Cost Analysis of Direct Hydrogen PEM Fuel Cell/Lithium Ion Battery Hybrid Power Source for Transportation

AUSTIN POWER ENGINEERING

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Objective

The due diligence objective was to assess the cost implications of a PEM fuel cell/lithium-ion battery hybrid power chain for mid-size passenger vehicles.

Power Chain Configurations

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Fuel Cell, Hydrogen Storage, and Lithium-ion Battery Cost Assessments

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Results:

- *Cost of fuel cell, on-board hydrogen storage, and lithium-ion battery*
- *Identification of factors with significant impact on power chain costs*
- *Identification of areas where more research could lead to significant reductions in power chain cost*

We employed a parametric approach in which Austin Power Engineering's manufacturing cost model was applied many times with different sets of input parameters.

INPUTS

- System power
- Cell voltage
- Power density
- System voltage
- Pt loading
- Pt price
- Membrane type
- Membrane thickness
- Bipolar plate material
- Bipolar plate thickness
- Production volume
- . . .

APPLICATION

Cost Model

ANALYSES*

- Economies of scale
- Single variable sensitivity analysis
- Monte Carlo simulation
- Scenario analysis
- System cost comparison
- Life cycle cost analysis

OUTPUTS

- System cost
- Stack cost
- Component cost
- Factors with significant influence on fuel cell cost

* Not shown in this presentation

The information used in this presentation was publicly available, which was mainly from DOE reports, patents, journal papers, etc.

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

Technology Assessment

- Definition of system and component diagrams
- Definition of technology options
- Kinetic analysis to size the components
- Develop component designs and integrate into system with piping, controls, and sensors
- Develop bill-of-materials for cost model

Manufacturing Cost Model

- Define value chain with split between purchased and internally fabricated materials and components
- Quote outsource parts
- Select materials
- Develop processes for internally produced items
- Assemble bottom-up activities based cost model (fixed and variable costs, yields, scrap, recycle, …)
- Develop baseline cost

Scenario Analyses

- Technology scenarios (system configuration, technology options, performance assumptions)
- Sensitivity analysis of impact of uncertainty on cost estimate
- Economies of Scale
- Supply Chain & manufacturing system optimization
- Life Cycle Cost
- Mathematic Scaling Formula

Verification & Validation

- Cost model internal verification reviews
- Discussions with technical developers
- Presentations to project and industrial partners
- Audition by independent reviewers
- Validate cost model with feedbacks

Austin Power Engineering’s manufacturing cost models can be used to determine the fully loaded selling price to the consumer 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
- 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

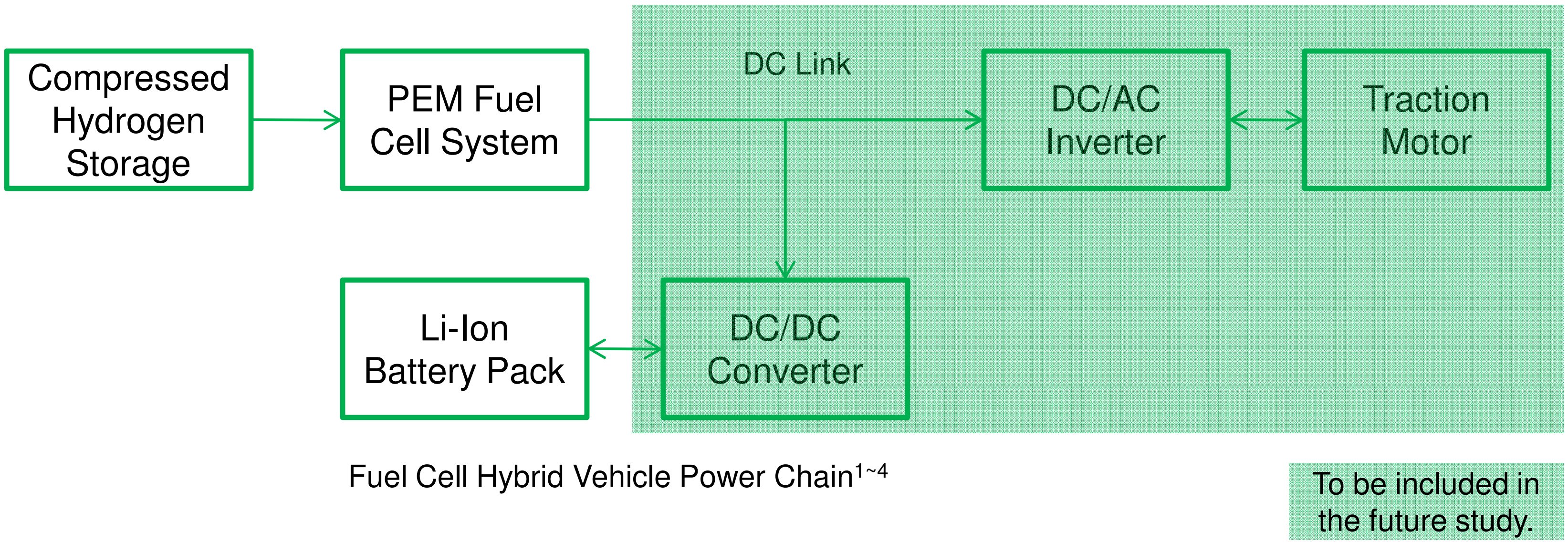
Direct labor

Direct Materials

Factory Cost

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

The bottom-up cost analysis included the PEM fuel cell system, compressed hydrogen storage tank, and lithium-ion battery pack.

