AUSTIN POWER ENGINEERING

Manufacturing Cost Analysis of Fuel Cell Plug-in Hybrid Electric Vehicle and Full Battery Electric Vehicle

2012 Fuel Cell Seminar

Yong Yang

November, 2012

Austin Power Engineering LLC
2310 W 9th ST Unit 1
Austin, TX 78703
USA

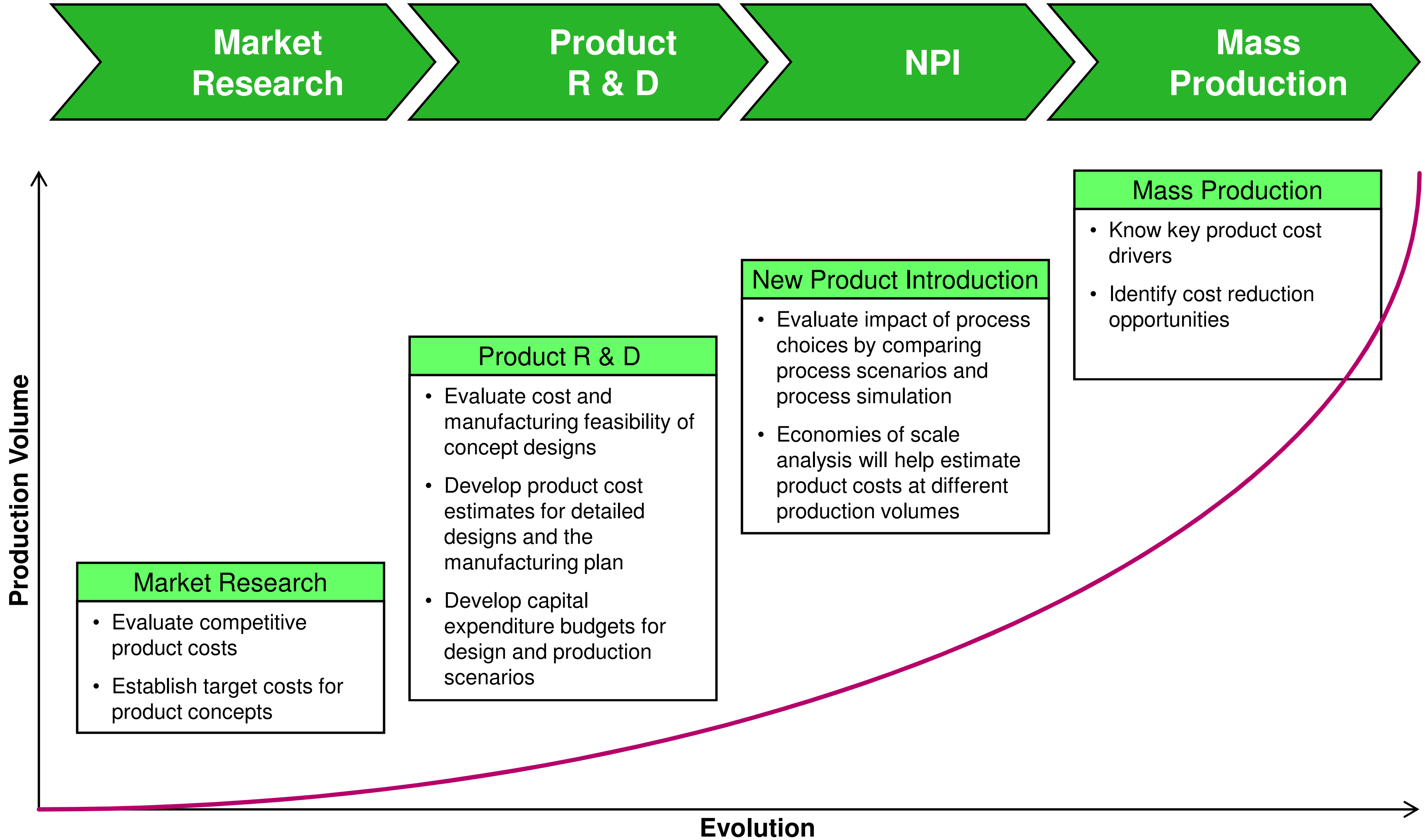
www.AUSTINPOWERENG.com
yang.yong@austinpowereng.com

The objective was to assess the cost implications of PEM fuel cell plug-in hybrid and full battery electric middle-size passenger vehicles using current technology at mass production volume (500,000 vehicles per year).

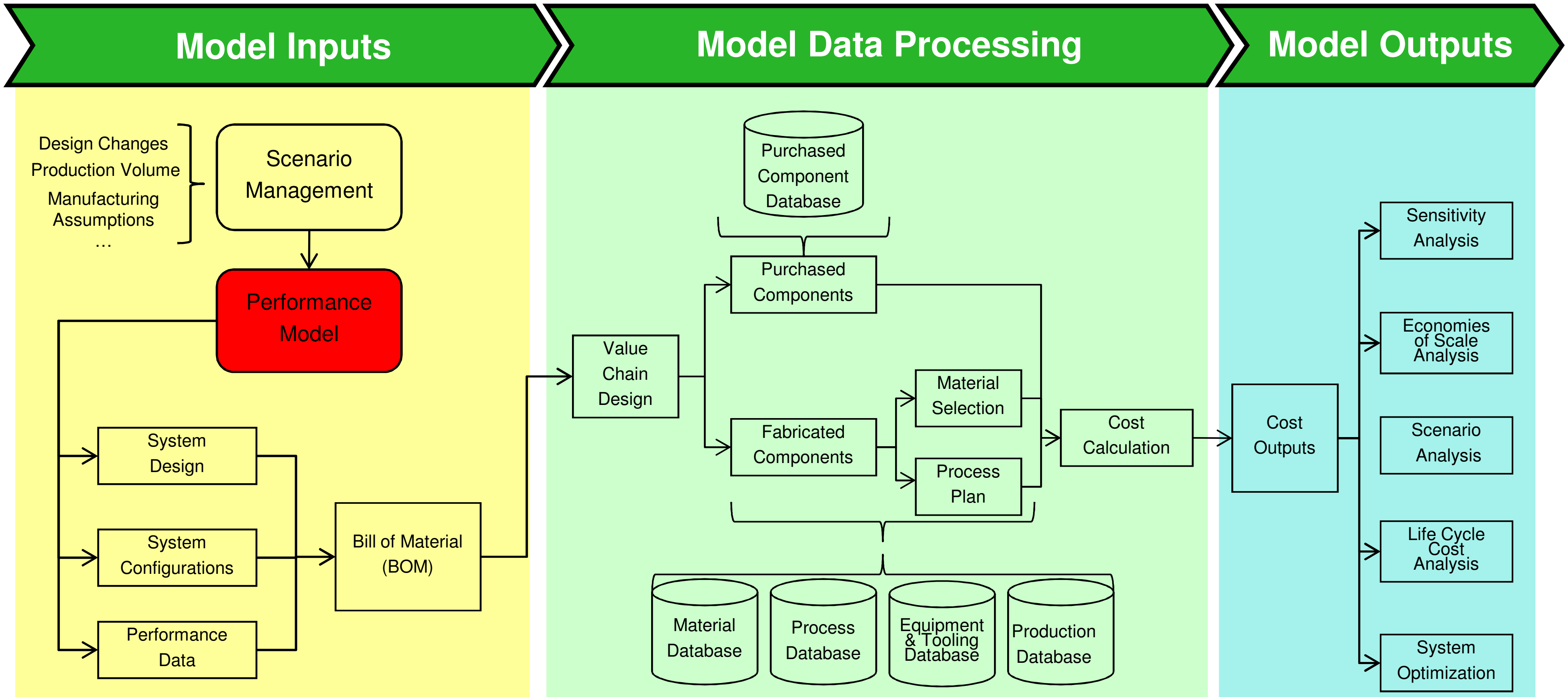
Project Objective	Contents	Results
PEM fuel cell /Lithium-ion battery hybrid power chain cost analysis	• 65kWe PEM fuel cell system • 5.6kg usable compressed H_2 tank • 16kWh lithium-ion battery pack	• *Cost of fuel cell, on-board hydrogen storage, and lithium-ion battery* • *Total cost of ownership of fuel cell plug-in hybrid and full battery electric vehicles* • *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*
Full electric /lithium-ion battery power chain cost analysis	•78kWh lithium-ion battery pack	
Total cost of ownership (TCO) analysis of fuel cell hybrid and full electric vehicles	• Fuel cell hybrid vehicle TCO • Full electric vehicle TCO • 3-year, 5-year, 10-year, and 15-year TCO	

