer Selling Price

Corporate Expenses
- Research and Development
- Sales and Marketing
- General & Administration
- Warranty
- Taxes

Fixed Costs
- Equipment and Plant Depreciation
- Tooling Amortization
- Equipment Maintenance
- Utilities
- Building
- Indirect Labor
- **Cost of capital**
- Overhead Labor

Variable Costs
- Manufactured Materials
- Purchased Materials
- Fabrication Labor
- Assembly Labor
- Indirect Materials

Profit

Sales Expense

General Expense

Factory Expense

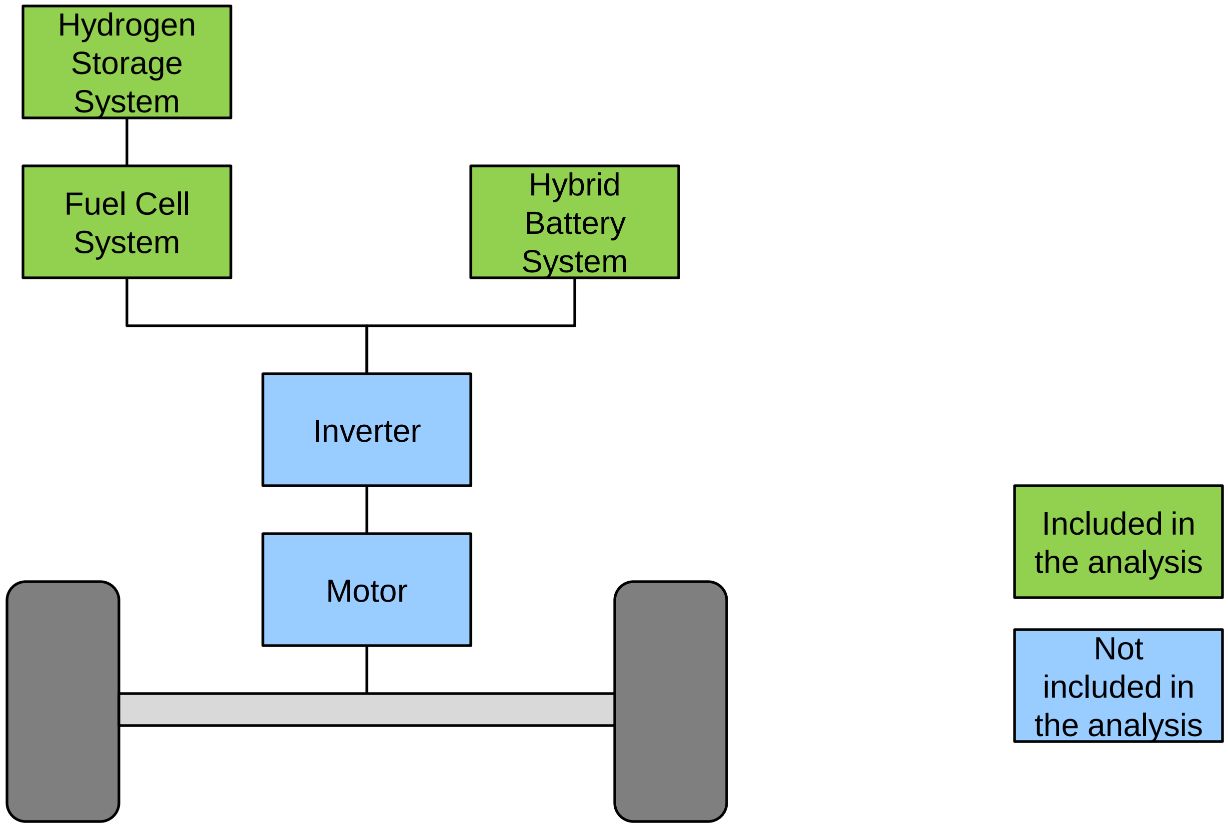
Direct Labor

Direct Materials

Manufacturing Cost

We assume 100% financing with an annual discount rate of 10%, a 10-year equipment life, a 25-year building life, and three months working capital.

Our fuel cell powertrain cost analysis are focus mainly on fuel cell system, hydrogen storage, and hybrid battery. Inverter and traction motor costs are not included.

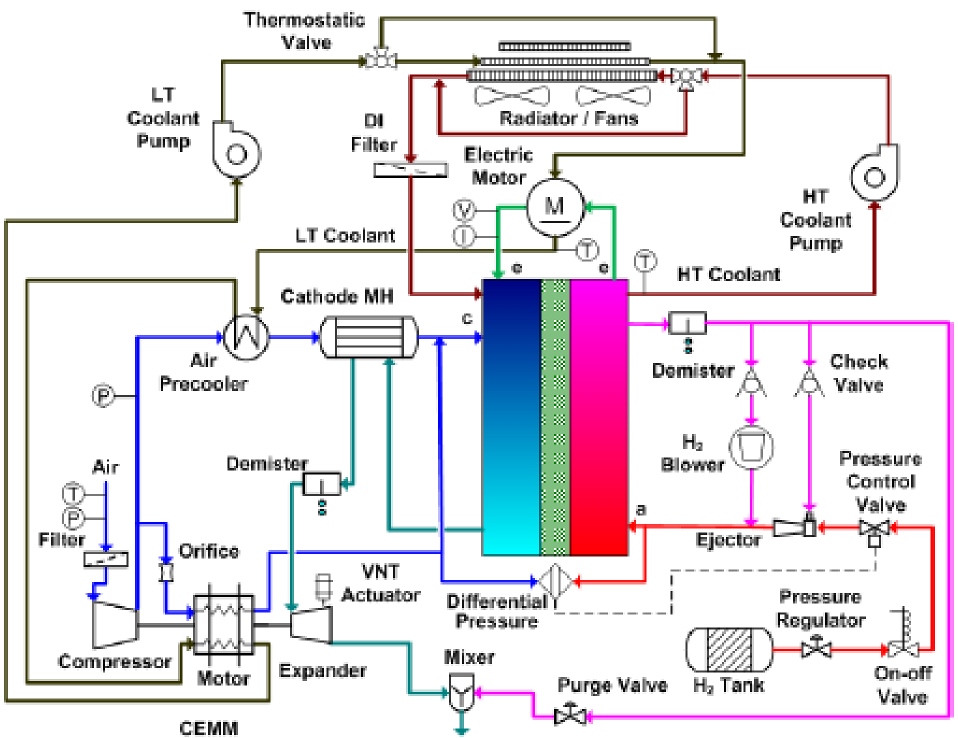


Approach Scope

In 2014 FCS, we update our 2013 FCS study with 2013 ANL system cost configuration, Treadstone coating metal bipolar plate, as well as a cryo-compressed H2 (CcH2) storage tank and a hybrid battery pack.

