PEM Fuel Cell System Manufacturing Cost Analysis for Automotive Applications

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November 17, 2015

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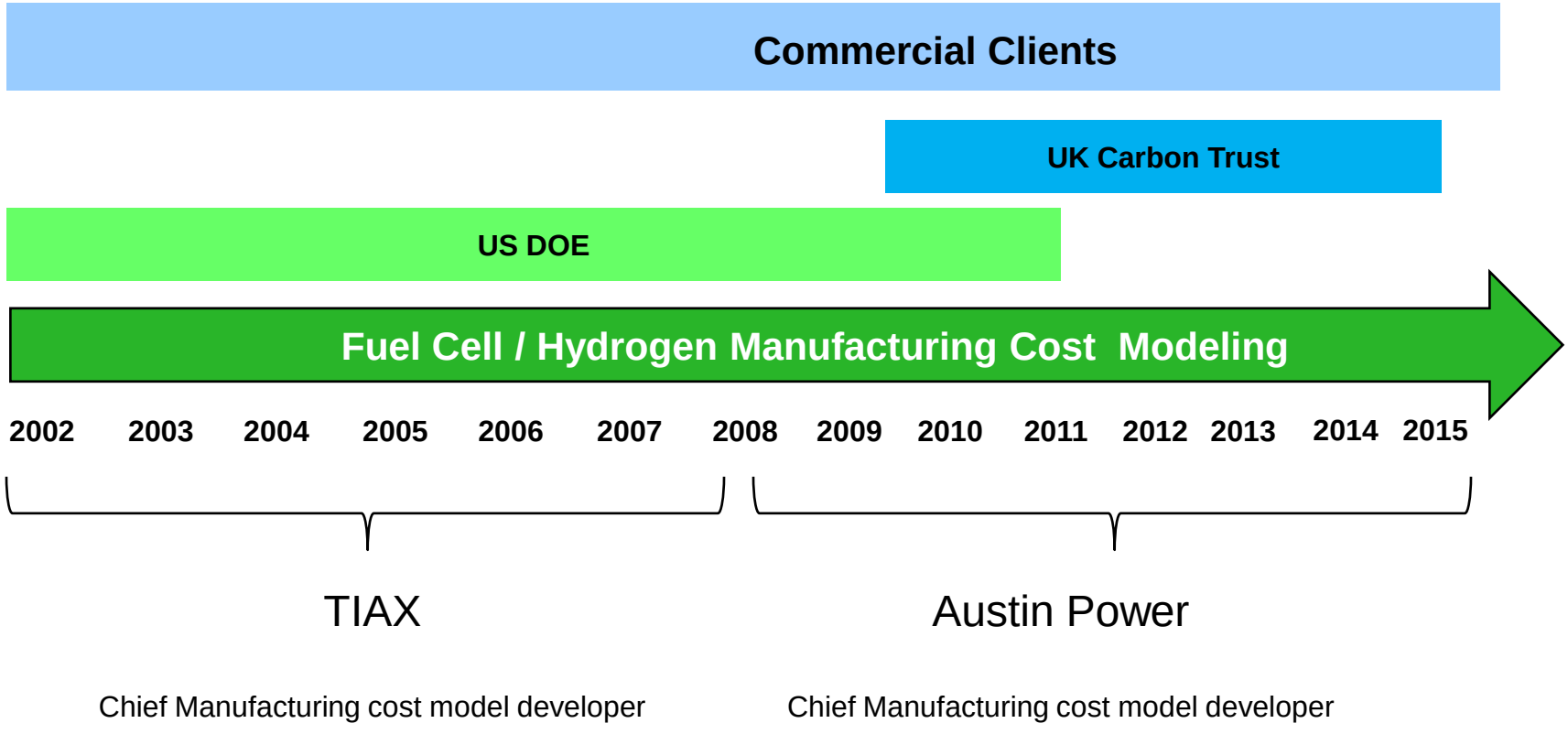
Have been working on fuel cell manufacturing cost modeling for US DOE, UK Carbon Trust, and commercial clients since 2002.



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

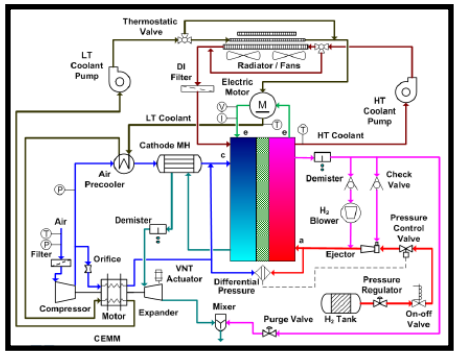
- Define system value chain
- Quote off-shelve parts and materials
- Select materials
- Develop processes
- Assembly bottom-up cost model
- Develop baseline costs