Total costs of ownership for mid-size passenger vehicles using PEM fuel cell hybrid and full electric power chains were evaluated.

A technical cost model can be applied to the product's entire life cycle.

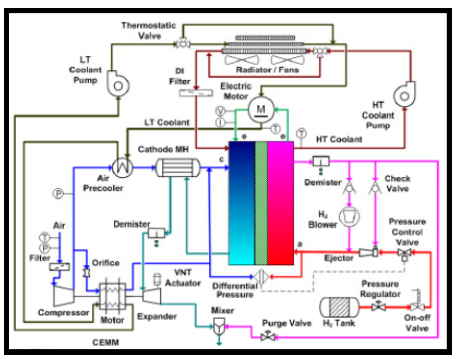


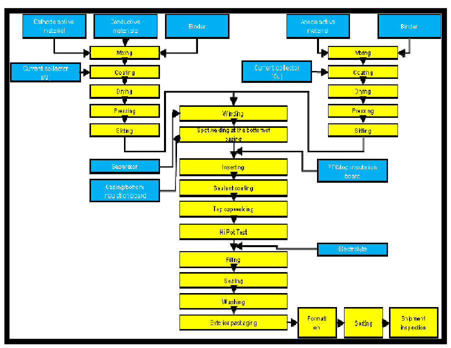
Combining performance and cost models will easily generate cost results, even when varying the design inputs.

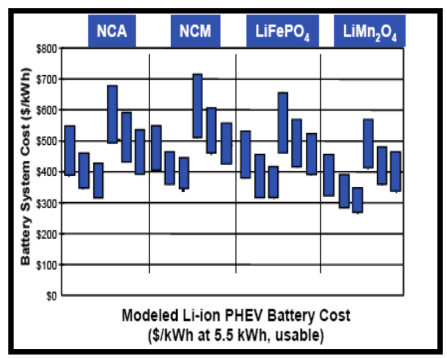


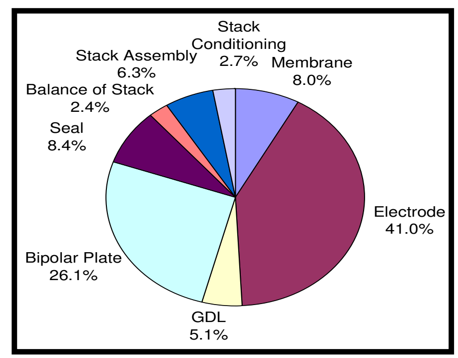
This approach has been used successfully for estimating the cost of various technologies for commercial clients and the DOE.

Technology Assessment	Manufacturing Cost Model	Scenario Analyses	Verification & Validation
• Literature research • Definition of system and component diagrams • Size components • Develop bill-of-materials (BOM)	• Define system value chain • Quote off-shelve parts and materials • Select materials • Develop processes • Assembly bottom-up cost model •Develop baseline costs	• Technology scenarios • Sensitivity analysis • Economies of Scale • Supply chain & manufacturing system optimization • Life cycle cost analysis	• Cost model internal verification reviews • Discussion with technical developers • Presentations to project and industrial partners • Audition by independent reviewers

