PEM Fuel Cell System Manufacturing Cost Analysis for Automotive Applications

AustinPower Engineering

Yong Yang
President

November 8, 2017

Austin Power Engineering LLC
1 Cameron St
Wellesley, MA 02482
USA

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

Have been working on various EV/FCEV powertrain manufacturing cost analysis since 2002.

Battery Packs
- Lithium ion battery
- Lithium metal solid electrolyte battery
- NiMH battery

Electric Powertrains
- Full battery powertrain
- Hybrid battery powertrain
- Fuel cell powertrain

On-board Fly Wheel Energy Storage System

Power Electronics
- Battery BMS
- Inverters
- Traction motors

Regenerative /Active Suspension System

Electric Turbo Chargers

Range-extension IC Engines

On-board Hydrogen Storage Systems
- Compressed H2 tanks
- MH H2 tanks
- Chemical H2 tanks
- Cryo-compressed H2 tanks
- MOF H2 tanks

Thermal-electrical Generator (Exhaust Heat Recovery)

Conduct a bottom-up manufacturing cost analysis of a 160 kW class 4 truck fuel cell power system* as well as a 80kW mid-size light-duty vehicle fuel cell power system.

Class 4 Fuel Cell Truck

Fuel cell power: 160 kW (2 stacks)

Battery power: 54 kW

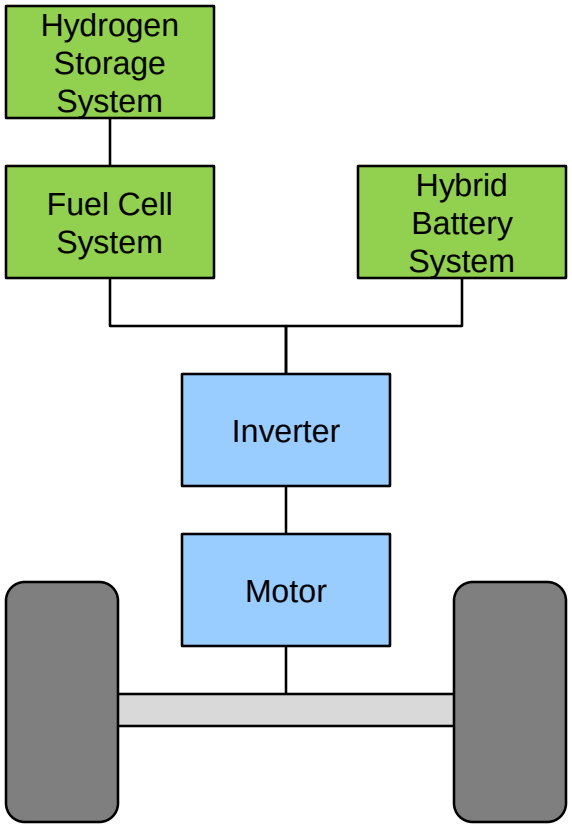
Battery energy: 1.6 kWh

Motor power: 210 kW

H2 storage: 20 kg (two tanks)

H2 storage tank: Cyro-compressed

Range: min. 200mile



Mid-size Light Duty Vehicle

Fuel cell power: 80 kW

Battery power: 40 kW

Battery energy: 1.6 kWh

Motor power: 120 kW

H2 storage: 10 kg (one tanks)

H2 storage tank: Cryo-compressed

Range: min. 500mile

Not included in the analysis

Included in the analysis

*Class4 Truck: 14001–16000lbs (Carb weight + max. cargo weight)
"Fuel cell electric truck (FCET) component sizing", ANL, 2016

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

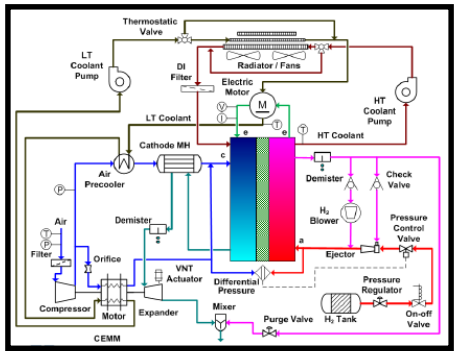
- Define system value chain
- Quote off-shelve parts and materials
- Select materials
- Develop processes
- Assembly bottom-up cost model
- Develop baseline costs