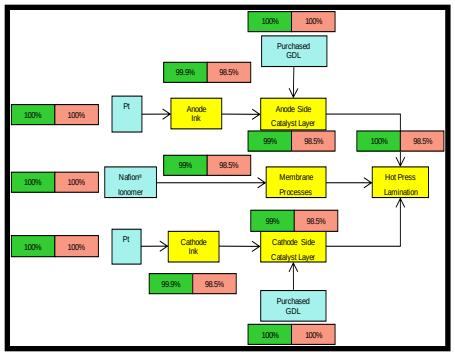
Scenario Analyses

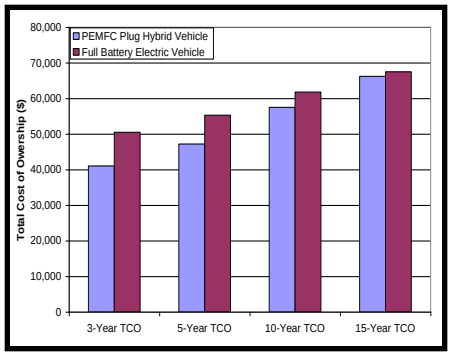
- Technology scenarios
- Sensitivity analysis
- Economies of Scale
- Supply chain & manufacturing system optimization
- Life cycle cost analysis

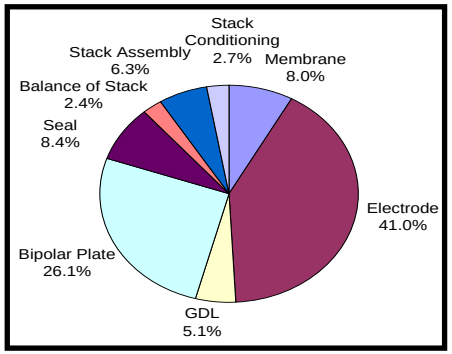
Verification & Validation

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



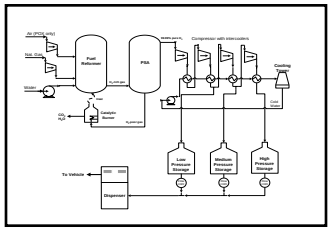






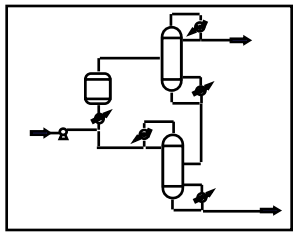
Combining performance and cost model will easily generate cost results, even when varying the design inputs.

Conceptual Design



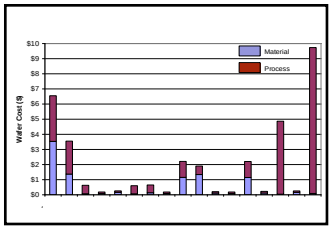
- System layout and equipment requirements

Process Simulation



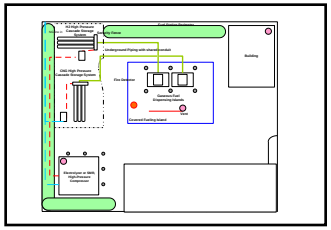
- Energy requirements
- Equipment size/ specs

Process Cost Calcs



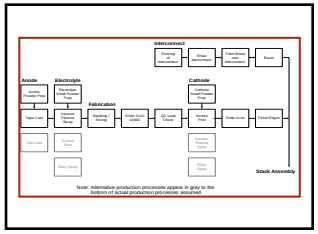
- Process cost
- Material cost

Site Plans



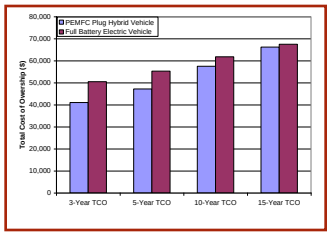
- Safety equipment, site prep, land costs