System Components	2013 FCS	2014 FCS
80kW PEM Fuel Cell	• *80 kW_{net} Stack* *Membrane* *Electrode* *GDL/MPL* *Nitride Metal Bipolar Plate* *Seal & Gasket* *Balance of Stack* • *BOP* *Fuel Management with H2 Circulation Pump* *Thermal Management* *Air Management* *Water Management* • *Assembly, Conditioning, & Testing*	• *80 kW_{net} Stack* *Membrane* *Electrode* *GDL/MPL* *Treadstone Coating Metal Bipolar Plate* *Seal & Gasket* *Balance of Stack* • *BOP* *Fuel Management with Revised H2 Circulation Pump* *Thermal Management* *Air Management* *Water Management* • *Assembly, Conditioning, & Testing*
H2 Storage Tanks	• *Type IV compressed H2Tank* • *5.6 kg usable H2*	• *Cryo-compressed H2 storage tank* • *10 kg usable H2*
Hybrid Battery	• *Li-Ion hybrid battery (40kW, 1.2 kWh)*	• *Li-Ion hybrid battery (40kW, 1.2 kWh)* • *Updated process parameters*

The 80 kW_{net} direct hydrogen PEM fuel cell system configuration is referenced in previous and current studies conducted by Argon National Laboratory (ANL).



80 kW_{net} Fuel Cell System Schematic[1]

1. R. K. Ahluwalia, X. Wang, "Fuel cells systems analysis," 2013 DOE Hydrogen and Fuel Cells Program Review, Washington DC, May13-16, 2013.

Key Parameters

Stack
- 3M NSTFC MEA
- 25 μm supported membrane
- 0.153 mg/cm^2 Pt
- Power density: 692 mW/cm^2
- Metal bipolar plates
- Non-woven carbon fiber GDL

Air Management
- Honeywell type compressor /expender
- Air-cooled motor / Air-foil bearing

Water Management
- Cathode planar membrane humidifier with pre-cooler
- No anode humidifier

Thermal Management
- Micro-channel HX

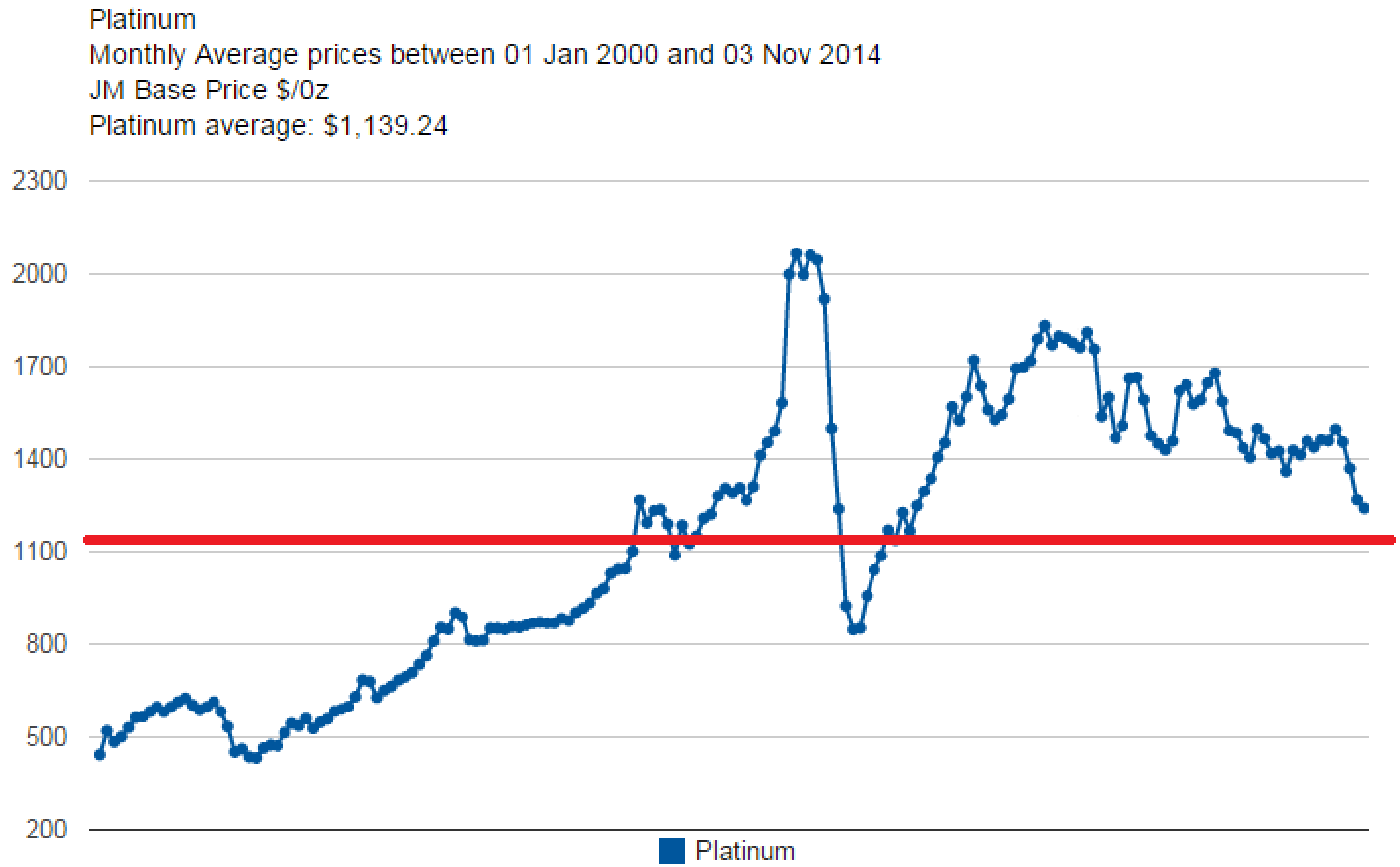
Fuel Management
- Parallel ejector / pump (100W) hybrid