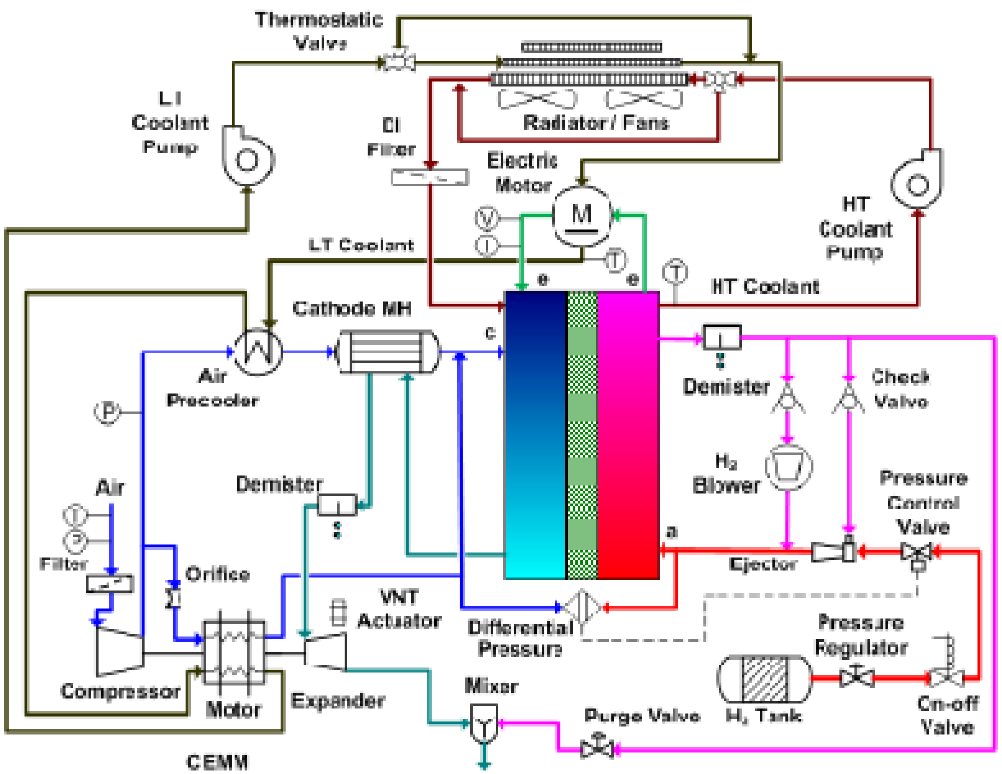


Fuel Cell Hybrid Vehicle Power Chain[1~4]

1. R. K. Ahluwalia, and X. Wang, "Direct hydrogen fuel cell systems for hybrid vehicles," *Journal of Power Sources* 139 (2005): 152-164.
2. P. Bubna, D. Brunner, S. G. Advani, and A. K. Prasad, "Prediction-based optimal power management in a fuel cell/battery plug-in hybrid vehicle," *Journal of Power Sources* 195 (2010): 6699-6708.
3. L. M. Fernandez, P. Garcia, C. A. Garcia, and F. Jurado, "Hybrid electric system based on fuel cell and battery and integrating a single dc/dc converter for a tramway," *Energy Conversion and Management* 52 (2011): 2183-2192.
4. J. Bernard, M. Hofer, U. Hannesen, A. Toth, A. Tsukada, F. Buchi, and P. Dietrich, "Fuel cell/battery passive hybrid power source for electric powertrains," *Journal of Power Sources*.

The bottom-up costs of the power electronic components (e.g., traction motor, inverter, and converter) will be included in a future study.

The 65 kW$_{net}$ direct hydrogen PEM fuel cell system configuration was referenced in previous and current studies conducted by Argon National Laboratory (ANL).



65 kW$_{net}$ Fuel Cell System Schematic[1]

1. R. K. Ahluwalia, and X. Wang, "Direct hydrogen fuel cell systems for hybrid vehicles," *Journal of Power Sources* 139 (2005): 152-164.
2. R. K. Ahluwalia, X. Wang, and R. Kumar, "Fuel cells systems analysis," 2011 DOE Hydrogen Program Review, Washington DC, May 9-13, 2011.

Key Parameters

Stack
- 3M NSTFC MEA
- 20 µm supported membrane
- 0.05 (a)/0.1 (c) mg/cm^2 Pt
- 75 ^{o}C, 1.5 atm
- Metal bipolar plates
- Non-woven carbon fiber GDL

Air Management
- CEM module
- 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 hybrid

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

Stack Components	Unit	Current System	Comments
Production volume	systems/year	500,000	High volume
Stacks' net power	kW	65	
Stacks' gross power	kW	72	
Stacks' gross power density	mW/cm^2	930	
Max. Stack Temp.	Degree C	90	
Platinum price	$/tr.oz.	$1,500	Last 5-year average
Pt Loading	mg/cm^2	0.15	
Membrane Type		Reinforced Nafion®	
Membrane Thickness	micro meter	20	
GDL Layer		None-woven Carbon Paper	
GDL Thickness	micro meter	185	@50 kPa pressure
MPL Layer Thickness	micro meter	40	
Bipolar Plate Type		76Fe-20Cr-4V with Nitridation Surface Treatment	
Bipolar Plate Base Material Thickness	micro meter	100	
Seal Material		Viton®	