Capital Cost Estimates



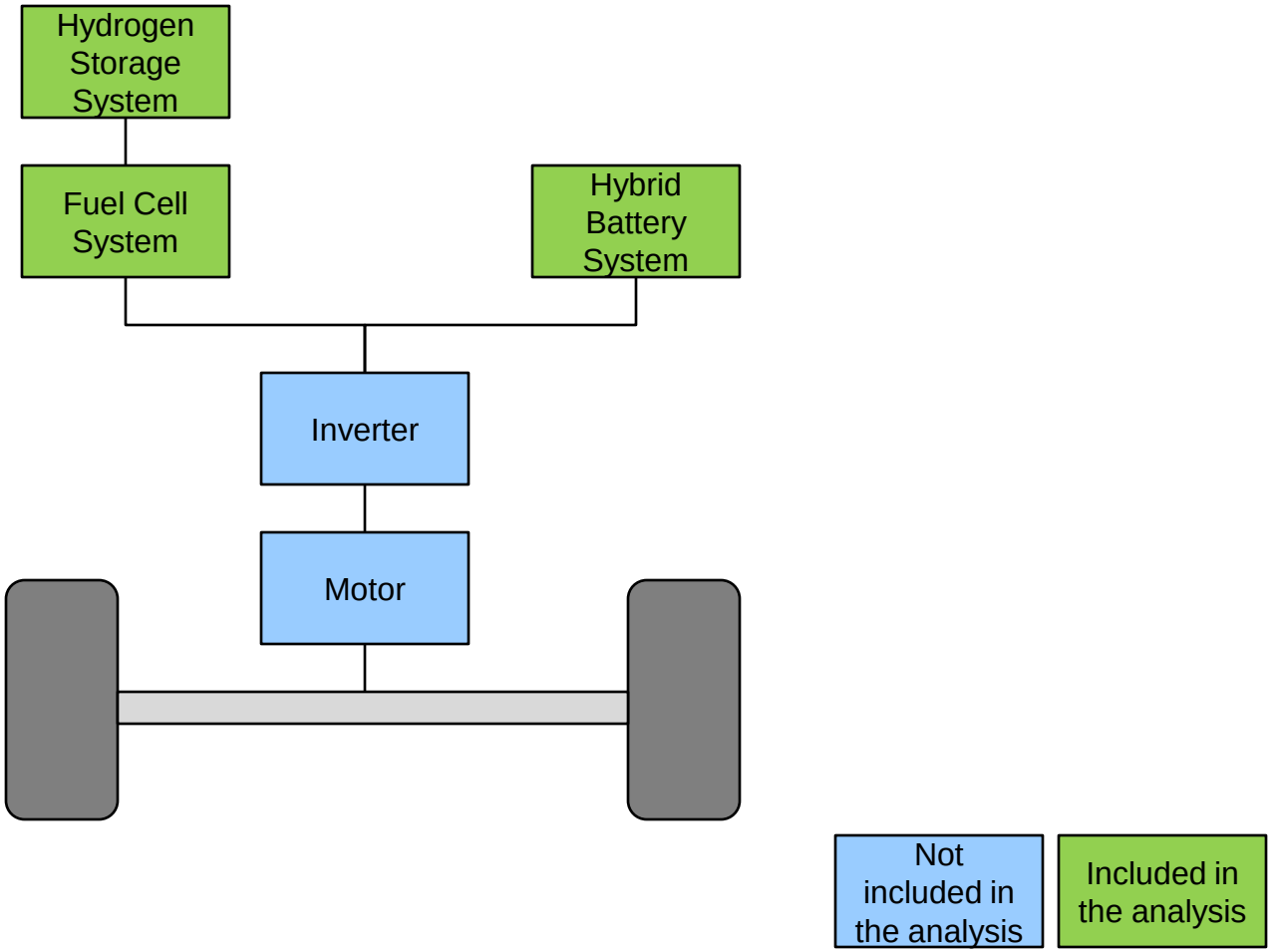
- High and low volume equipment costs

Product Costs



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

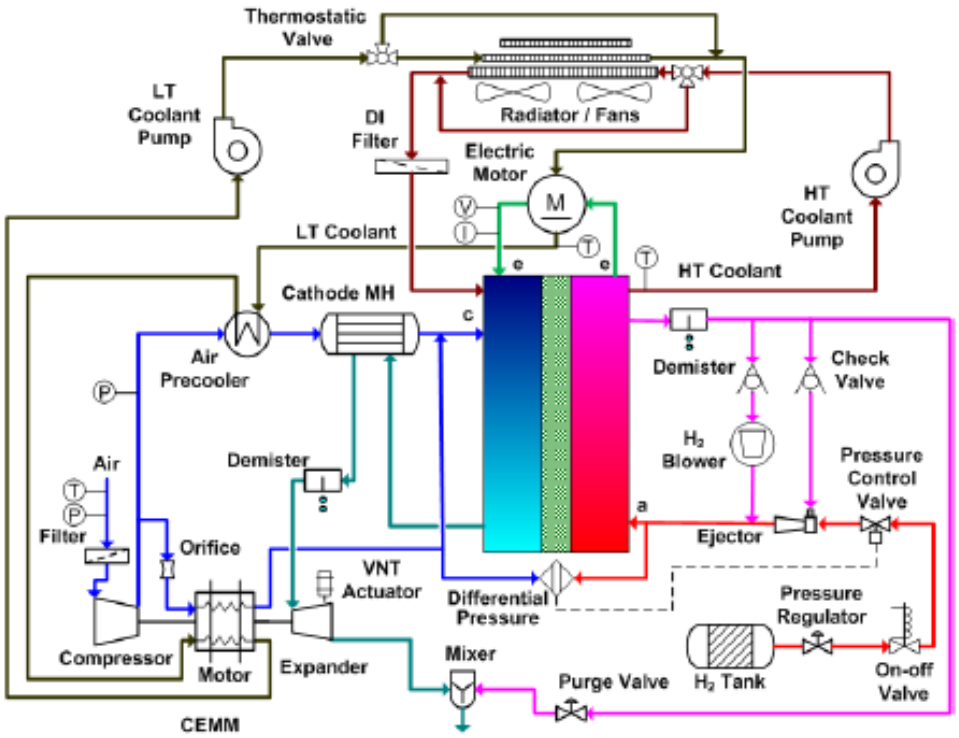
Conduct a bottom-up manufacturing cost analysis of a 80kW light-duty vehicle fuel cell power system which includes a fuel cell system, a hydrogen storage tank , and a hybrid NIMH battery pack.



We published various fuel cell vehicle powertrain configurations manufacturing cost analysis in the past years.

Specifications	2012 FCS	2013 FCS	2014 FCS	2015 FCS
PEM fuel cell system	*•65 kWe*	*•80 kWe*	*•80 kWe*	*•80 kWe*
On-board hydrogen storage	*-Compressed H2 -5,000 psi -Single tank -5.6 kg usable H2*	*-Compressed H2 -5,000 psi -Single tank -5.6 kg usable H2*	*-Cryo-compressed H2 -Single tank -10 kg usable H2*	*-Compressed H2 -10,000 psi -Two tanks -5.6 kg usable H2*
Hybrid battery pack	*-Li-ion battery -16 kWh*	*-Li-ion battery -1.2 kWh*	*-Li-ion battery -1.2 kWh*	*-NiMH battery -1.6 kWh*
Comments	*Plug-in hybrid fuel cell vehicle*	*hybrid fuel cell vehicle*	*hybrid fuel cell vehicle*	*hybrid fuel cell vehicle*