System Assumptions 80 kW_{net} PEM Fuel Cell System *Preliminary Design*

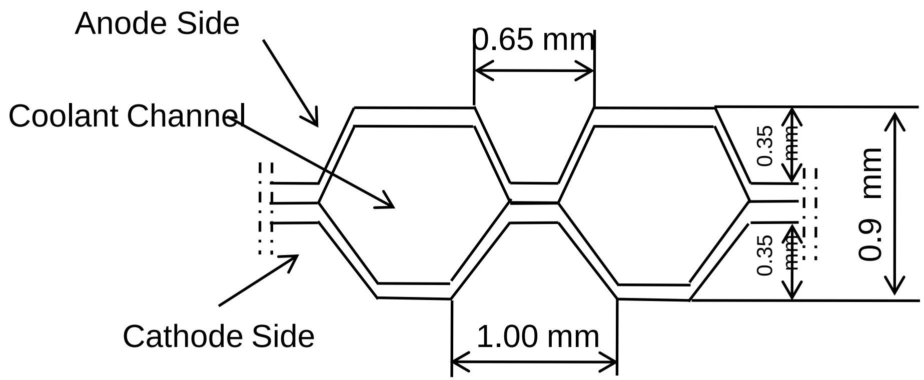
Based on ANL's stack performance analysis, we make the following system and material assumptions for the cost estimation.

Stack Components	Unit	2013	2014
Production volume	systems/year	500,000	500,000
Stacks' net power	kW	80	80
Stacks' gross power	kW	88	89.4
Cell power density	mW/cm^2	984	692
Peak stack temp.	Degree C	87	92.3
Peak stack pressure	Bar	2.5	2.5
Cell Voltage	Volt	0.676	0.695
System Voltage (rated power)	Volt	300	300
Platinum price	$/tr.oz.	$1,100	$1,100
Pt loading	mg/cm^2	0.196	0.153
Membrane type		Reinforced 3M PFSA	Reinforced 3M PFSA
Membrane thickness	micro meter	25	25
GDL layer		None-woven carbon paper	None-woven carbon paper
GDL thickness	micro meter	185	185
MPL layer thickness	micro meter	40	40
Bipolar plate type		76Fe-20Cr-4V with nitridation surface treatment	SS316L with Treadstone Coating
Bipolar plate base material Thickness	micro meter	100	100
Seal material		Viton®	Viton®

We use Pt price at $1,100/troz which is the similar to past 15 year average Pt price. The current Pt price is about $1,200/troz.



The metal bipolar plate cost is based on discussions with Treadstone on their thermal spray process[1].



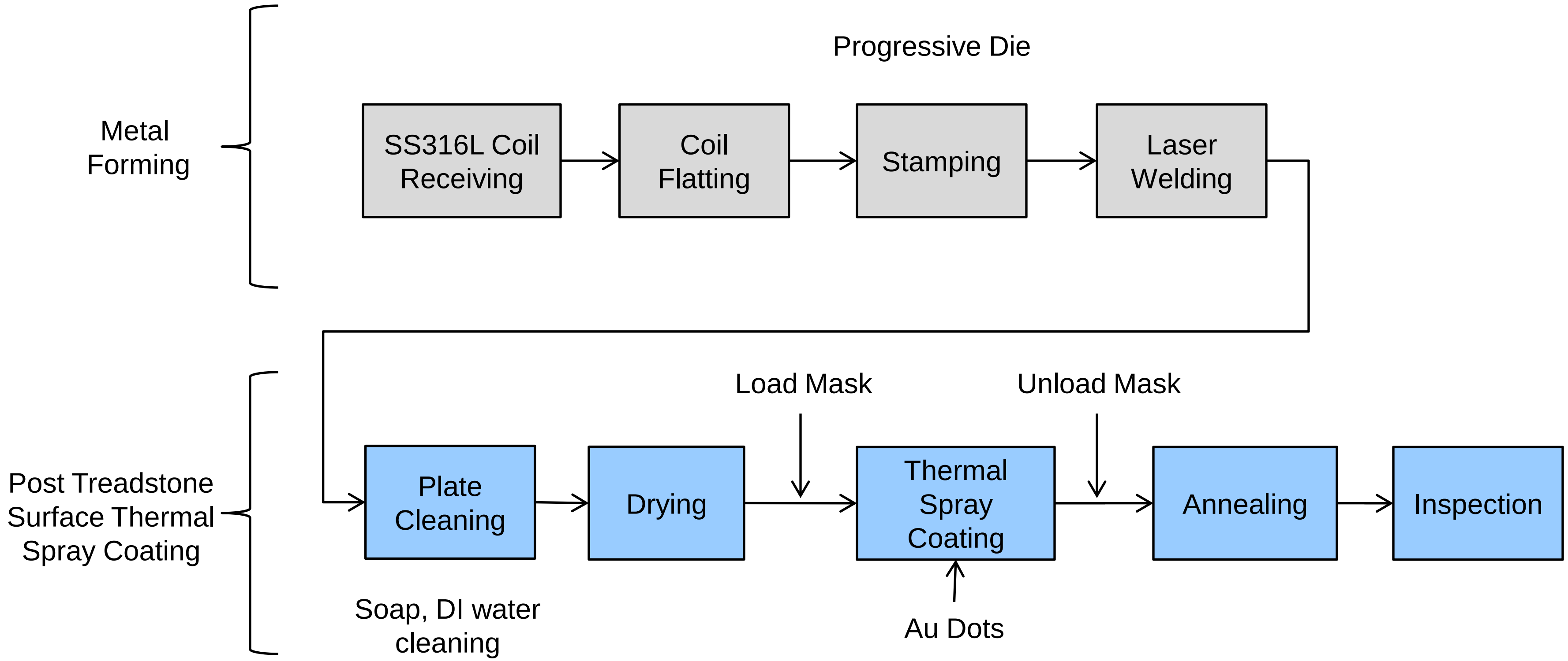
Flow Channel Dimension

System /Component	Annual Production Volume
Fuel cell system	500,000
Bipolar Plate	216.5 Million

Parameter	Specifications
Base Material Thickness (mm)	0.1
Base Material	SS316L
# of Tiles in a Pair of Bipolar Plate	2
Cooling Channel	Yes
Stamping [2.3]	Progressive Die
Joint Method	Spot + Edge Laser Welding