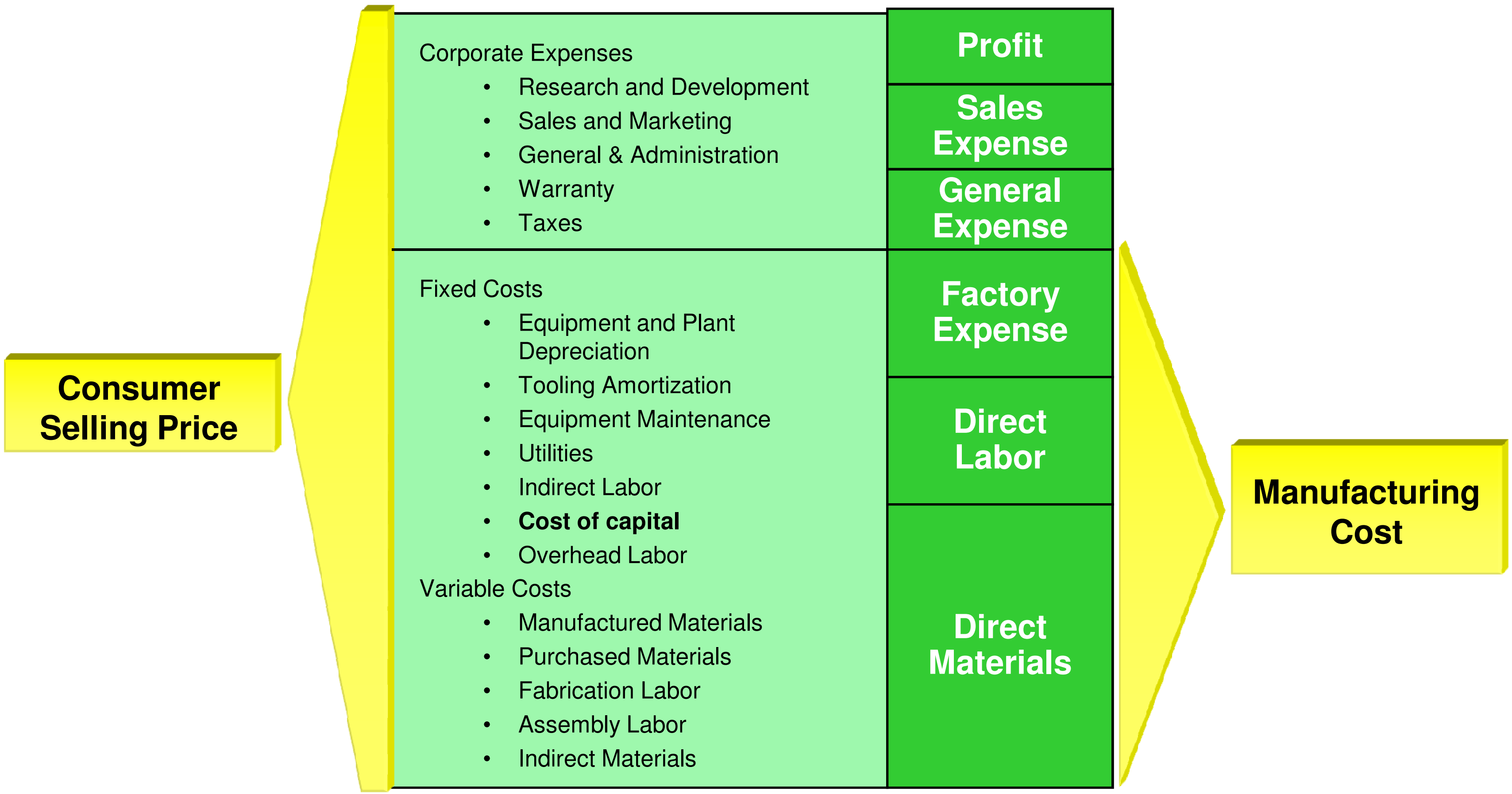








Austin Power Engineering’s manufacturing cost models can be used to determine a fully loaded selling price to consumers at high or low volumes.

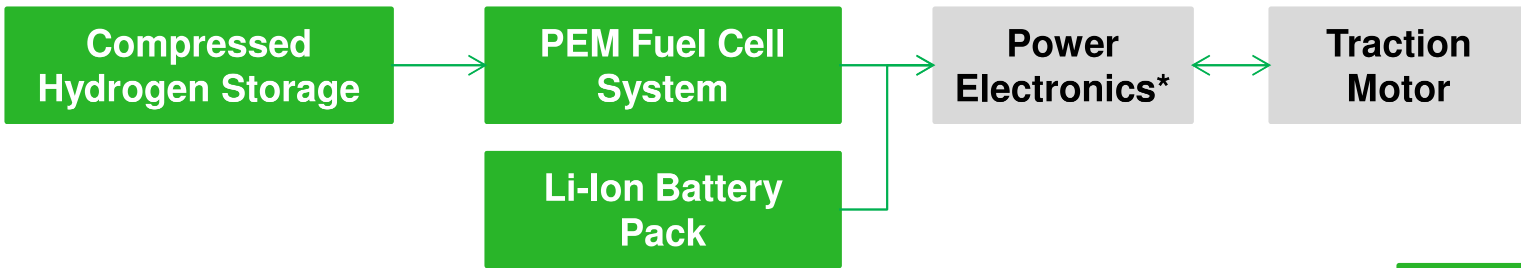


We assume 100% financing with an annual discount rate of 10%, a 10-year equipment life, and a 25-year building life.

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

Specification	PEMFC Plug Hybrid Vehicle	Full Electric Vehicle
Glider	Middle size passenger vehicle	Middle size passenger vehicle
Fuel cell system	65 kWe Net PEM fuel cell system	N/A
Hydrogen tank	5.6 Kg usable H2	N/A
Battery pack	16kWh total energy Lithium-ion battery pack (~40 miles w/o FC)	78kWh total energy lithium-ion battery pack
Traction motor	120 kW AC	120 kW AC
Power electronics	• Battery charger • Main inverter • DC/DC converter • Auxiliary inverter, etc	•Battery charger • Main inverter • DC/DC converter • Auxiliary inverter, etc
Range	350 miles	200miles

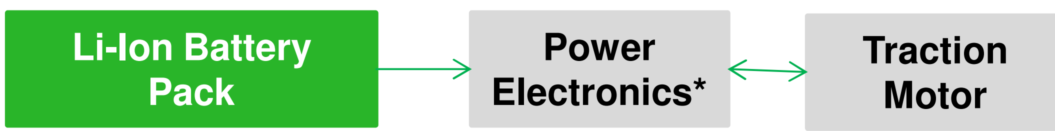
Power electronics and traction motor manufacturing cost will be evaluated later.



Fuel Cell Hybrid Electric Vehicle Power Chain

Bottom-up

Reference

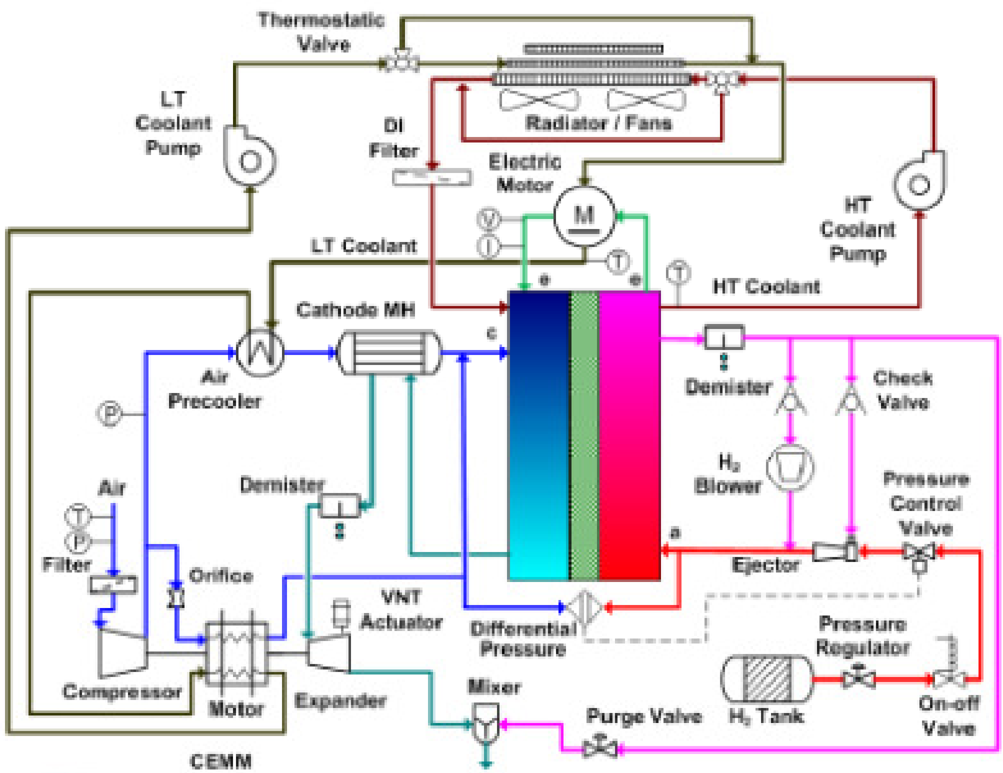


Full Electric Vehicle Power Chain

* Include battery charger, main inverter, DC/DC converter and auxiliary inverter, etc.