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: 834mW/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

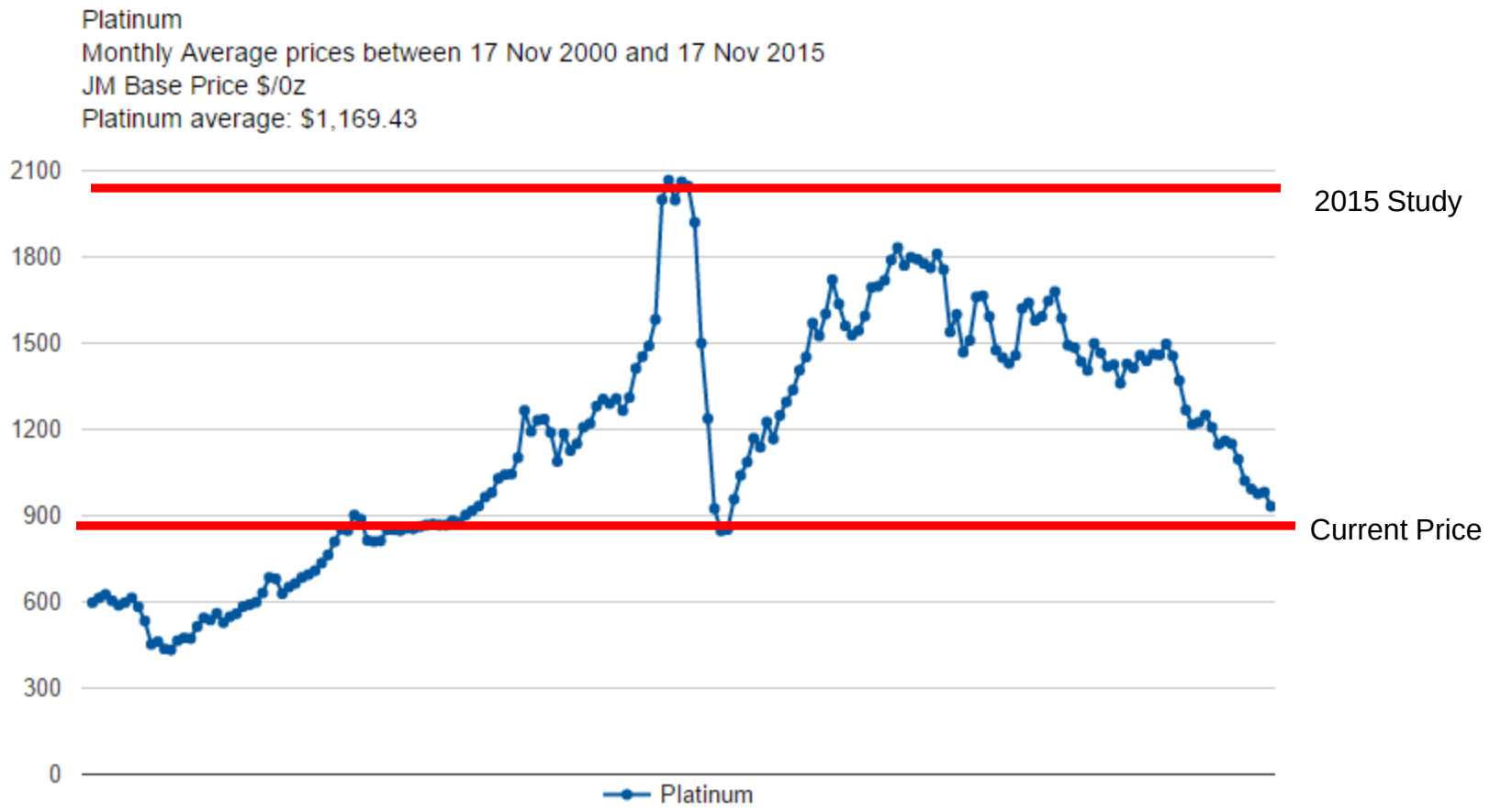
Thermal Management
- Micro-channel HX

Fuel Management
- Parallel ejectors

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

Stack Components	Unit	2012	2013	2014	2015
Production volume	systems/year	500,000	500,000	500,000	500,000
Stacks' net power	kW	65	80	80	80
Stacks' gross power	kW	72	88	89.4	88
Cell power density	mW/cm^2	930	984	692	834
Peak stack temp.	Degree C	90	87	92.3	100
Peak stack pressure	Bar	2.5	2.5	2.5	2.5
Cell Voltage	Volt	0.67	0.676	0.695	0.67
System Voltage (rated power)	Volt	300	300	300	300
Platinum price	$/tr.oz.	$1,475	$1,100	$1,100	$2,000
Pt loading	mg/cm^2	0.15	0.196	0.153	0.153
Membrane type		Reinforced Nafion®	Reinforced 3M PFSA	Reinforced 3M PFSA	Reinforced 3M PFSA
Membrane thickness	micro meter	20	25	25	25
GDL layer		None-woven carbon paper	None-woven carbon paper	None-woven carbon paper	None-woven carbon paper
GDL thickness	micro meter	185	185	185	185
MPL layer thickness	micro meter	40	40	40	40
Bipolar plate type		76Fe-20Cr-4V with nitridation surface treatment	76Fe-20Cr-4V with nitridation surface treatment	SS316L with Treadstone Coating	SS316L with Treadstone Coating
Bipolar plate base material Thickness	micro meter	100	100	100	100
Seal material		Viton®	Viton®	Viton®	Viton®