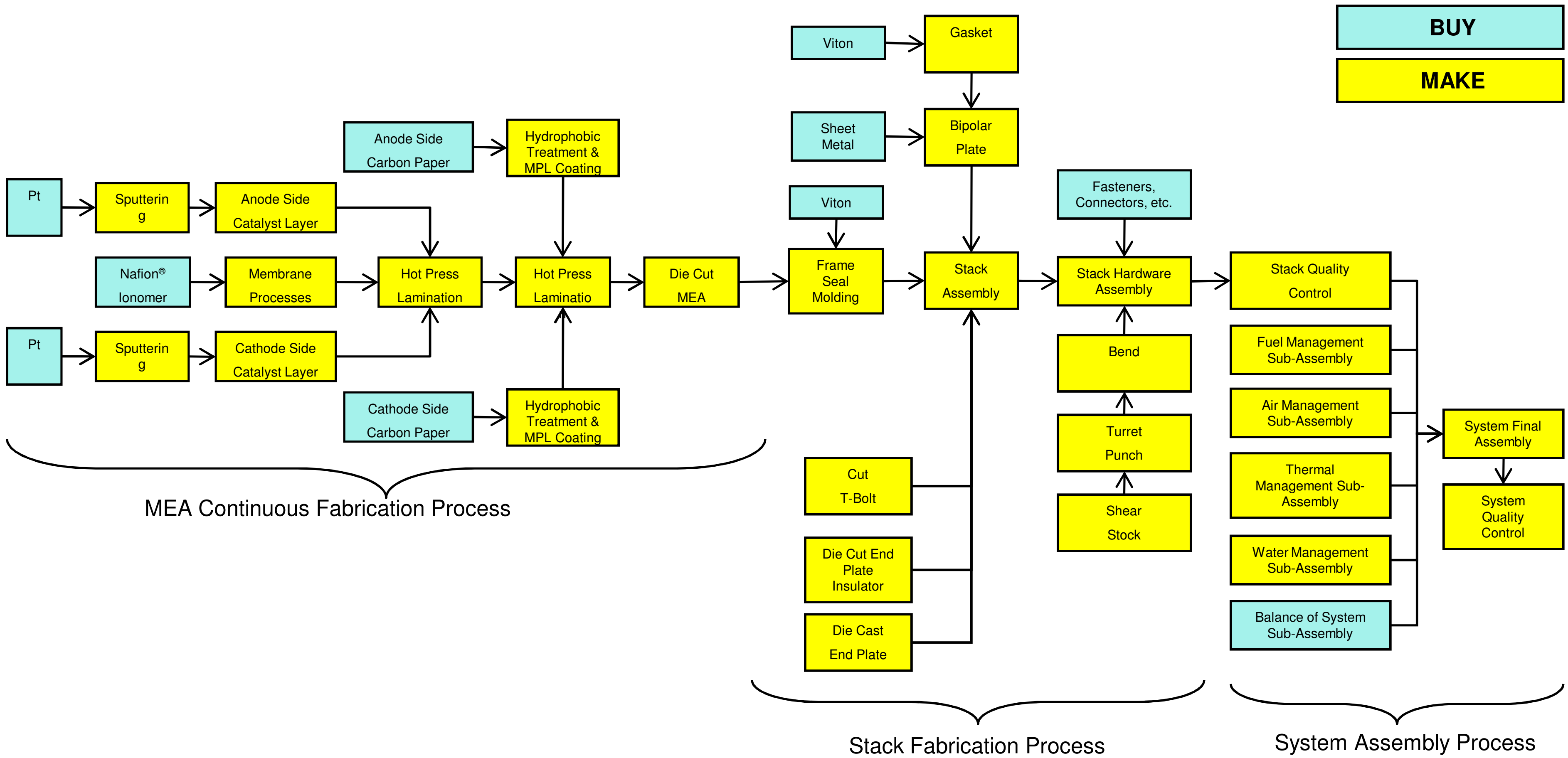
Pt price was $1,500/tr.oz. for the baseline. This was the average price for the last five years.

We used a bottom-up approach to determine the high-volume (500,000 units/year) manufacturing cost for the major stack and BOP components.

Major Stack Components	Major BOP Components
• Reinforced Membrane • 3M NSTFC Type Electrodes • Gas Diffusion Layer (GDL) with MPL Layers • Membrane Electrode Assembly (MEA) • Bipolar Plates • Seals	• Micro-Channel Radiators (HT, LT) • Cathode Planar Membrane Humidifier (MH) • Compressor-Expander-Motor Module (CEM) • H_2 Blower

- Developed Bill of Materials (BOM)
- Developed production process steps for major components and sub-systems
- Used quotations / experience-based estimates for raw materials and off-shelve components
- Used the Austin Power Engineering technology cost model for major stack and BOP components
- Validated cost analysis from industrial feedbacks

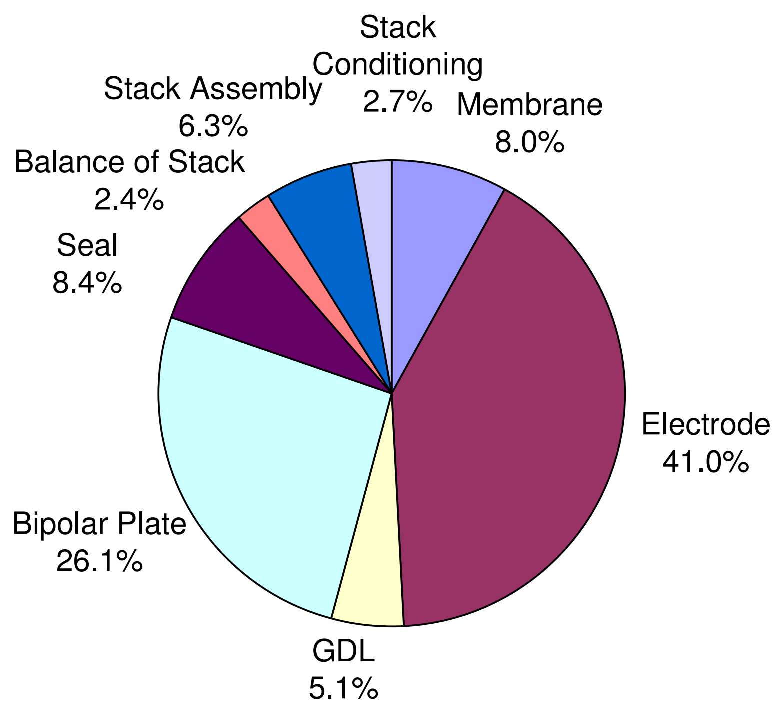
A vertically integrated manufacturing process was assumed for the major stack and BOP components.