1. Discussion with Treadstone, 2013, 2014
2. US 20090081520 (Hitachi)
3. Discussion with Minster Press Inc., April 2010

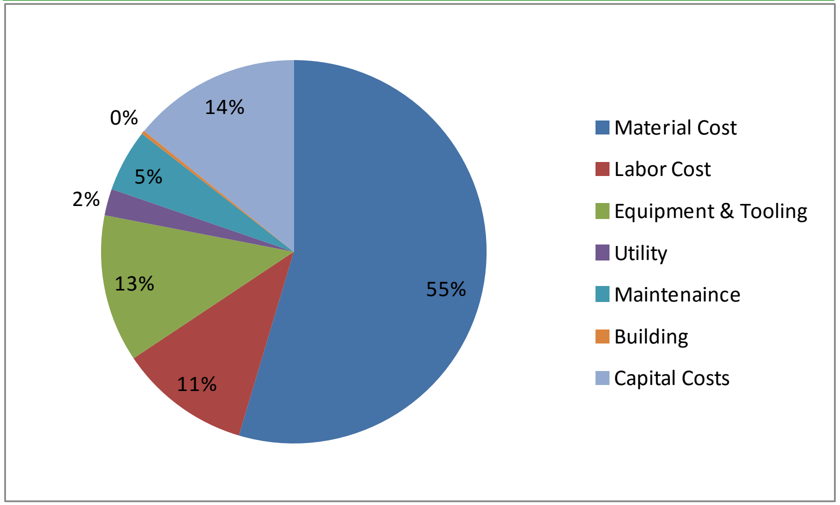
Fabrication processes include base metal plate stamping, plate laser welding, and Treadstone thermal spray post coating.



The thermal spray coating process costs about $0.35 per plate. The total cost of Treadstone thermal spray coated metal plate is approximately $8.38/kW.

	Bipolar Plate Manufacturing Cost[1] ($/kW)
Stamping[2]	$5.28
Laser Welding	$0.95
Treadstone Coating[3]	$2.16
Total	$8.38

Bipolar Plate Manufacturing Cost ($8.38/kW)



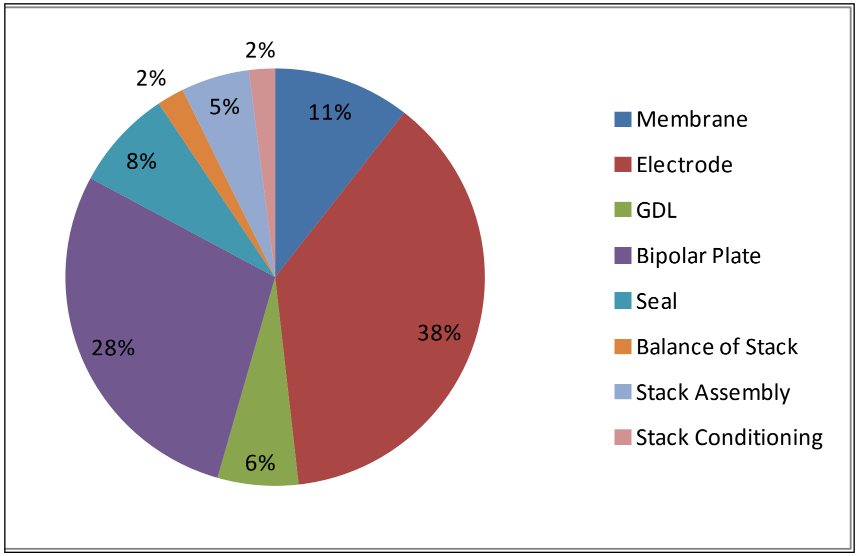
[1] Manufactured cost on a kW$_{net}$ basis
[2] Includes SS316L material cost
[3] Includes Au dot material cost

80 kW_{net} PEMFC System Stack Costs

The 80 kW_{net} PEM fuel cell stack costs approximately \$30/kW. Electrodes, bipolar plates, and membranes are the top three cost drivers.

Stack Components	2014Stack Cost (\$/kW)	2014Stack Cost (\$/kW)	Comments
Membrane	\$2.14	\$3.13	PFSA ionomer (\$80/lb)
Electrode	\$9.51	\$11.11	3M NSTFC
GDL	\$1.30	\$1.85	No-Woven carbon paper
Bipolar Plate	\$6.36	\$8.38	Treadstone Coating metallic plates
Seal	\$2.00	\$2.30	Viton
BOS	\$0.55	\$0.62	Manifold, end plates, current collectors, insulators, tie bolts, etc.
Final Assembly	\$1.40	\$1.56	Robotic assembly
Stack Conditioning	\$0.60	0.60	2 Hours
Total stack[2]	\$23.85	\$29.53	

80 kW_{net} PEM Fuel Cell Stack Cost (\$29.5/kW_{net})



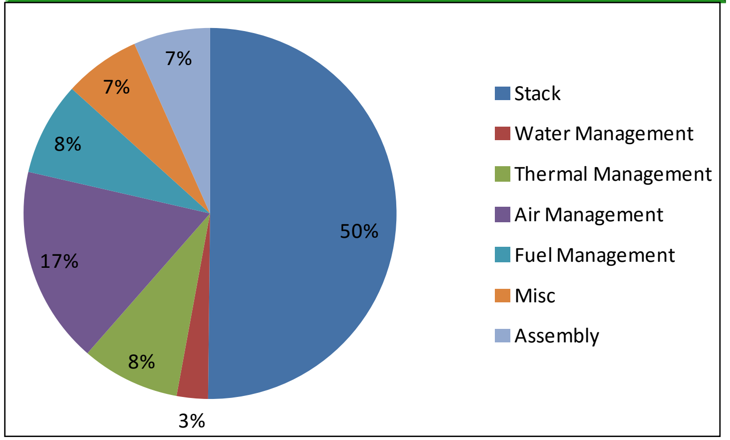
1. Stack assembly cost category included MEA assembly and stack QC; QC included visual inspection, and leak tests for fuel, air, and coolant loops.
2. Results may not appear to calculate due to rounding of the component cost results.

The 80 kW_{net} PEM fuel cell system costs $59/kW at the mass production volume. Stack, air management, and thermal management are the top three cost drivers.