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 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 ^oC, 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.	$1,475	This 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 $1,475/tr.oz. for the baseline, which was the average Pt price this year.

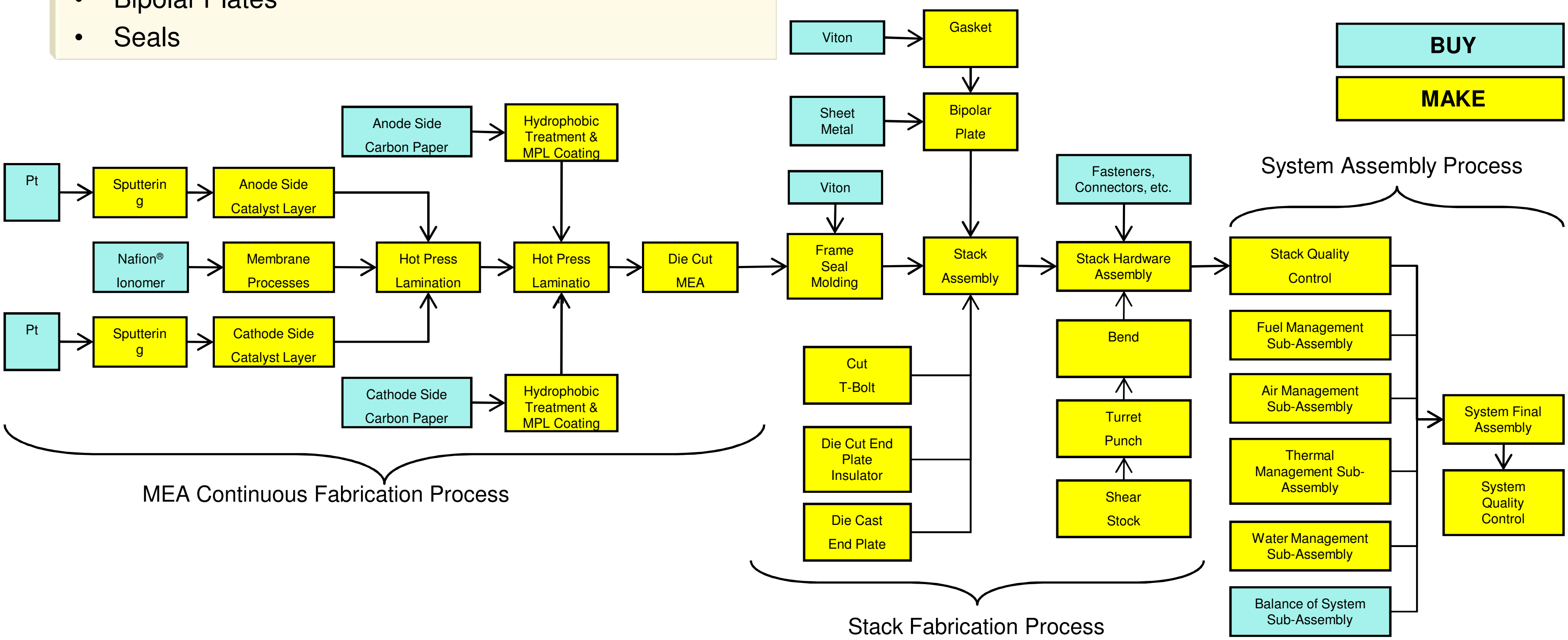
We used a vertically integrated approach to determine the mass production volume manufacturing cost for major stack and BOP components.

Major Stack Components

- Reinforced Membrane
- 3M NSTFC Type Electrodes
- Gas Diffusion Layer (GDL) with MPL Layers
- Membrane Electrode Assembly (MEA)
- Bipolar Plates
- Seals

Major BOP Components

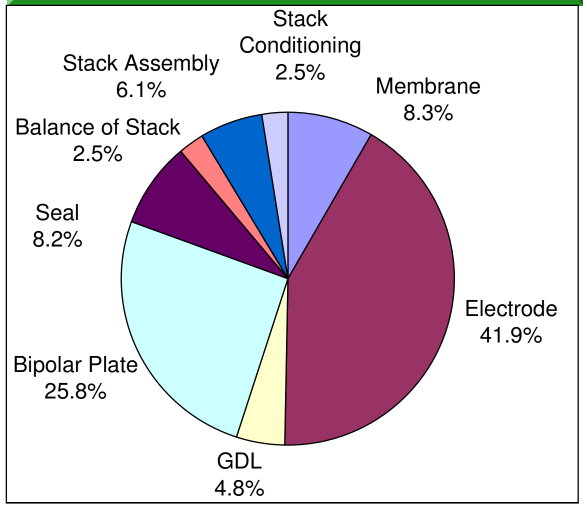
- Micro-Channel Radiators (HT, LT)
- Cathode Planar Membrane Humidifier (MH)
- Compressor-Expander-Motor Module (CEM)
- H_2 Blower



A 65 kW_{net} PEM fuel cell stack cost $26/kW. Electrodes, bipolar plates, and membranes were the top three cost drivers.