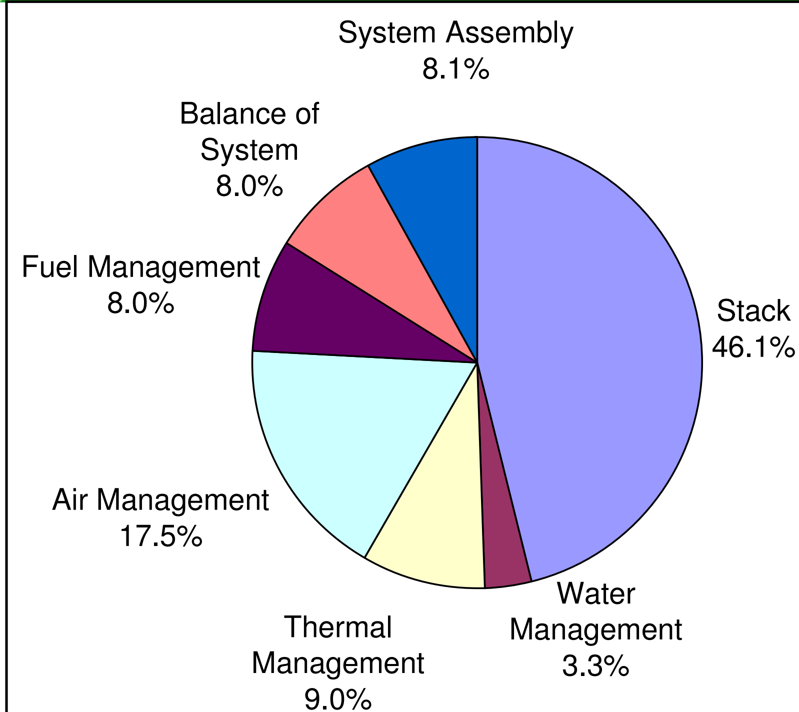
Supplier markups were included for the raw materials and purchased components.

The 65 kW_{net} PEM fuel cell stack cost \$27/kW. The electrode, bipolar plates, and seals were the top three cost drivers.

65 kW_{net} PEM Fuel Cell Stack Cost (\$27.3/kW_{net})

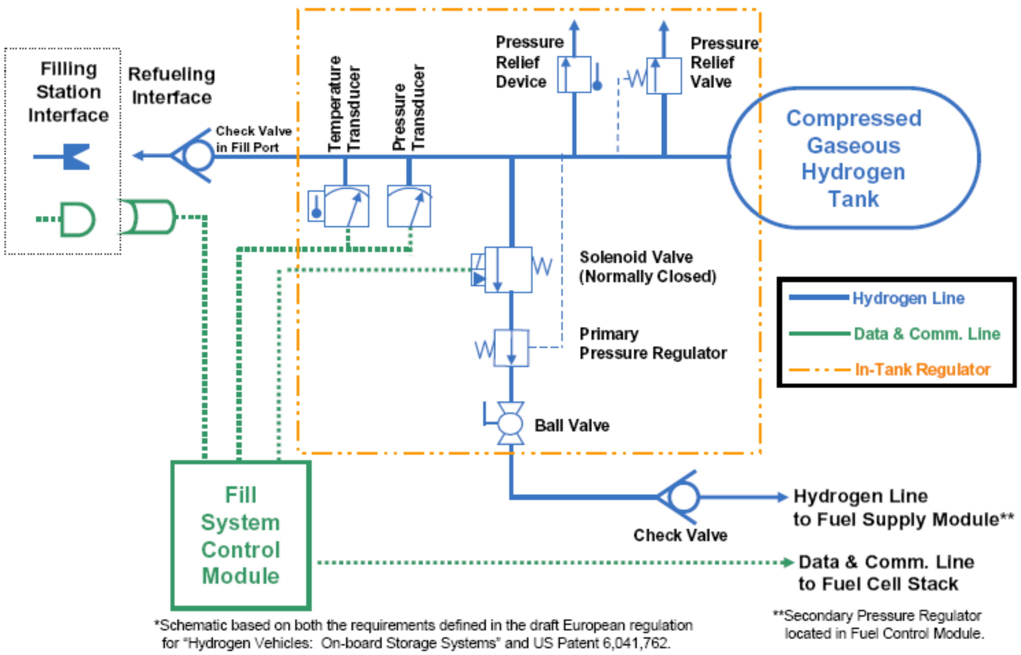


65 kW_{net} PEM Fuel Cell System Cost (\$64.2/kW_{net})



The 65 kW_{net} PEM fuel cell system cost \$64/kW. Stack, air management, and thermal management were the top three cost drivers.

The 5,000 PSI type IV compressed hydrogen tank design was referenced in studies TIAX conducted on hydrogen storage[1, 2].



Compressed Hydrogen Storage System Schematic[1, 2]

Key Parameters

System
- Pressure: 5,000 PSI
- Single Tank Design
- Usable H2: 5.6 kg
- Safety Factor: 2.25

Tank
- Carbon Fiber: Toray T700S
- Carbon Fiber Cost: $12/lbs
- Carbon Fiber / Resin Ratio: 0.68 : 0.32 (weight)
- Translational Strength Factor: 81.5%
- Fiber Process: Filament Winding
- Liner: HDPE