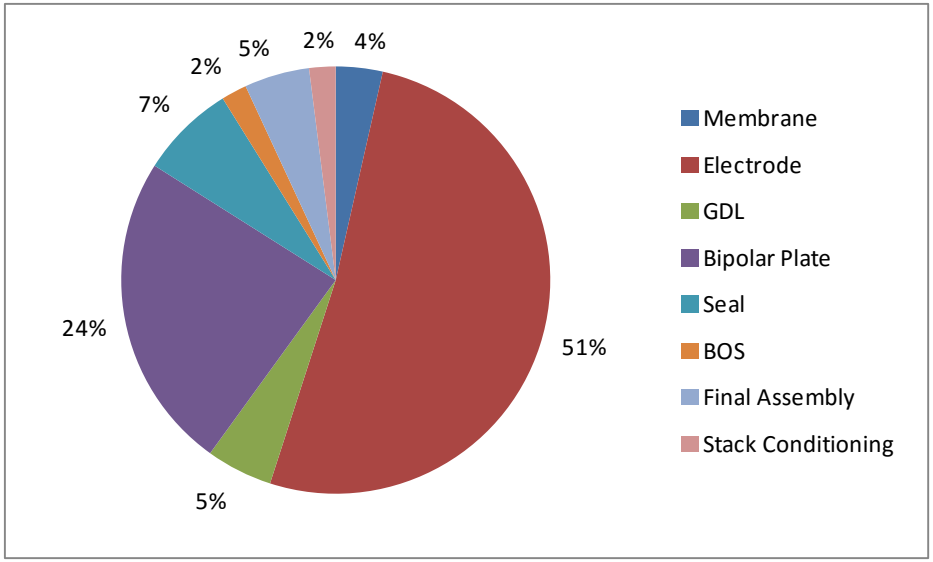
We use Pt price at $2,000/troz which is the similar to highest Pt price in the history.



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

Stack Components	2015 Stack Cost ($/kW)	Comments
Membrane	$1.06	PFSA ionomer ($75/kg)
Electrode	$15.37	Pt ($2,000/troz)
GDL	$1.50	No-Woven carbon paper
Bipolar Plate	$7.16	Treadstone Coating metallic plates
Seal	$2.14	Viton
BOS	$0.58	Manifold, end plates, current collectors, insulators, tie bolts, etc.
Final Assembly	$1.47	Robotic assembly
Stack Conditioning	0.60	2 Hours
Total stack[2]	$29.88	

80 kW_{net} PEM Fuel Cell Stack Cost ($30/$kW_{net}$)



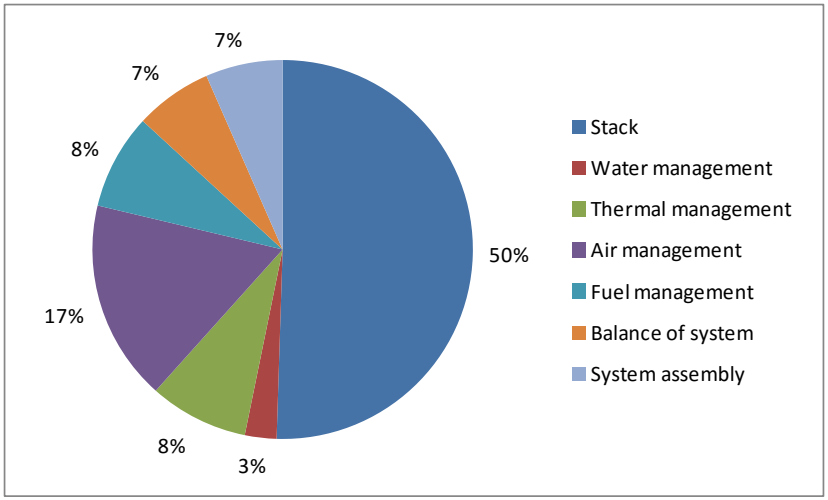
1. Stack assembly cost category included MEA assembly and stack QC; QC included visual inspection, and leak tests for fuel, air, and coolant loops.
2. Results may not appear to calculate due to rounding of the component cost results.

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.