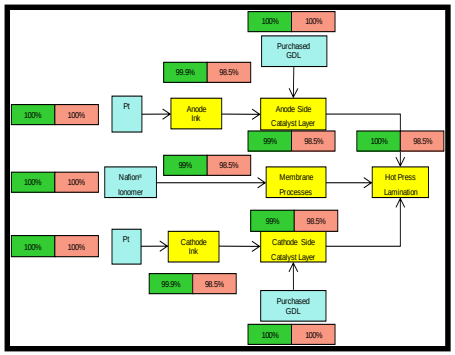
Scenario Analyses

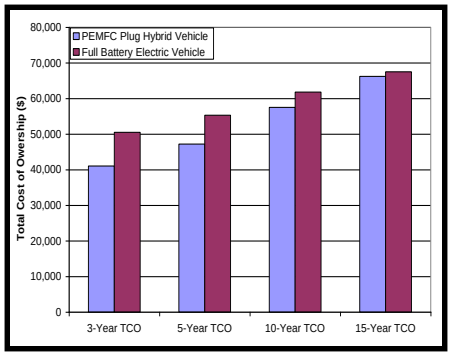
- Technology scenarios
- Sensitivity analysis
- Economies of Scale
- Supply chain & manufacturing system optimization
- Life cycle cost analysis

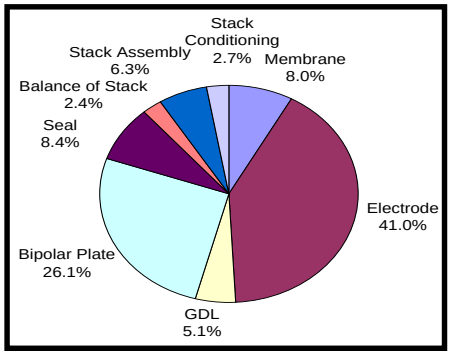
Verification & Validation

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



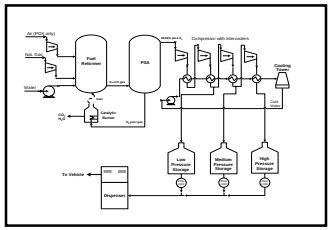






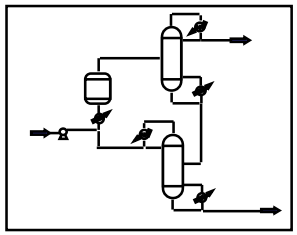
Combining performance and cost model will easily generate cost results, even when varying the design inputs.

Conceptual Design



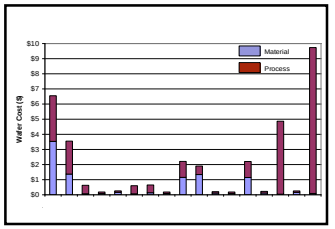
- System layout and equipment requirements

Process Simulation



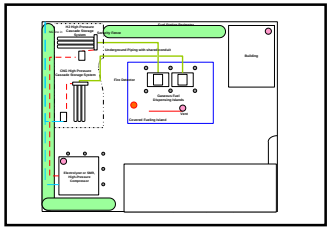
- Energy requirements
- Equipment size/ specs

Process Cost Calcs



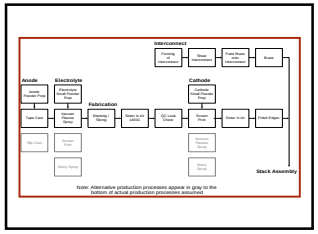
- Process cost
- Material cost

Site Plans



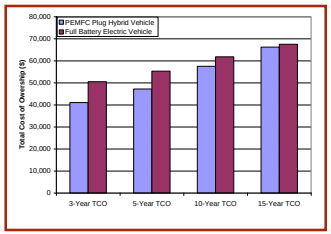
- Safety equipment, site prep, land costs