Pressure Regulator
- In-tank

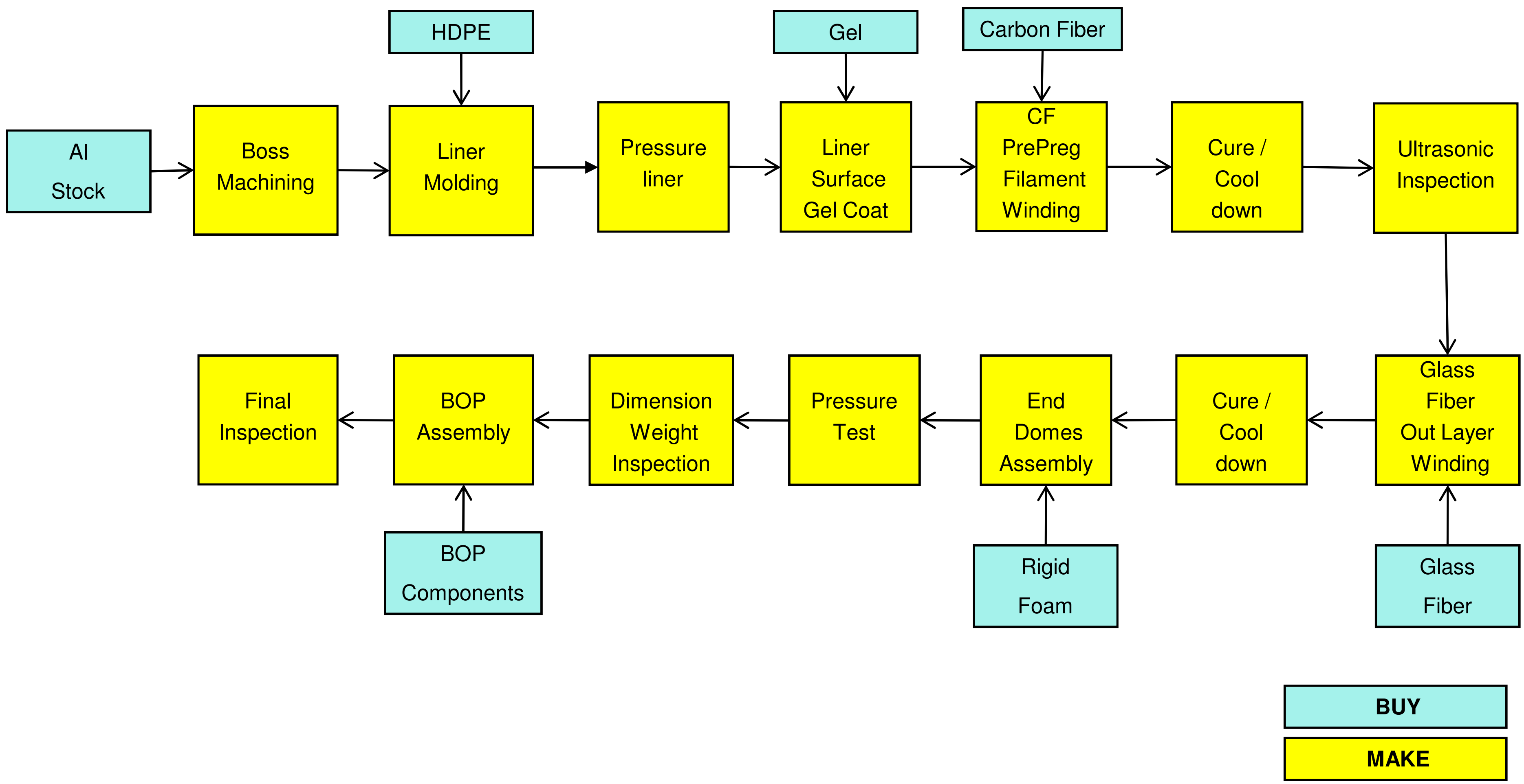
1. E. Carlson and Y. Yang, "Compressed hydrogen and PEM fuel cell system," Fuel cell tech team freedomCar, Detroit, MI, October 20, 2004.
2. S. Lasher and Y. Yang, "Cost analysis of hydrogen storage systems - Compressed Hydrogen On-Board Assessment – Previous Results and Updates for FreedomCAR Tech Team", January , 2007

The single tank design has a storage capacity of 5.6 kg usable hydrogen.

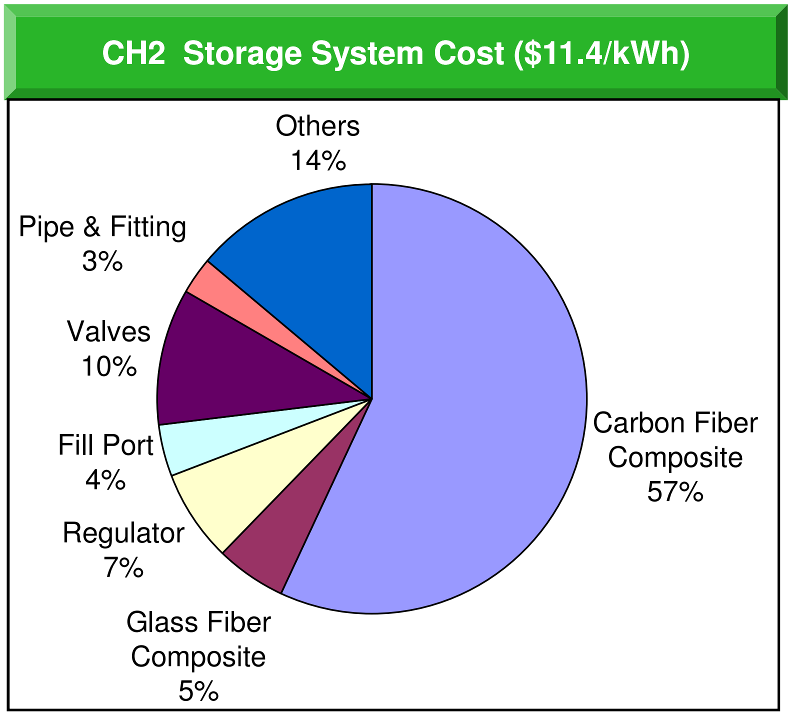
The assumptions for the hydrogen storage tank design were based on the literature review and third-party discussions.