Stack Components	2012 Stack Manufacturing Cost ($/kW)	Comments
Membrane	2.14	PFSA ionomer ($80/lb)
Electrodes	10.77	3M NSTFC
GDL	1.23	No-Woven carbon paper
Seals	2.10	Viton
Bipolar plates	6.63	Nitrided metallic plates
Balance of stack	0.64	Manifold, end plates, current collectors, insulators, tie bolts, etc.
Stack assembly[1]	1.58	Robotic assembly
Stack conditioning	0.65	2 hours
Total stack[2]	25.7	

65 kW_{net} PEM Fuel Cell Stack Cost ($25.7/$kW_{net}$)

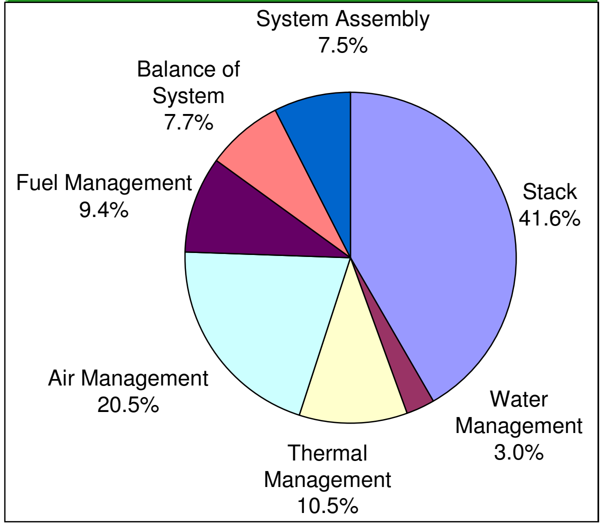


1. Stack assembly cost category included MEA assembly and stack QC; QC included visual inspection, and leak tests for fuel, air, and coolant loops.
2. Results may not appear to calculate due to rounding of the component cost results.

A 65 kW_{net} PEM fuel cell system cost $62/kW. Stack, air management, and thermal management were the top three cost drivers.

System Components	2012 System Manufacturing Cost ($/kW)	Comments
Stack	**25.7**	
Water management	1.8	Cathode side humidifier, etc.
Thermal management	6.5	HX, coolant pump, etc.
Fuel management	5.8	H2 pump, etc.
Air management	12.7	CEM, etc.
Balance of system	4.8	Sensors, controls, wire harness, piping, etc.
System assembly	4.6	
Total system[1, 2]	**62.0**	

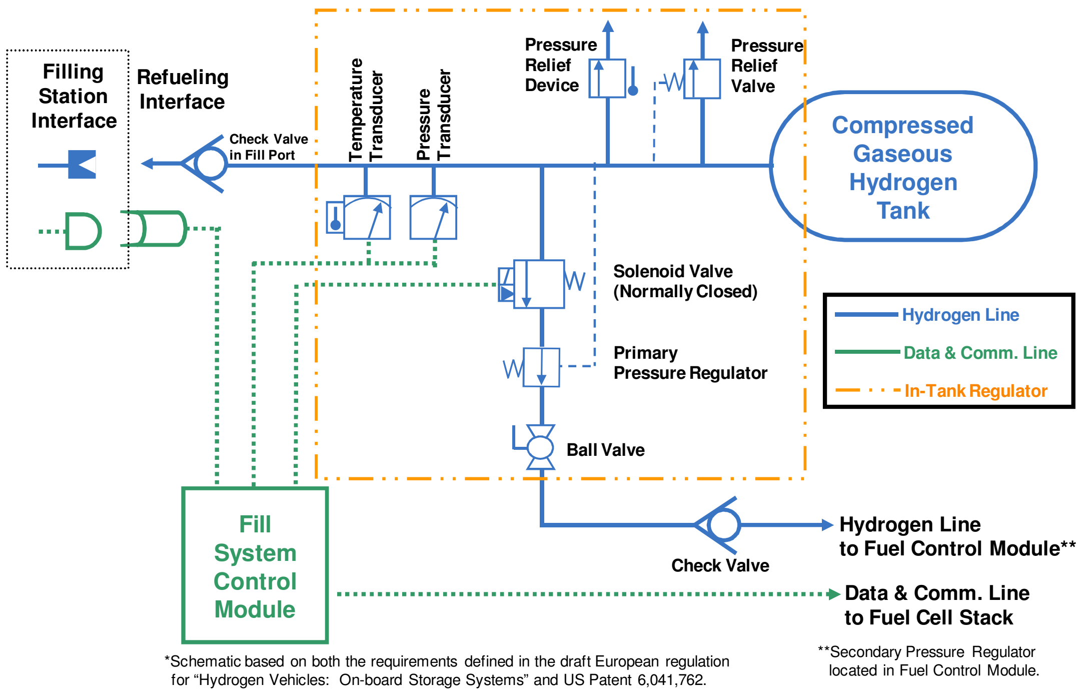
65 kW_{net} PEM Fuel Cell System Cost ($4,030/system)



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.

The 65 kW_{net} direct hydrogen PEM fuel cell system cost $4,030 at the mass production volume.

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]

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

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

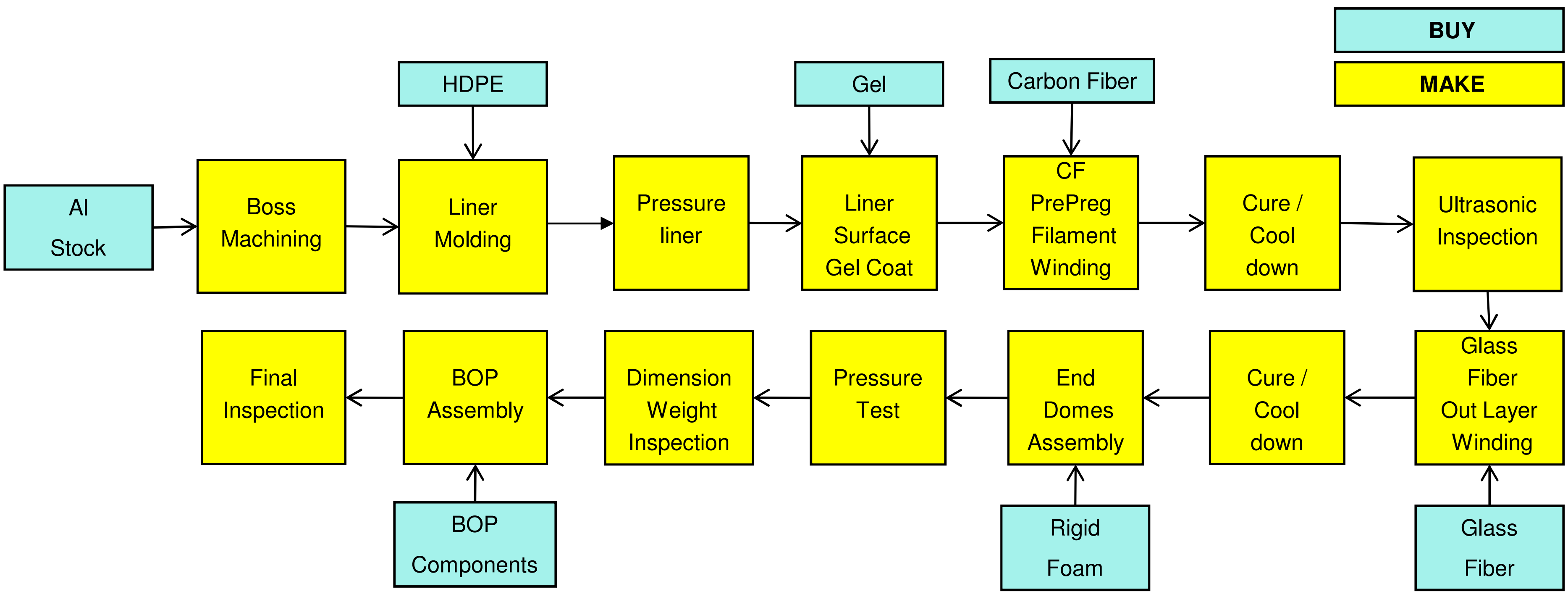
The single tank design had a usable hydrogen storage capacity of 5.6 kg.