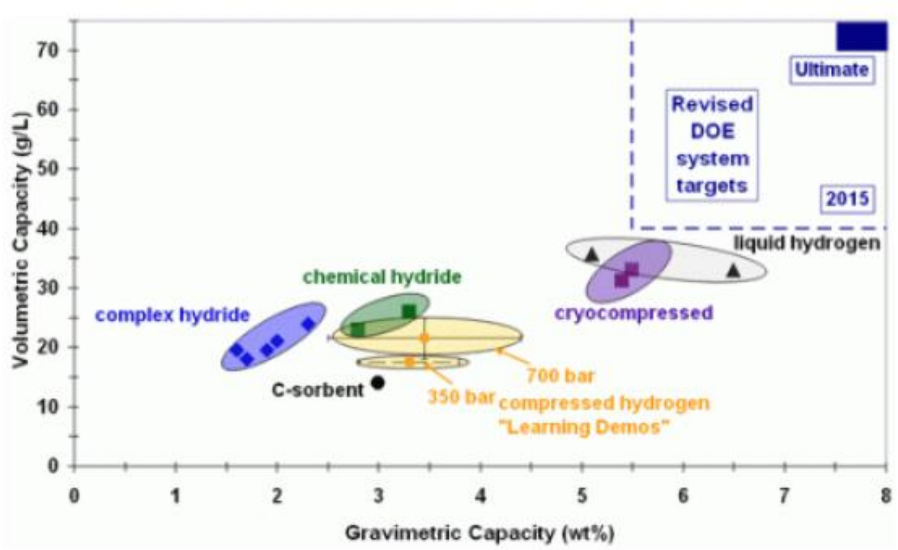
System Components	2013 System Cost ($/kW)	2014 System Cost ($/kW)	Comments
Stack	$23.9	$29.6	
Water management	$1.6	$1.6	Cathode side humidifier, etc.
Thermal management	$5.0	$5.0	HX, coolant pump, etc.
Air management	$10.1	$10.1	CEM, etc.
Fuel management	$4.8	$4.8	H2 pump, etc.
Balance of system	$3.9	$3.9	Sensors, controls, wire harness, piping, etc.
System assembly	$3.9	$3.9	
Total system[1, 2]	**$53.2**	**$58.9**	

1. Assumed 15% markup to the automotive OEM for BOP components
2. Results may not appear to calculate due to rounding of the component cost results.

80 kW_{net} PEM Fuel Cell System Cost ($4,713/system)

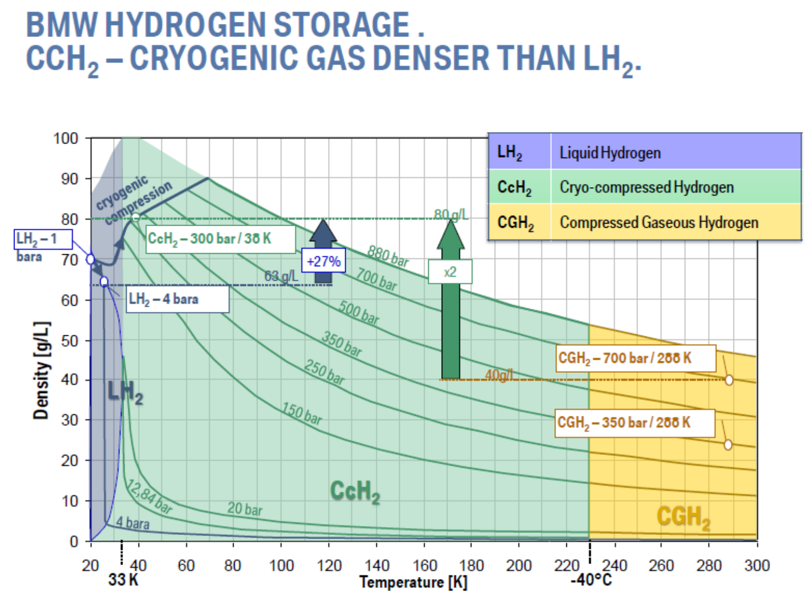


Cryo-compressed H2 storage tanks have gravimetric and volumetric capacity advantage comparing to compressed h2 storage tanks.



Status of Current Hydrogen Storage Technologies

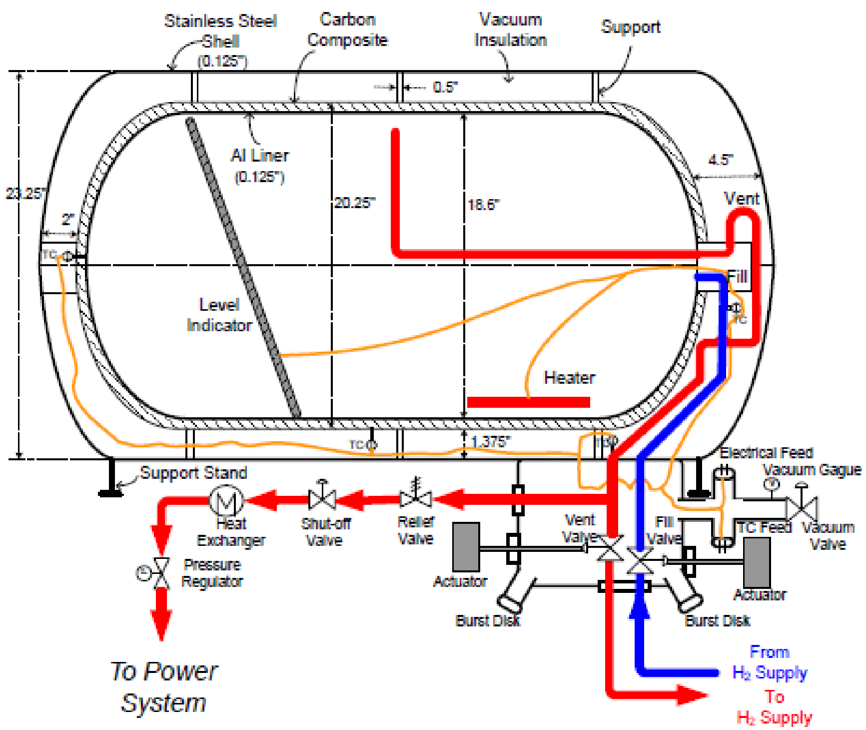
http://energy.gov/eere/fuelcells/status-hydrogen-storage-technologies



K. Kunze, O. Kircher, Cryo-compressed hydrogen storage, BMW, Sept. 28, 2012,

The cryo-compressed hydrogen tank design is referenced in studies TIAX conducted on hydrogen storage[1].