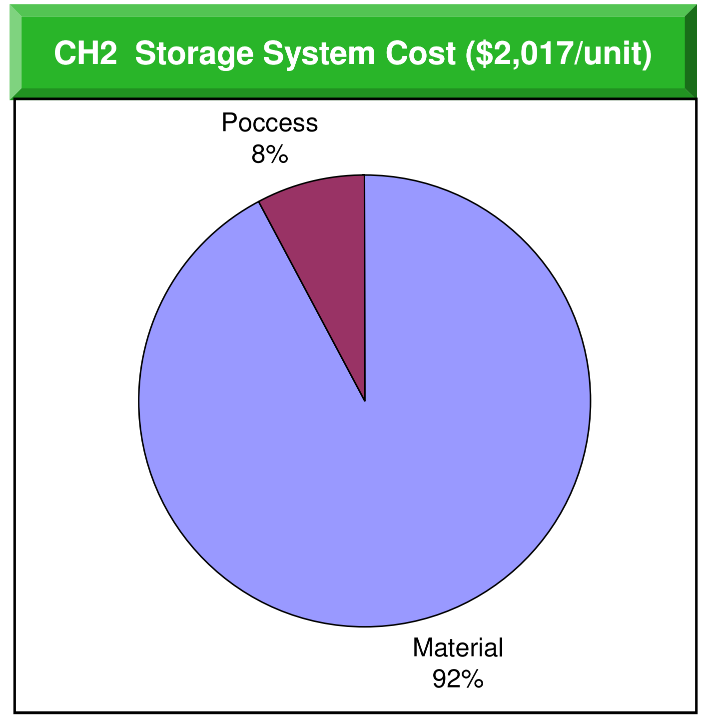
Stack Components	Unit	Current System	Comments
Production volume	systems/year	500,000	High Volume
Usable Hydrogen	Kg	5.6	
Tank Type		IV	With HDPE liner
Tank Pressure	PSI	5,000	
# of Tanks	Per System	1	
Safety Factor		2.25	
Tank Length/Diameter Ratio		3:1	
Carbon Fiber Type		Toray T700S	
Carbon Fiber Cost	$/lbs	12	
Carbon Fiber vs. Resin Ratio		0.68:0.32	Weight
Carbon Fiber Translational Strength Factor		81.5%	
Damage Resistant Outer Layer Material		S-Glass	Could be replaced by cheaper E-glass
S-Glass Cost	$/lbs	7	
Impact Resistant End Dome Material		Rigid Foam	
Rigid Foam Cost	$/kg	3	
Liner Material		HDPE	
Liner Thickness	Inch	1/4	
In Tank Regulator Cost	$/unit	150	

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



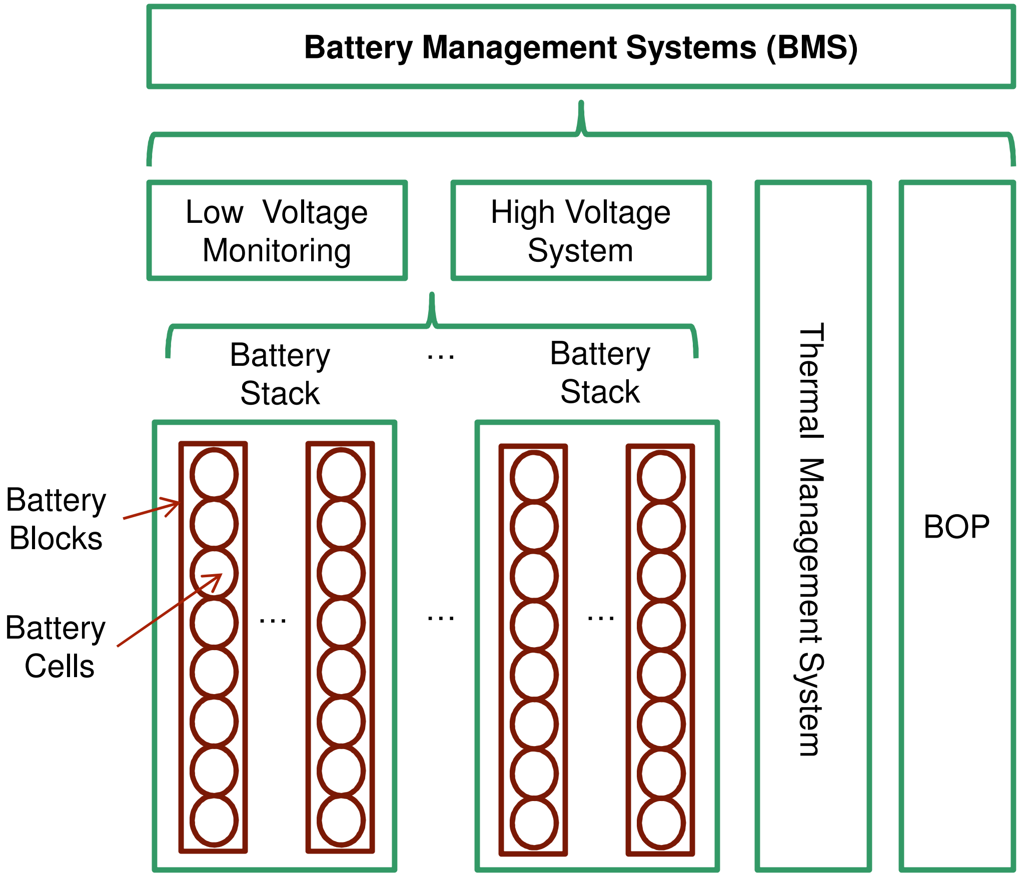
Material costs were a major cost driver. Cost reduction efforts need to focus on reducing material unit costs and weight.





In the 5,000 PSI baseline system, the carbon fiber layer is the dominant cost contributor.