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	
Recoverable H2 in the tank		IV	With HDPE liner
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.

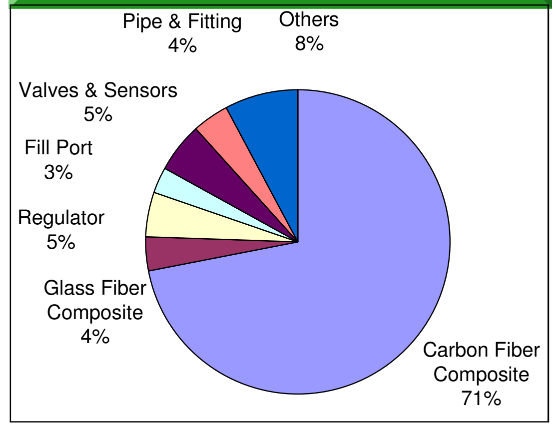
Major Tank Components	Major BOP Components
• Aluminum End Boss • HDPE liner • Carbon fiber composite layer • Glass fiber composite layer • End domes (rigid foam)	• In-tank primary pressure regulator • Valves & sensors • Filling interface • Pressure release devices • Piping & fitting



In the 5,000 PSI baseline system, the carbon fiber composite layer was the dominant cost driver.

System Components	2012 System Manufacturing Cost ($/kWh)	Comments
Hydrogen	0.09	5.9 kg H2
Pressure Tank	12.69	Pre-preg carbon fiber cost $36/kg
- Liner	- 0.09	
- Carbon fiber layer	- 11.79	
- Glass fiber layer	- 0.59	
- Foam	- 0.22	
Primary pressure regulator	0.80	In-tank design
Valves & sensors	0.86	4 valves, 1 temperature sensor, 1 pressure sensor
Fill port	0.43	
Fittings, piping, safety device, etc.	0.64	Pressure relive valve, burst valve, etc.
Assembly & inspection	0.88	Including pressure test
Total system[2]	16.39	

CH2 Storage System Cost ($3,058/system)



The 5,000 PSI compressed hydrogen storage tank system cost $3,058 at the mass production volume.

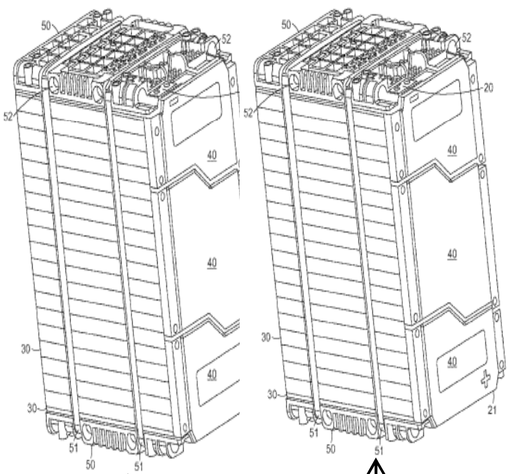
A lithium-ion battery pack was designed to drive a middle-sized vehicle approximately 40 miles without using the fuel cell.

Lithium-ion Battery Pack

Battery Management Systems (BMS)

- Low Voltage Monitoring
- High Voltage System

Battery Modules



Battery Cells[2] Battery Cells[2]

Thermal Management System

BOP

Key Parameters

System

- Energy storage capacity: 10 kWh usable
- Total energy capacity: 16kWh
- Percent SOC: 80%
- Fade: 20%

Cell

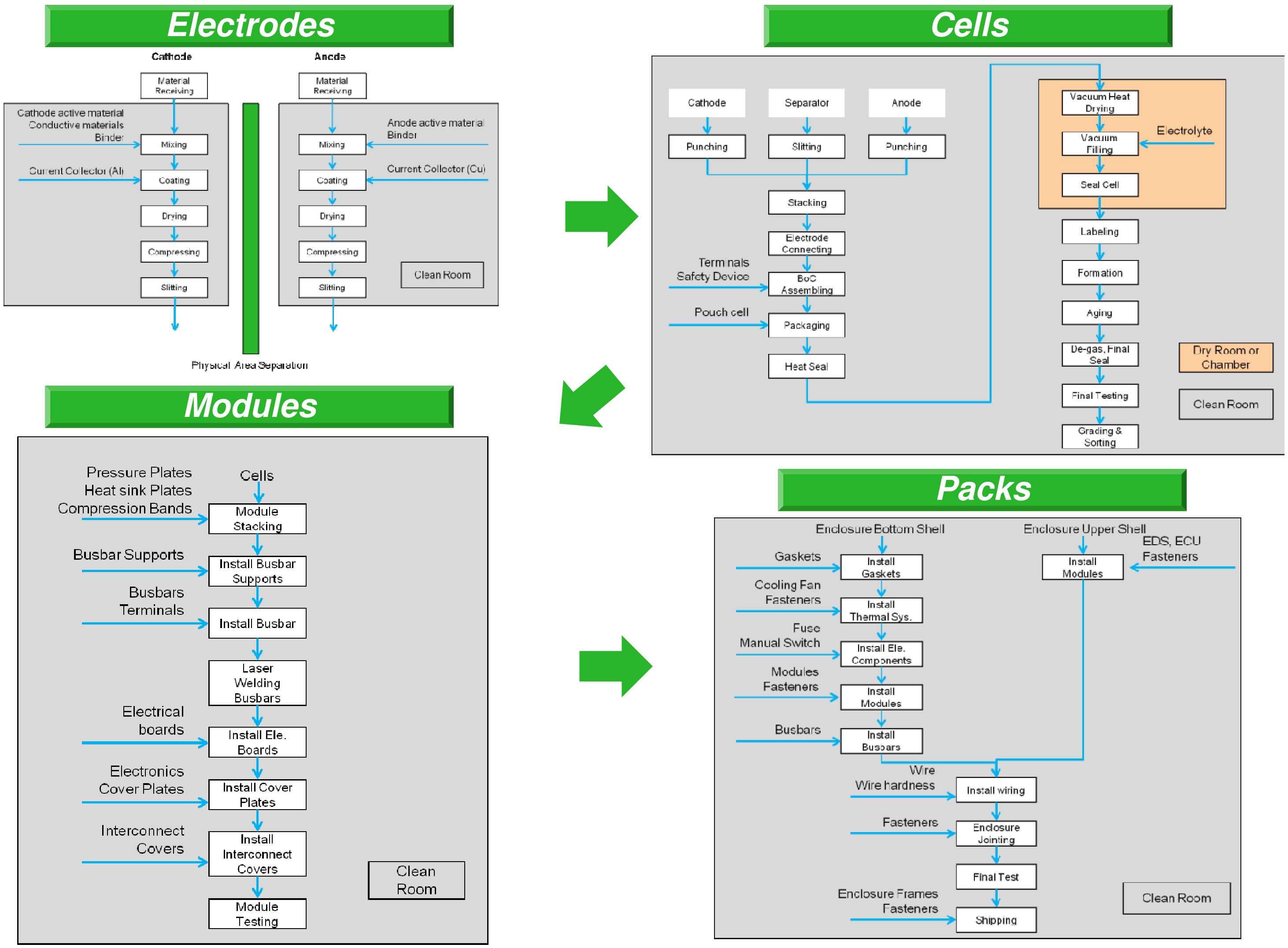
- Cell format: Pouch cell
- Cathode active Material: manganese spinel
- Anode active material: graphite