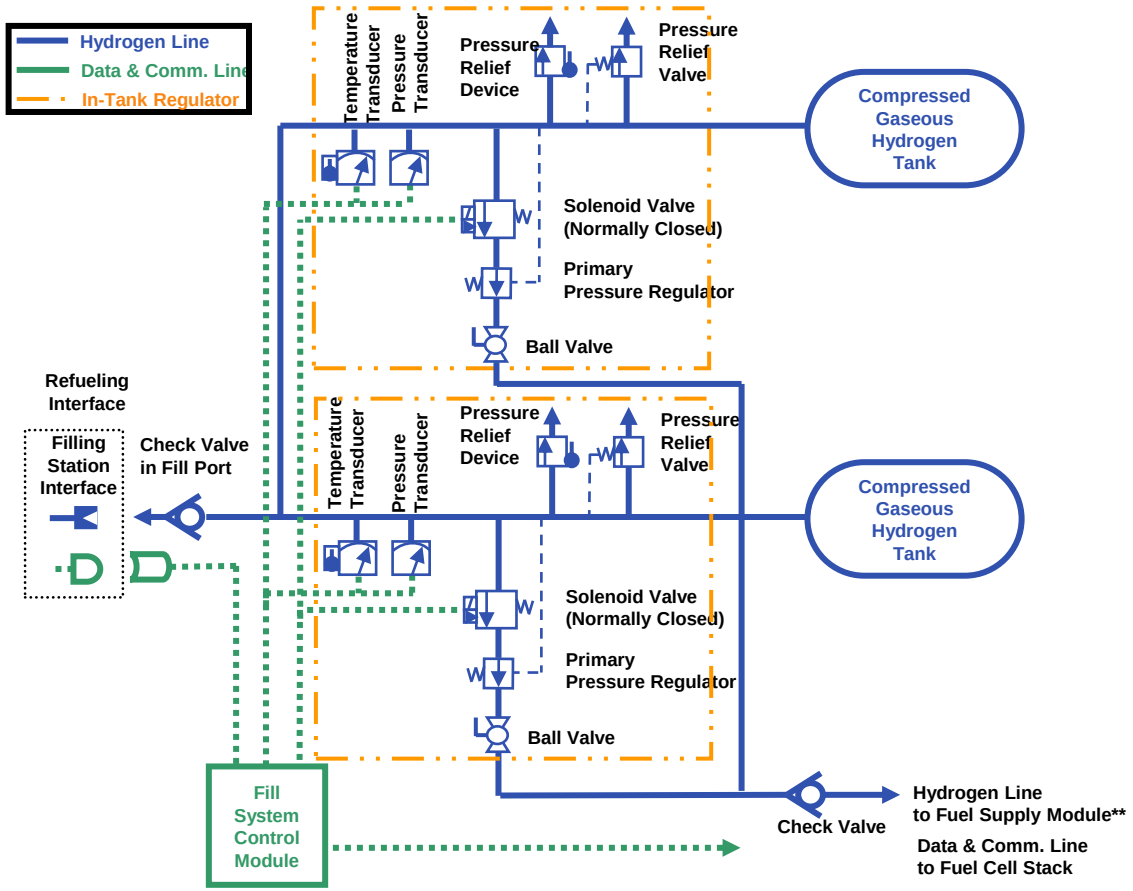
System Components	2015 System Cost ($/kW)	Comments
Stack	$29.9	
Water management	$1.6	Cathode side humidifier, etc.
Thermal management	$5.0	HX, coolant pump, etc.
Air management	$10.1	CEM, etc.
Fuel management	$4.8	H2 pump, etc.
Balance of system	$3.9	Sensors, controls, wire harness, piping, etc.
System assembly	$3.9	
Total system[1, 2]	$59.3	

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 ($4,742/system)



The 700 bar compressed hydrogen tank design is referenced in studies TIAX conducted on hydrogen storage[1].



700 bar Compressed Hydrogen Storage System Schematic[1, 2]

Key Parameters

System Volume

- CH2 storage: 5.6kg usable H2
- System pressure: 700 bar
- # of tanks: 2

Tank

- Carbon fiber: Toray T700S
- Carbon fiber / resin ratio: 0.68 : 0.32 (weight)
- Translational strength factor: 63%
- Safety factor: 2.25
- Al liner
- Glass fiber projection layer

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

Assumptions for the hydrogen storage tank design were based on calculations, literature reviews, 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	Kg	6.0	
Tank type		IV	With Al liner
Tank pressure	PSI	10,000	
# of tanks	Per System	2	
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		63%	
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		Al	

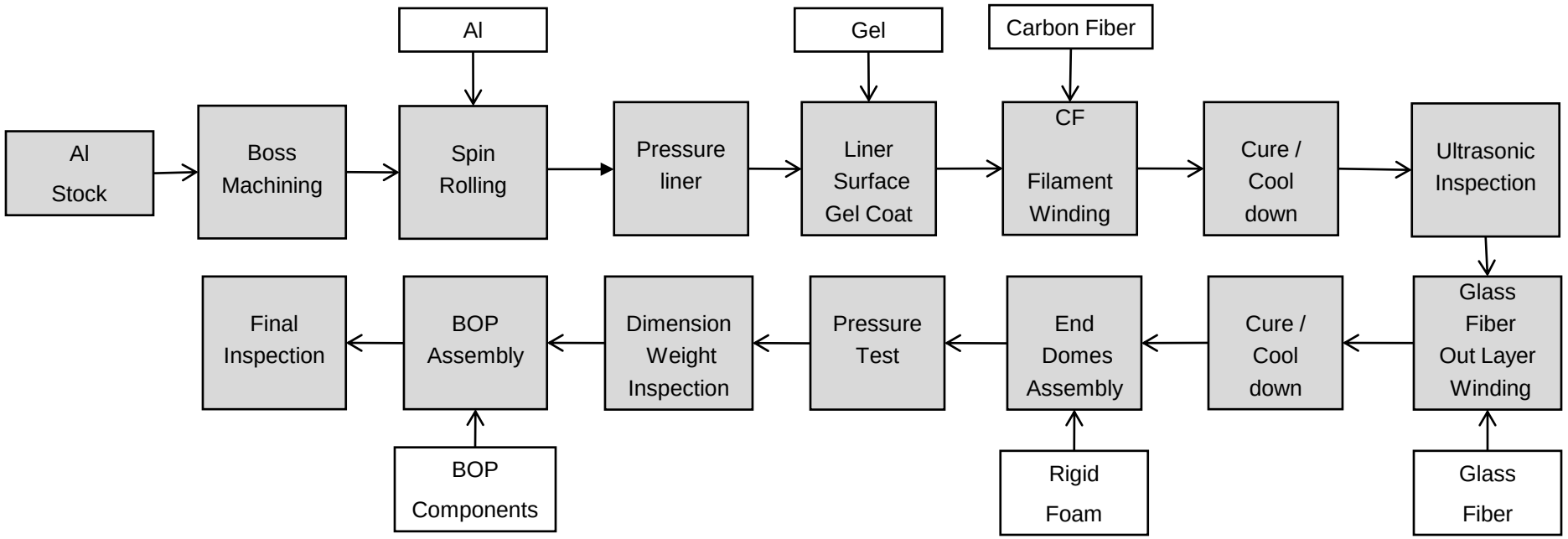
A vertically integrated manufacturing process was assumed for the tank and BOP components.