Capital Cost Estimates



- High and low volume equipment costs

Product Costs



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

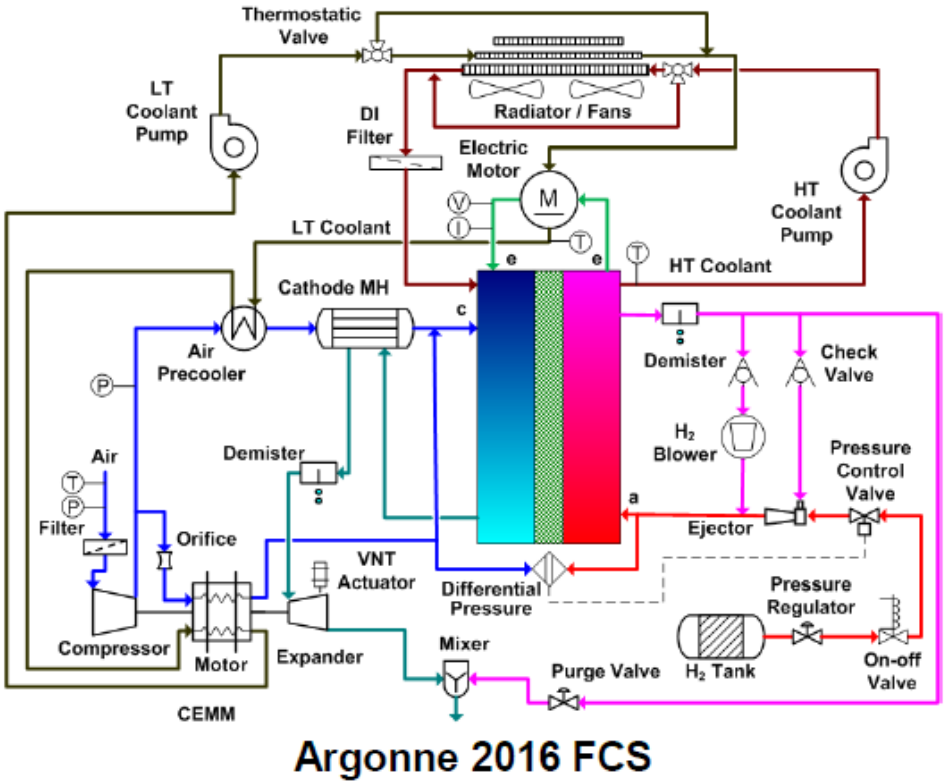
Manufacturing Assumptions

We assume class4 truck has an annual production volume of 5,000 units and the mid-size light duty vehicle has an annual production volume of 500,000 units.

System Components	Class4 Truck	Mid-size Light Duty Vehicle
Vehicle production volume (unit/year)	5,000	500,000
Stack source	Assume two 80 kW stacks at the annual system production volume of 5,000 units	80kWnet at the annual production volume of 500,000 units
Battery source	1.6 kWh NiMH battery pack at the annual production volume of 500,000 units	1.6 kWh NiMH battery pack at the annual production volume of 500,000 units
H2 storage system production volume	10 kg x 2 cryo-compressed H2 tanks at 5,000/yr	10 kg cryo-compressed H2 tank at 500,000/yr

* In 2015, the class 4 truck sales is about 14,000 in US.

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 modeling and analysis," 2017 DOE Hydrogen and Fuel Cells Program Review, Washington DC, 2017.

Key Parameters

Stack
- 3M NSTFC MEA
- 25 μm supported membrane
- 0.125 mg/cm^2 Pt
- Power density: 1,095mW/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.

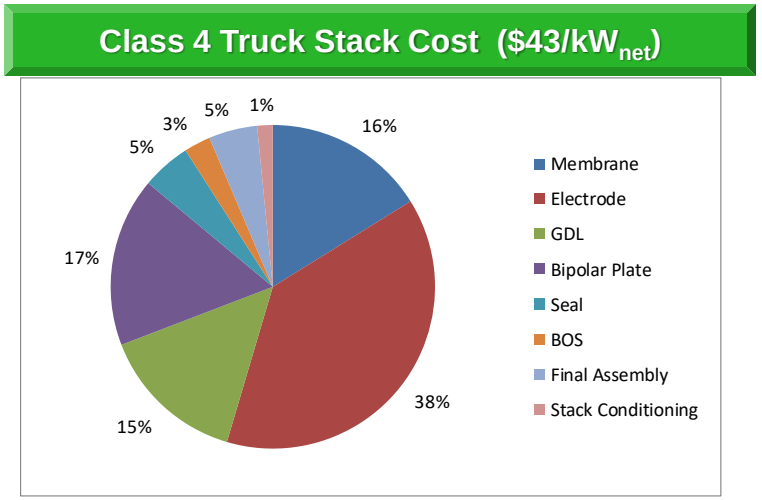
Stack Components	Unit	Class 4 Truck	Light Duty Vehicle
Production volume	systems/year	5,000	500,000
Stacks' net power	kW	80 x 2	80
Stacks' gross power	kW	88 x 2	88
Cell power density	mW/cm^2	1,095	1,095
Peak stack temp.	Degree C	100	100
Peak stack pressure	Bar	2.5	2.5
Cell Voltage	Volt	0.67	0.67
System Voltage (rated power)	Volt	300	300
Platinum price	$/tr.oz.	$2,000	$2,000
Pt loading	mg/cm^2	0.125	0.125
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		SS316L with Treadstone Coating	SS316L with Treadstone Coating
Bipolar plate base material Thickness	micro meter	100	100
Seal material		Viton®	Viton®