1. US patent 20100247999
2. US patent 20090169990

The assumptions for the 16kWh lithium-ion battery pack design were based on the literature review and third-party discussions.

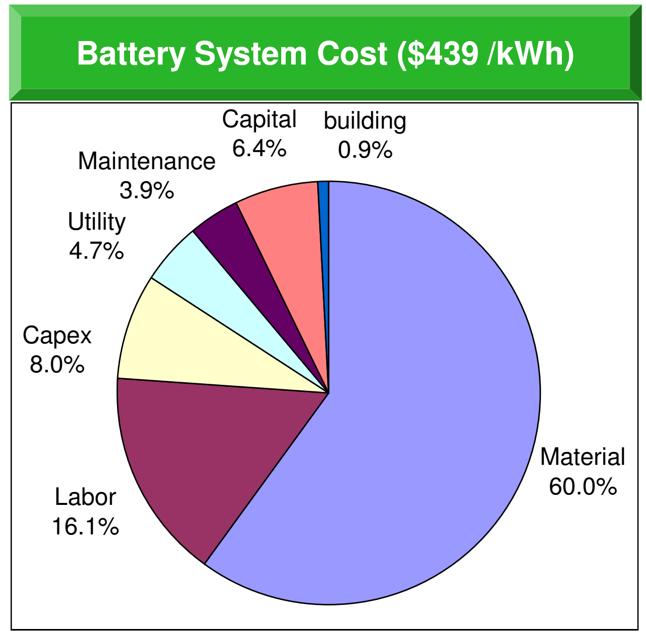
Stack Components	Unit	Current System	Comments
Production volume	systems/year	500,000	
Gross Energy Storage Capacity	kWh	16	Applied SOC and Fade
Usable Energy Storage Capacity	kWh	10	
Percentage SOC	%	80	
Fade in Life	%	20	
Drive All Electric Range	Mile	~40	
Cell Type		Pouch cell	20 Ah / 65W
Anode Active 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: electrode, cell, module, and pack.



The lithium-ion battery system cost $439 /kWh. Of that, the material costs were approximately 60% and the process costs were approximately 40%.

Cost Category	Cell Cost ($/cell)	Module Cost ($/module)	Pack Cost ($/pack)
Material	6.44	277.36	2,699
Labor	1.51	77.25	724
Equipment & tooling	0.79	25.96	210
Utility	0.65	21.74	176
Maintenance	1.33	44.68	361
Capital cost	1.12	35.95	288
Building	0.14	4.84	40
Total	**11.98**	**487.79**	**4,497**
Total ($/kWh)*	**288**	**366**	**439**



* Based on usable energy (16 kWh x 0.8 x0.8 = 10 /kWh)

The 16 kWh lithium-ion battery system cost $4,497 per pack at the mass production volume.

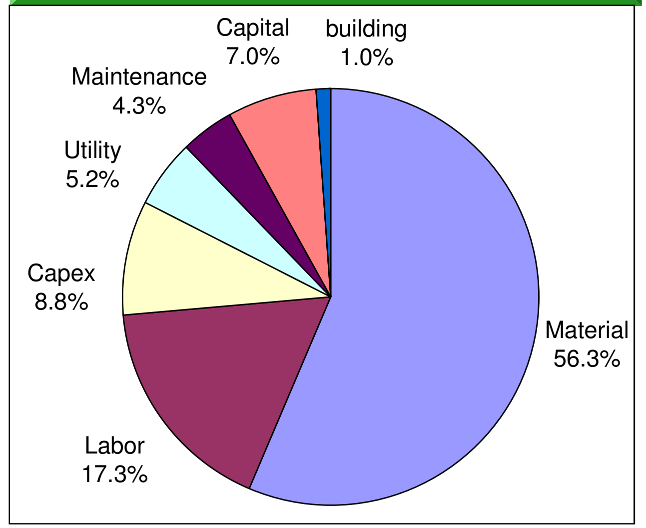
Assumptions for the 78kWh lithium-ion battery pack design were based on the literature review and third-party discussions.

Stack Components	Unit	Current System	Comments
Production volume	systems/year	500,000	
Gross Energy Storage Capacity	kWh	78	Applied SOC and Fade
Usable Energy Storage Capacity	kWh	50	
Percentage SOC	%	80	
Fade in Life	%	20	
Drive All Electric Range	Mile	~200	
Cell Type		Pouch cell	20 Ah / 65W
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	

The lithium-ion battery system cost $390 /kWh. Of that, the material costs were approximately 56% and the process costs were approximately 44%.

Cost Category	Cell Cost ($/cell)	Module Cost ($/module)	Pack Cost ($/pack)
Material	5.79	250.25	10,958
Labor	1.48	76.09	3,375
Equipment & tooling	0.79	25.90	1,017
Utility	0.63	21.39	841
Maintenance	1.30	43.90	1,722
Capital cost	1.10	35.06	1367
Building	0.14	4.79	190
Total	**11.23**	**457.38**	**19,470**
Total ($/kWh)*	**270**	**344**	**390**

Battery System Cost ($390 /kWh)



* Based on usable energy (78 kWh x 0.8 x0.8 = 50 /kWh)

The 78 kWh lithium-ion battery system cost $19,470 per pack at the mass production volume.

PEM fuel cell plug-in hybrid vehicle purchase price was $30,113 and full battery electric vehicle purchase price was $41,625 at the mass production volume.