A lithium-ion battery pack was designed to drive a mid-sized vehicles(~1,600 kg) for approximately 35 miles without using the fuel cell.



Lithium-Ion Battery Pack Schematic

Key Parameters

System
- Energy Storage Capacity: 9 kWh Usable
- Percent SOC: 70%
- Fade: 20%

Cell
- Cell Format: Cylindrical Cell
- Cathode Active Material: Manganese Spinel
- Anode Active Material: Graphite

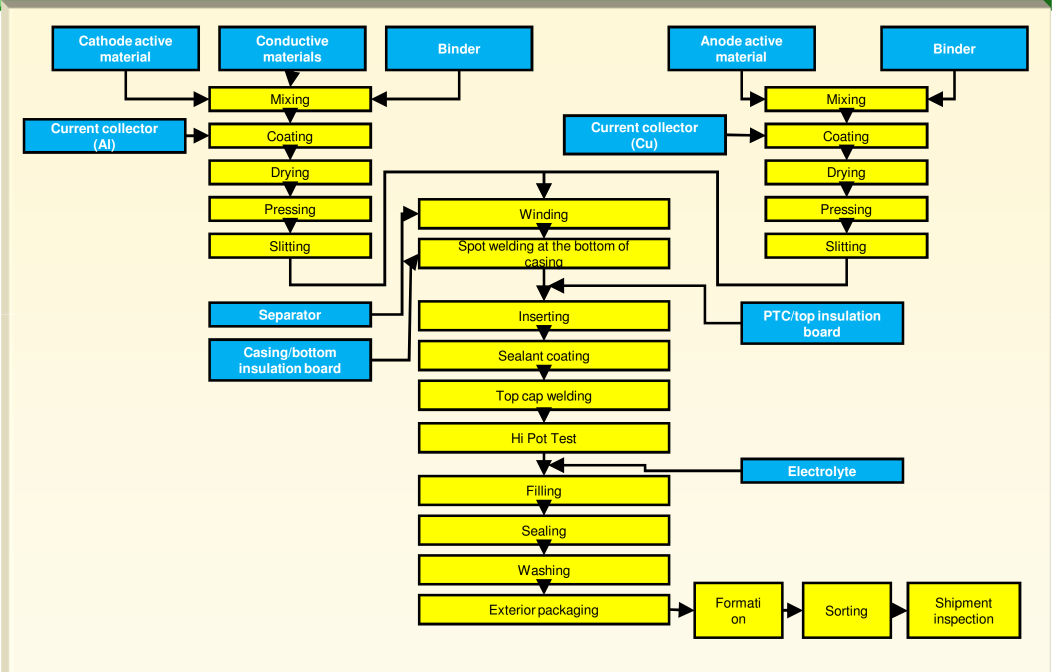
The battery blocks were repeat units containing battery cells and were used to assemble different size battery stacks.

The assumptions for the lithium-ion battery pack design were based on the literature review and third-party discussions.

Stack Components	Unit	Current System	Comments
Production volume	systems/year	500,000	
Gross Energy Storage Capacity	kWh	16	Applied SOC and Fade
Usable Energy Storage Capacity	kWh	9	
Percentage SOC	%	70	
Fade in Life	%	20	
Drive All Electric Range	Mile	~35	
Cell Type		Cylindrical Cell	
Anode Active Material		Graphite (MCMB 6-28)	
Cathode Active Material		$LiMn_2O_4$	
Electrolyte Material		$LiPF_6$	
Anode Current Collector Material		Cu	
Cathode Current Collector Material		Al	
Separator		Tri-layer PP/PE/PP	

A vertically integrated manufacturing process was assumed for the four-level battery pack fabrication: cell, block, stack, and pack.

Cell Production[1]