LLNL 2nd Gen Design with ANL Modifications



Cryo-Compressed Hydrogen Storage System Schematic[1, 2]

1. S. Lasher and Y. Yang, "Cryo-compressed and Liquid Hydrogen System Cost Assessments", DOE Merit Review, 2008
2. R.K. Ahluwalia, i.e. "Cryo-compressed hydrogen storage: performance and cost review" Februrary, 2011

Key Parameters

System Volume

- Storage: 151L
- Vessel: 224L

System Weight: 144.7kg

- LH2 storage: 10.7kg (usable 10.1 kg)
- CH2 storage: 2.8kg

Tank

- Carbon fiber: Toray T700S
- Carbon fiber / resin ratio: 0.68 : 0.32 (weight)
- Translational strength factor: 81.5%
- Safety factor: 2.25
- Carbon fiber composite layer thickness: 12 mm
- Liner: 3mm Al
- Vacuum gap: 40 mm with 40 layers of MLVI
- Outer Shell: 3 mm thick SS304
- Gravimetric capacity: 7.1 wt%
- Volumetric capacity: 44.5 kg/m^3

The single tank design had a usable hydrogen storage capacity of 10.1 kg.

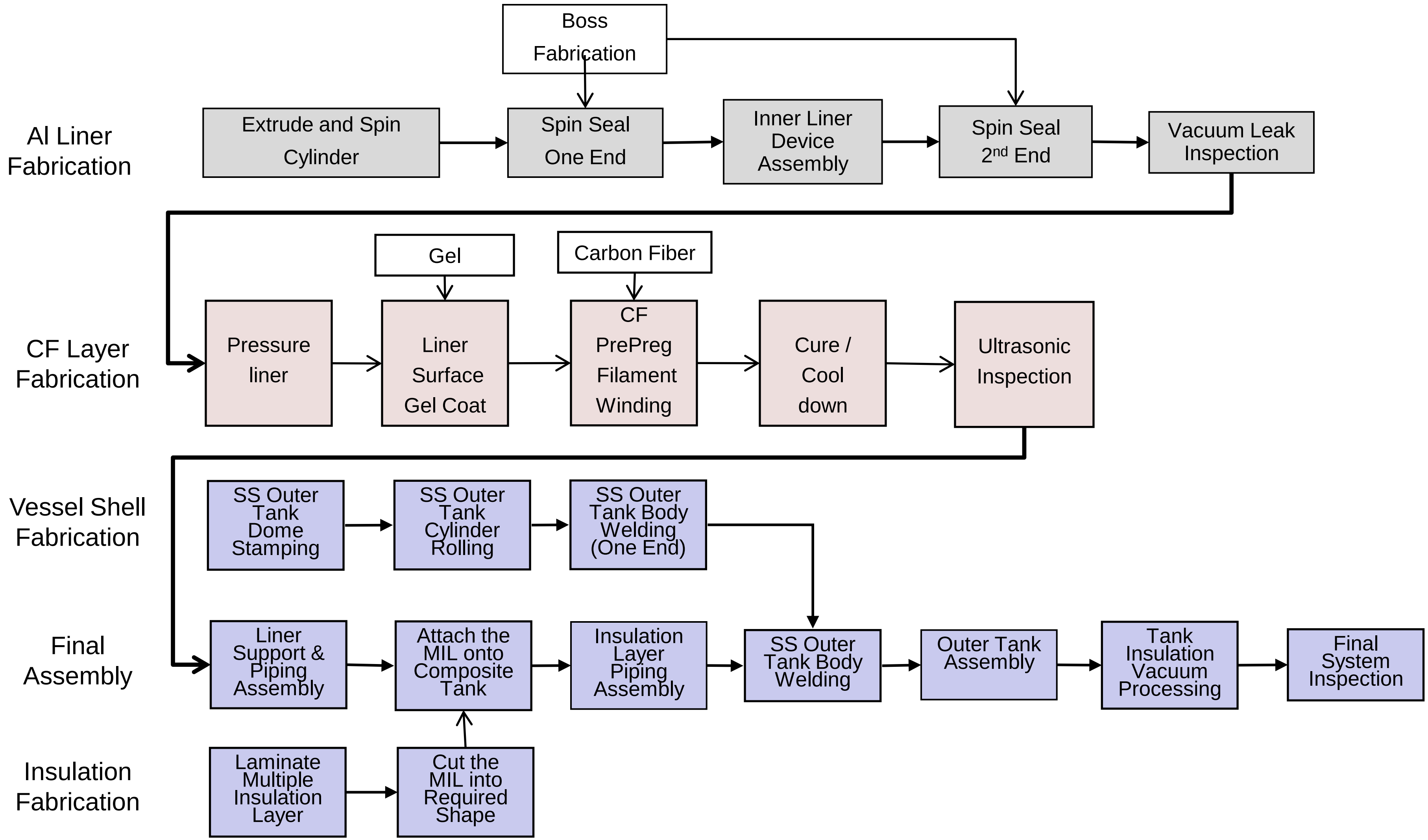
The cryo-compressed H2 system major components are listed.

Major Tank Components	Major BOP Components
	• Fuel receptacle
• Aluminum End Boss	• Vent & release devices
• Aluminum liner	• Electronic control unit
• Carbon fiber composite layer	• System control unit (pressure regulator, etc.)
• MLVI insulation	• HX
• SS304 vacuum shell tank	• Piping & fittings
• Balance of vessel	• Wire hardness
	• Frame, supporting, etc.

Assumptions for the hydrogen storage tank design are based on the literature review and third-party discussions.

Stack Components	Unit	Current System	Comments
Production volume	systems/year	500,000	High Volume
Usable hydrogen	Kg	10.1	
Total H2 in the tank	Kg	10.7	
Tank type		III	With Al liner
Tank max pressure	PSI	5,000	
# of tanks	Per System	1	
Safety factor		2.25	
Tank length/diameter ratio		3:1	
Liner material		Al	
Liner thickness	mm	3	
Carbon fiber type		Toray T700S	
Carbon fiber cost	$/lbs	12	
Carbon fiber vs. resin ratio		0.68:0.32	Weight
Carbon fiber translational Strength factor		81.5%	
Carbon fiber composite layer thickness	mm	12	
Vacuum gap	mm	40	
# of MLVI layer		40	
Outer layer		SS304	
Outer layer thickness	mm	3	

A vertically integrated manufacturing process is assumed for the tank and BOP components.