Component Category		PEMFC Plug Hybrid ($/unit)	Full Battery Electric ($/unit)	Comments
Glider	**Glider**	***7,000***	***7,000***	Mid-size passenger vehicle
Power Chain	**PEMFC**	4,030	N/A	Bottom-up costing
	H2 storage	3,058	N/A	Bottom-up costing
	Battery system	4,497	19,470	Bottom-up costing
	Traction motor[1]	1,200	1,200	Motor + controller + transmission
	Power electric[1]	840	840	Battery charger, main inverter, DC/DC converter, auxiliary inverter, etc
	Power chain sub-total	***13,625***	***22,760***	
Total vehicle manufacturing cost		**20,625**	**28,510**	
Markup[2]		**46%**	**46%**	Corporation cost & profit, dealer cost, shipping cost, tax
Purchase price for consumer		**30,113**	**41,625**	

1. The DOE advanced power electronics & electric motors (APEEM) team reported the power electronics cost $7/kW and the motor cost $10/kW in 2012.
1. Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers, EPA, 2009

Total cost of ownership (TCO) included the purchase price, financing cost, fuel cost, maintenance cost, and salvage value.

TCO = Purchase Price + Financing Cost + Fuel Cost + Maintenance Cost* - Salvage value

3 Year TCO	PEMFC Plug Hybrid Vehicle	Full Battery Electric Vehicle
Purchase Price	30,113	41,625
Financing cost	2,780	3,842
Fuel cost	4,376	1,055
Maintenance cost	3,892	4,135
Salvage Value	-131	-180
TCO	41,030	50,476

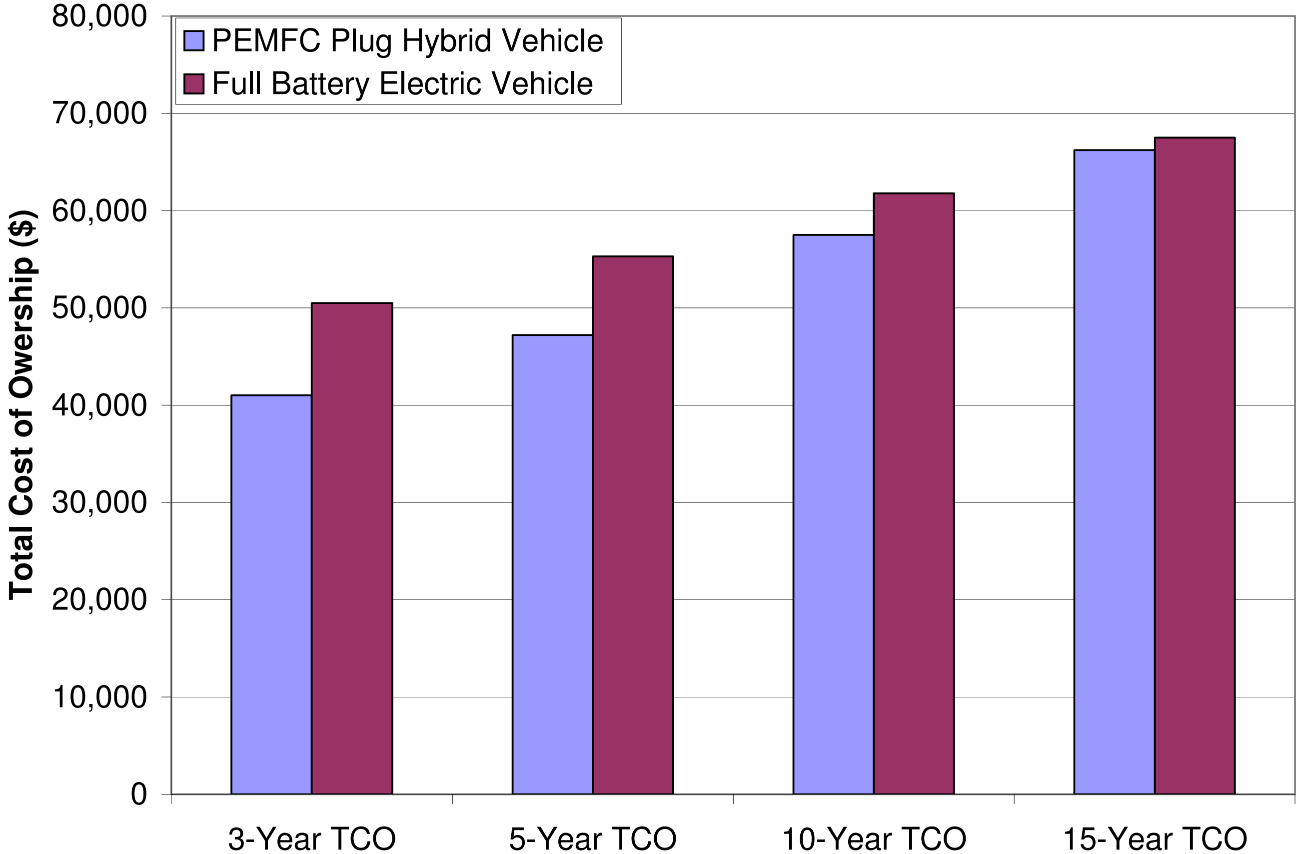
5 Year TCO	PEMFC Plug Hybrid Vehicle	Full Battery Electric Vehicle
Purchase Price	30,113	41,625
Financing cost	4,040	5,584
Fuel cost	6,956	1,677
Maintenance cost	6,187	6,573
Salvage Value	-118	-163
TCO	47,178	55,295

10 Year TCO	PEMFC Plug Hybrid Vehicle	Full Battery Electric Vehicle
Purchase Price	30,113	41,625
Financing cost	4,040	5,584
Fuel cost	12,405	2,990
Maintenance cost	11,033	11,721
Salvage Value	-91	-126
TCO	57,500	61,793

15 Year TCO	PEMFC Plug Hybrid Vehicle	Full Battery Electric Vehicle
Purchase Price	30,113	41,625
Financing cost	4,040	5,584
Fuel cost	16,675	4,018
Maintenance cost	15,437	16,362
Salvage Value	-71	-97
TCO	66,194	67,491

* Included property tax and insurance cost

PEMFC plug-in hybrid vehicle had a TCO advantage compared to a full battery electric vehicle, especially in the first 3~5 years.



* Polymer Fuel Cells – Cost reduction and market potential, Carbon Trust, Austin Power Engineering, et al. 2012

Consumers like to consider annual costs in a limited time when they make a purchase decision which is most likely in 3~5 years instead of 10~15 years*.

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

- More analysis items, such as power electronics, the traction motor, system modeling, and sensitivity
- Feedback from system integrators
- Communication with component suppliers and equipment suppliers
- Possible funding opportunities for the extended work

Thank You!