Block Assembly

- Cells
- Bus Bars
- Block shells

Stack Assembly

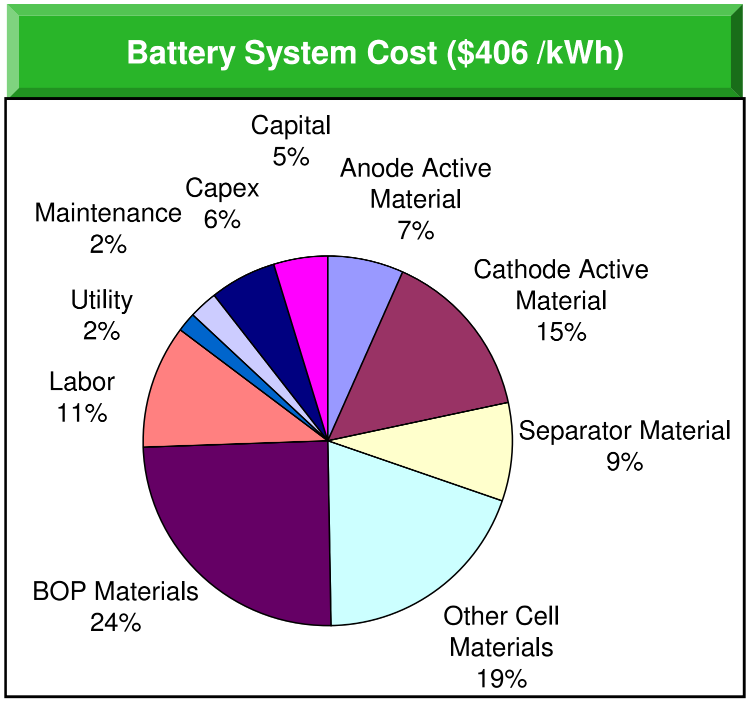
- Blocks
- Bus Bars
- Stack Shells

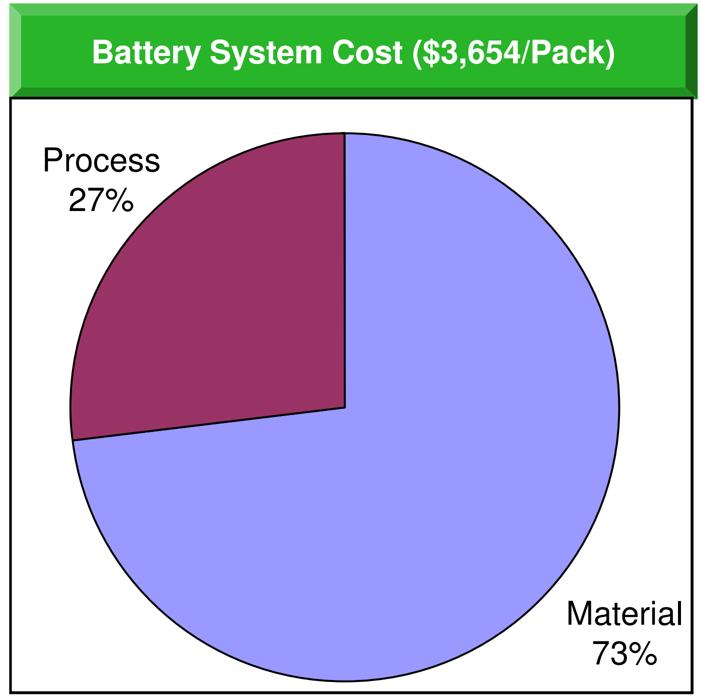
Pack Assembly

- Stacks
- Thermal Management
- Low Voltage Electric System
- High Voltage Electric System
- packaging

1. B., Barnett, Y. Yang, et ai. “PHEV Battery Cost Assessment, PHEV Battery Costing Phase II”, 2009 DOE Hydrogen Program Annual Merit Review, Arlington, VA

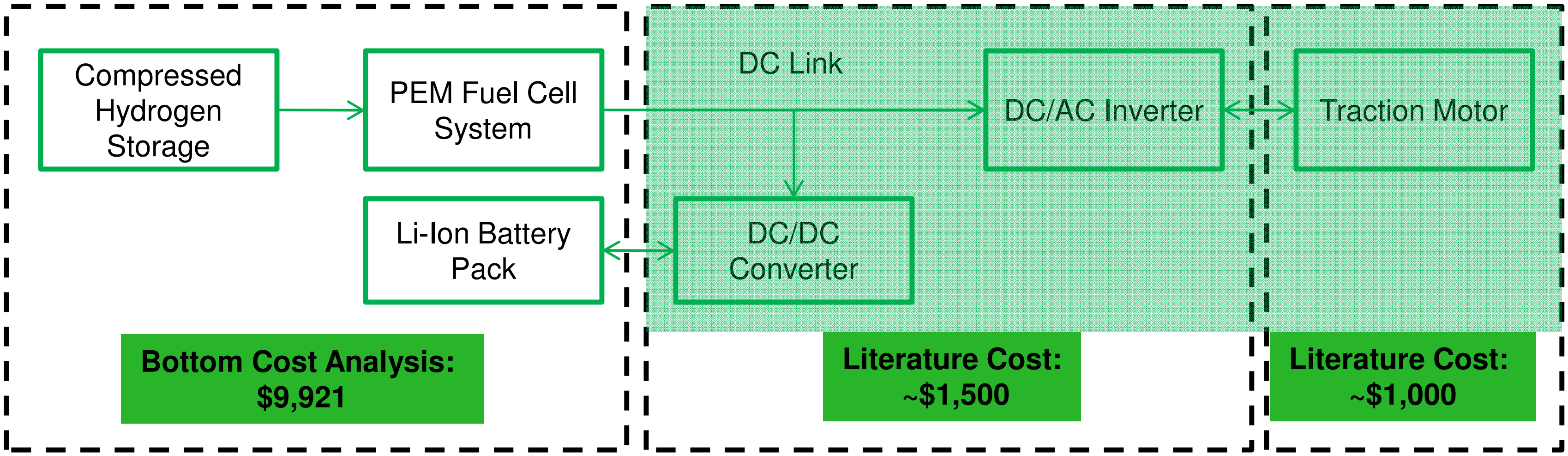
The lithium-ion battery system cost $406 /kWh. Of that, the material costs were approximately 70% and the process costs approximately 30%.



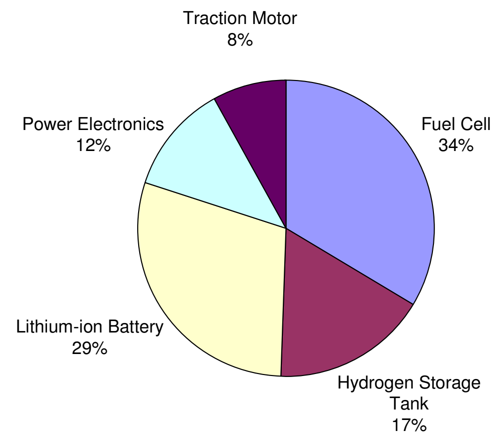


The lithium-ion battery system cost $3,654 per pack.

The PEM fuel cell, on-board hydrogen storage, and lithium-ion battery pack cost $9,921 per system at mass production volume.



Components	Unit Cost	System Cost
Fuel Cell	$65 /kW	$4,160
Hydrogen Storage Tank	$11.4 /kWh	$2,107
Lithium-ion Battery	$406/kWh	$3,654
Sub-total		**$9,921**
Power Electronics	-	$1,500
Traction Motor	-	$1,000
Total		**$12,421**



The complete PEM fuel cell/lithium-ion battery hybrid power chain cost $12,421 per system.

The due diligence was preliminary. The following actions are needed to improve the current work:

- More analysis needs to be done, such as on power electronics, the traction motor, system modeling, sensitivity, and life cycles.
- Feedback from system integrators.
- Communication with component suppliers and equipment suppliers.
- Possible funding opportunities for the extended work.

Thank You!