Major Tank Components

- Aluminum End Boss
- Al liner
- Carbon fiber composite layer
- Glass fiber composite layer
- End domes (rigid foam)

Major BOP Components

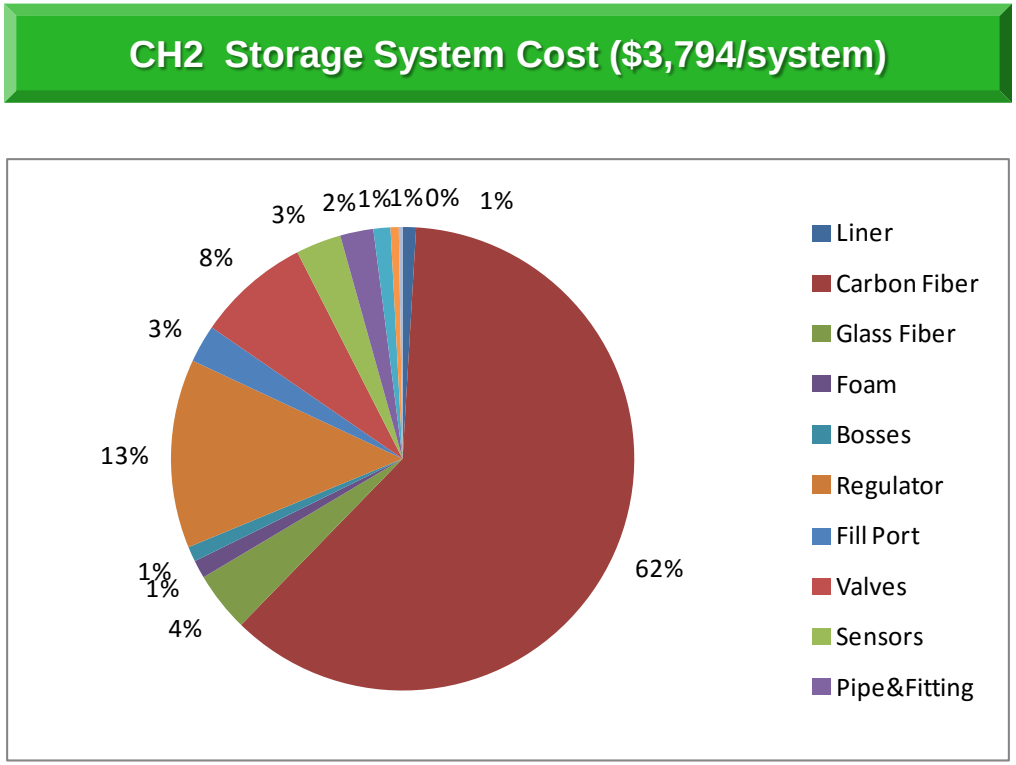
- In-tank primary pressure regulator
- Valves & sensors
- Filling interface
- Pressure release devices
- Piping & fitting



Compressed H2 Storage System Cost

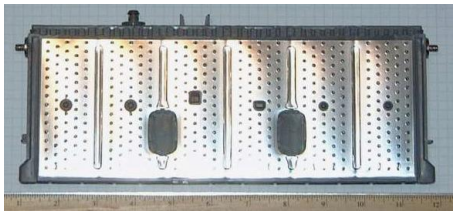
In the 700 bar compressed hydrogen storage system, the carbon fiber composite layers, in-tank regulators, system control valves are the top three cost drivers.

System Components	2015 CH2 Cost ($/kWh)
Liner	$ 0.19
Carbon Fiber	$ 12.47
Glass Fiber	$ 0.85
Foam	$ 0.26
Bosses	$ 0.21
Regulator	$ 2.68
Fill Port	$ 0.54
Valves	$ 1.61
Sensors	$ 0.64
Pipe&Fitting	$ 0.47
Assembly	$ 0.24
Inspections	$ 0.12
Misc	$ 0.05
Total	$ 20.33



A NiMH battery pack will provide hybridization of a fuel cell vehicle which improves fuel economy as well as having the function as a startup battery. There are 34 6.5Ah-7.2V NiMH battery modules in the battery pack.