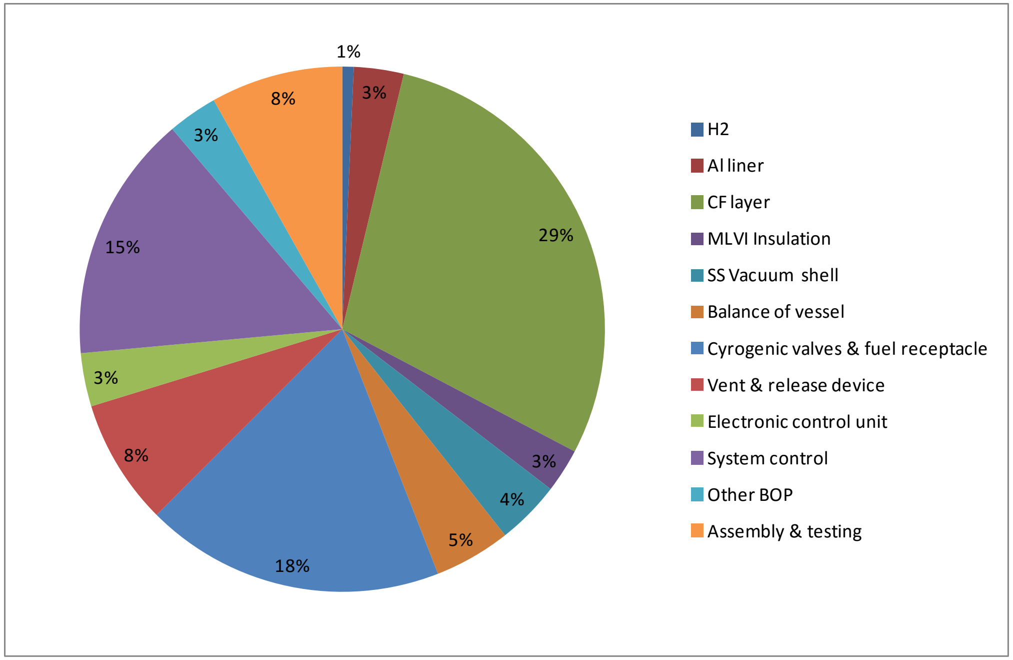


Cryo-compressed H2 Storage System Cost

In the 10.1kg cryo-compressed hydrogen storage system, the carbon fiber composite layer , cryogenic valves, system control valves are the top three cost drivers.

System Components	2014 CcH2 Cost ($/kWh)
H2	$0.10
Al liner	$0.42
CF layer	$3.93
MLVI Insulation	$0.37
SS Vacuum shell	$0.53
Balance of vessel	$0.64
Cyrogenic valves & fuel receptacle	$2.50
Vent & release device	$1.05
Electronic control unit	$0.45
System control	$2.07
Other BOP	$0.42
Assembly & testing	$1.10
Total:	$13.57

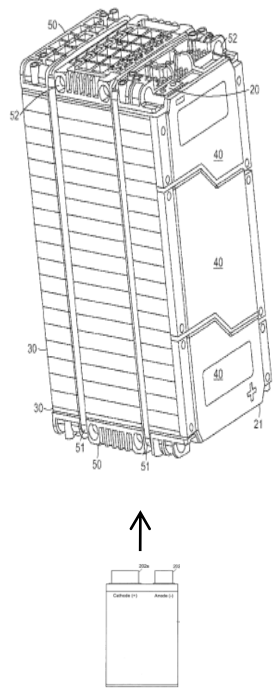
CcH2 Storage System Cost ($4,567/system)



A lithium-ion battery pack will provide hybridization of a fuel cell vehicle which improves fuel economy as well as having the function as a startup battery.

Battery price is decreasing[1]:

- Process throughput increased in the past a few years.
- Tooling & equipment costs are decreasing
- Cathode active material cost did not change much.
- Some battery components prices decreased, such as separator, etc..



Battery Cells[2]

Key Parameters

System

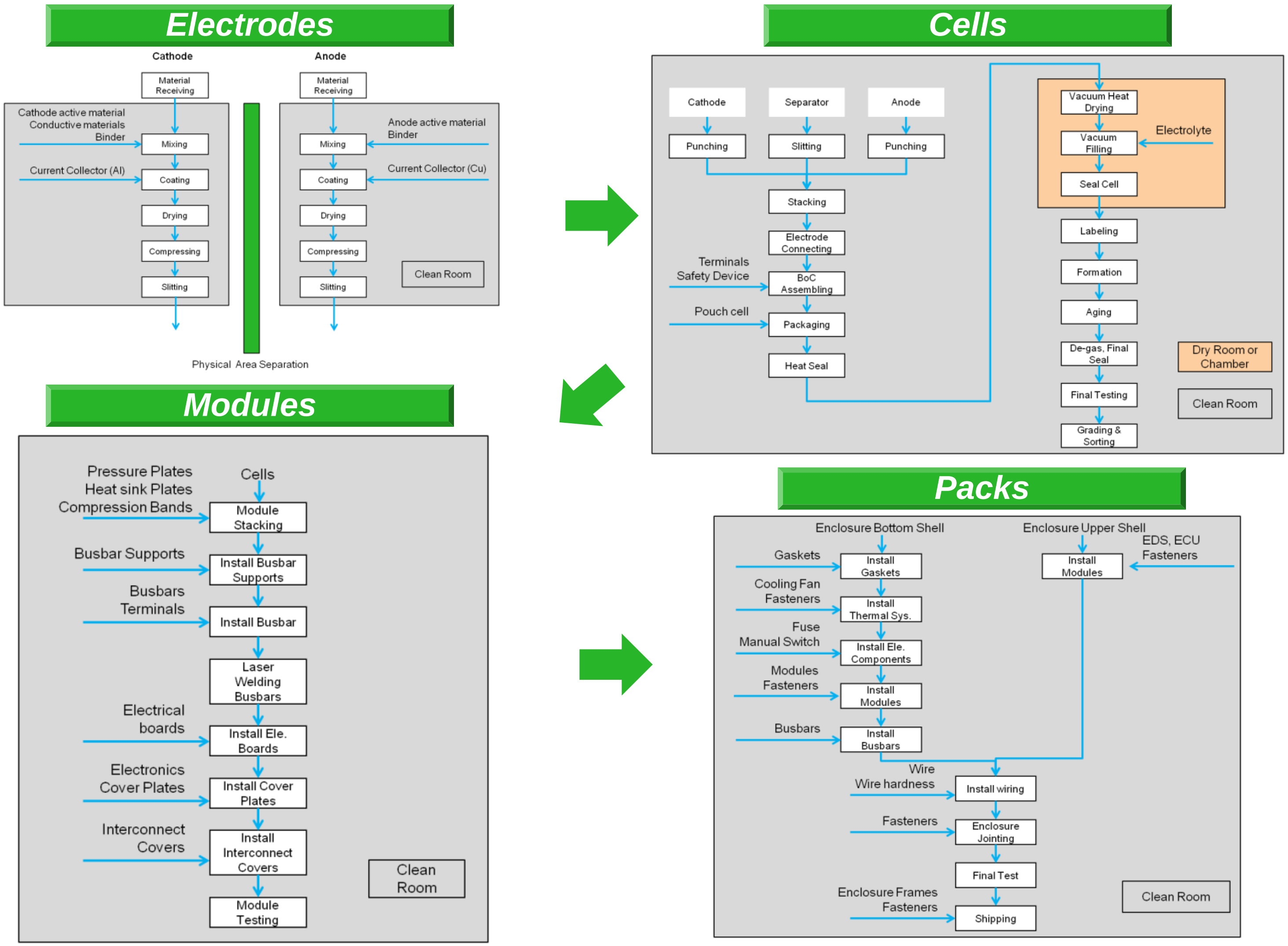
- Power: 40 kW
- Energy capacity: 1.2 kWh usable
- Power to energy ratio: 33:1
- Percent SOC: 80%
- Fade: 20%