Battery Pack



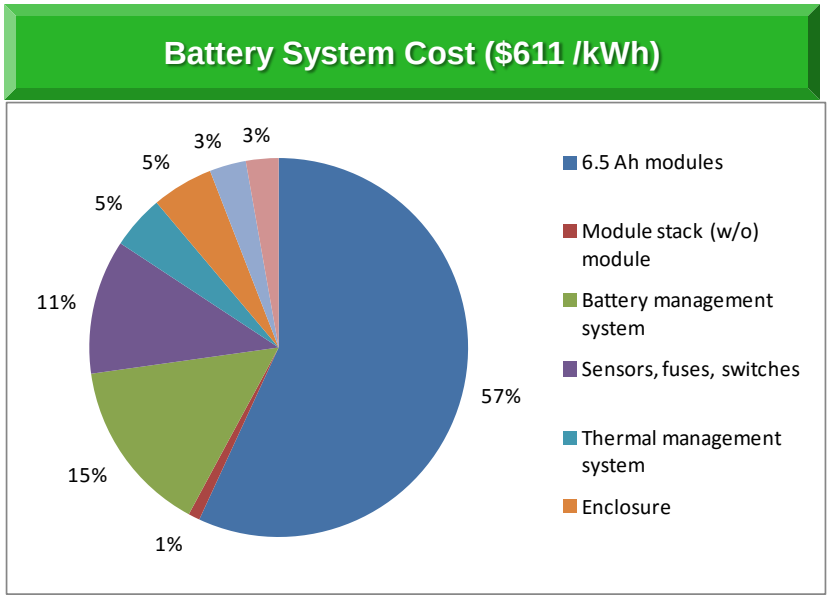
Battery Module

http://afvsafetytraining.com/erg/Toyota-Camry-HV-2007-11.pdf
http://www.peve.jp/en/product/np2/index.html

Specifications	
Battery pack voltage	245 V
Battery pack dimension	190 x 850 x 495 mm
Battery pack weight	52 kg
Battery pack energy	1.6 kWh
Number of NiMH battery modules in the pack	34
NiMH battery module nominal voltage	7.2 V
NiMH battery module nominal capacity	6.5 Ah
NiMH battery module Output	1,350 W
Anode active material	AB_5
Cathode active material	$Ni(OH)_2$

The hybrid NiMH battery pack costs $611/kWh. Battery modules, battery management system, and sensors have higher cost contributions.

Cost Category	2015 Pack Cost ($/kWh)
6.5 Ah modules	$347
Module stack (w/o) module	$6
Battery management system	$91
Sensors, fuses, switches	$70
Thermal management system	$28
Enclosure	$32
Misc.	$19
Assembly and Testing	$17
Total ($/kWh)	$611



The 1.6 kWh lithium-ion battery system cost $978 per pack at the mass production volume (500,000 packs/year).

Conclusion

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

Cost Category	2012 Pack Cost ($/pack)	2013 Pack Cost ($/pack)	2014 Pack Cost ($/pack)	2015 Pack Cost ($/pack)
80 kW_e Fuel Cell	$4,030[1]	$4,256	$4,713	$4,742
5.6 Kg Useable H2 Storage	$3,058	$3,028	$4,567[2]	$3,794
Hybrid Battery Pack	$4,497[3]	$1,034	$790	$978
Total:	$11,585	$8,318	$10,070	$9,514
Comments	FC-PHEV	FC-HEV	FC-HEV	FC-HEV

1. 65kWe fuel cell system
2. 10 kg useable hydrogen.
3. 16 kWh li-ion battery pack

- 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 5.6 kg 2-tank compressed on-board hydrogen storage system is estimated to be $20/kWh at the mass production.
- The hybrid NiMH battery (1.6kWh) costs $978 per pack or $611/kWh.

The PEM fuel cell middle size passenger vehicle purchase price is approximately $27,089 at the mass production volume.

Component Category		PEMFC Hybrid ($/unit)	Comments
Glider	**Glider**	***7,000***	Mid-size passenger vehicle
Power Chain	**PEMFC**	4,742	Bottom-up costing
	H2 storage	3,794	Bottom-up costing
	Battery system	978	Bottom-up costing
	Traction motor[1]	1,200	Motor + controller + transmission
	Power electric[1]	840	Battery charger, main inverter, DC/DC converter, auxiliary inverter, etc
	Power chain sub-total	***11,554***	
Total vehicle manufacturing cost		**18,554**	
Markup[2]		**46%**	Corporation cost & profit, dealer cost, shipping cost, tax
Purchase price for consumer		**27,089**	

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.
2. Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers, EPA, 2009

Comparing a PEM FC vehicle with a middle size passenger electric vehicle which both have a drive range approximately 250 miles.

EV Battery Pack Cost	80kWh EV Battery Pack Cost ($)	80kW PEMFC System* Cost ($)
$100 /kWh	$8,000	$9,514
$150 /kWh	$12,000	
$200 /kWh	$16,000	
$250 /kWh	$20,000	
$300 /kWh	$24,000	

	Energy (kWh)	Total Energy (kWh)	Cost ($/kWh)
EV battery	80kWh	80 kWh	$100~300/kWh
PEMFC System* (Chemical Energy + Electric Energy)	185 kWh (Chemical) 1.6 kWh (Electric)	186.6 kWh	$51 /kWh
PEMFC System* (Converted Chemical Energy** + Electric Energy)	92.5 kWh (Converted Chemical) 1.6 kWh (Electric)	94.1 kWh	$101 /kWh

- * Includes an 80kWe PEMFC, a CH2 storage tank, and a 1.6 kWH NiMH battery
- ** Assume the hydrogen to electricity efficiency is 50%

Thank You!

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