Cell

- Cell format: Pouch cell
- Cathode active Material: manganese spinel
- Anode active material: graphite

1. B. Barnett, PHEV battery cost analysis, TIAX, 2013
2. US patent 20090169990

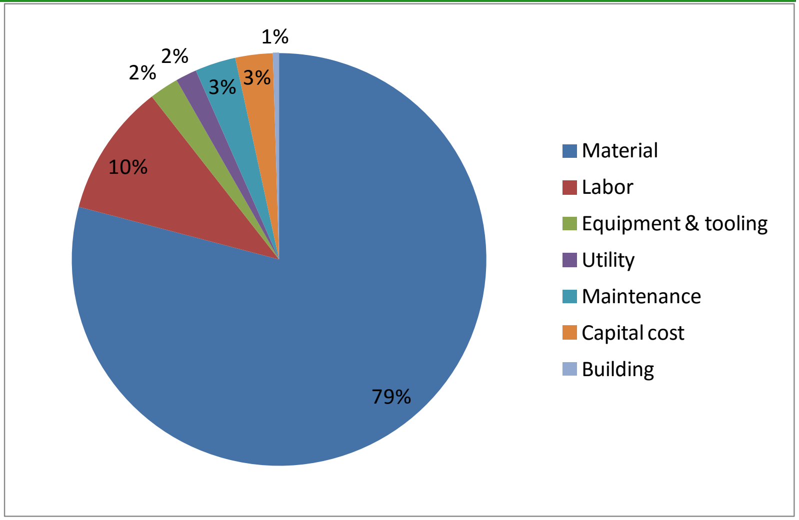
A vertically integrated manufacturing process is assumed for the four-level battery pack fabrication: electrode, cell, module, and pack.



The hybrid lithium-ion battery pack costs $658/kWh. Battery management system and packaging have higher cost contributions.

Cost Category	2013 Pack Cost ($/pack)	2014 Pack Cost ($/pack)
Material	$775	$624.8
Labor	$116.96	$81.8
Equipment & tooling	$48.03	$18.1
Utility	$26.76	$13.1
Maintenance	$23.79	$25.2
Capital cost	$37.85	$23.1
Building	$5.72	$3.8
Total	**$1,033.83**	$790.0
Total ($/kWh)*	**$861.52**	$658.3

Battery System Cost ($658 /kWh)



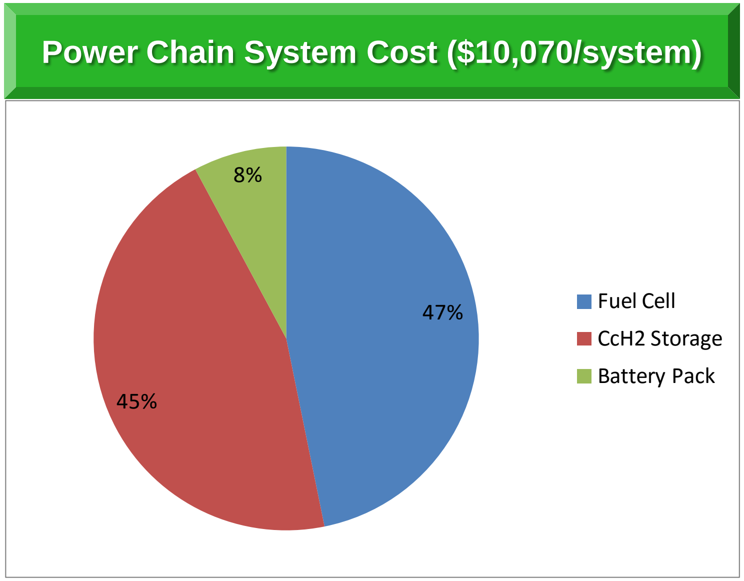
* Based on usable energy (1.88 kWh x 0.8 x0.8 = 1.2 /kWh)

The 1.2 kWh* lithium-ion battery system cost $790 per pack at the mass production volume.

Conclusion

PEM fuel cell system, onboard hydrogen storage, and hybrid battery cost approximately $10,070 per vehicle.

Cost Category	2013 Pack Cost ($/pack)	2014 Pack Cost ($/pack)	Comments
Fuel Cell	$4,256	$4,713	2014 has lower power density.
H2 Storage	$3,028	$4,567	2014 CcH2 has 10kg usable hydrogen vs. 2013 5.6 kg CH2
Battery Pack	$1,034	$790	Reduce material cost and increase process throughputs in 2014.
Total:	$8,318	$10,070	



- The mass production manufacturing cost of the 80 kW_{net} PEMFC stack is estimated to be $30/kW.
- The mass production OEM cost of the 80 kW_{net} PEMFC system is estimated to be $59/kW
- The 10.1kg cryo-compressed on-board hydrogen storage system is estimated to be $13.6/kWh at the mass production.
- The hybrid lithium-ion battery (40kW, 1.2kWh) costs $790 per pack.

Thank You!

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