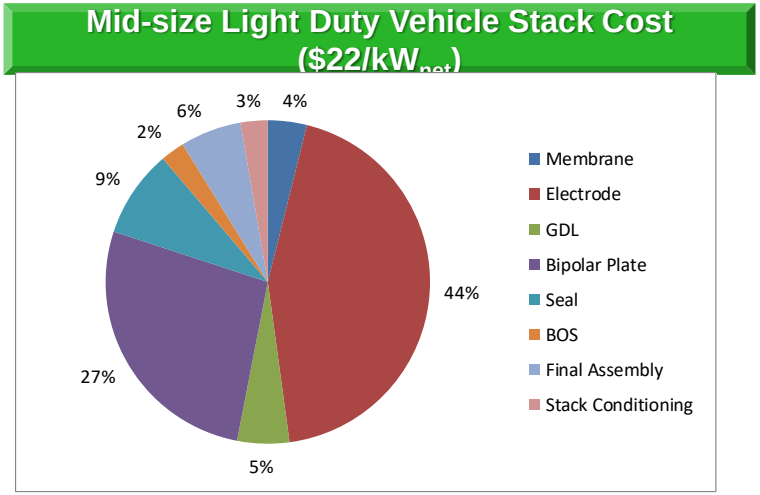
We use Pt price at $2,000/troz which is the similar to highest Pt price in the history.

The class 4 truck fuel cell stack costs approximately $43/kW and the mid-size light duty vehicle fuel cell stack costs about $22/kW.

Stack Components	Class4 Truck Stack Cost ($/kW)[3]	Mid-size Light Duty Vehicle Stack Cost ($/kW)	Comments
Membrane	$6.87	$0.86	PFSA ionomer ($75/kg)
Electrode	$16.35	$9.74	Pt ($2,000/troz)
GDL	$6.21	$1.15	No-Woven carbon paper
Bipolar Plate	$7.19	$5.98	Treadstone Coating metallic plates
Seal	$2.08	$1.94	Viton
BOS	$1.13	$0.53	Manifold, end plates, current collectors, insulators, tie bolts, etc.
Final Assembly[1]	$2.06	$1.35	Robotic assembly
Stack Conditioning	0.66	0.60	2 Hours
Total stack[2]	$42.54	$22.15	

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.
3. Actual stack production volume: 10,000 stacks/yr.

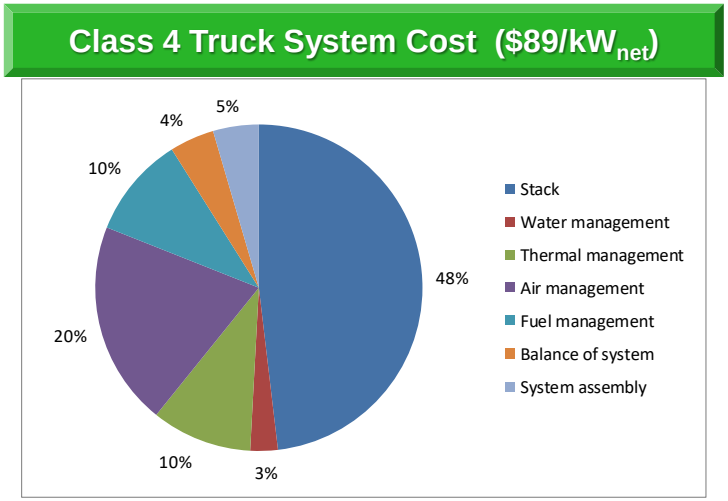


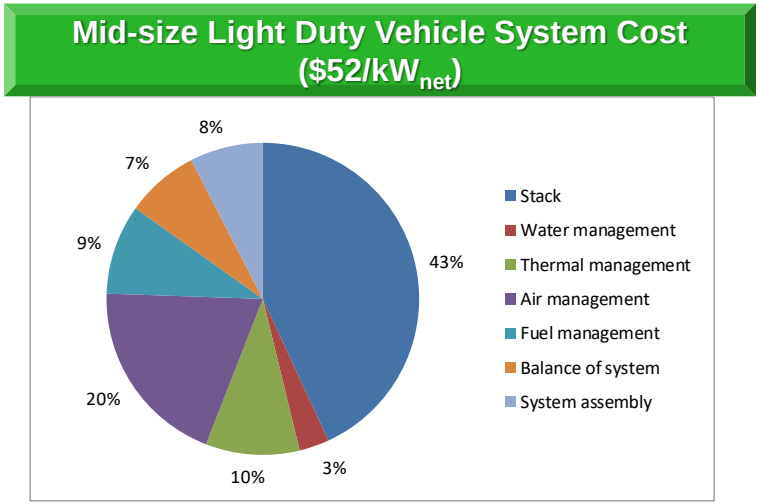


The class 4 truck fuel cell system costs approximately $89/kW and the mid-size light duty vehicle fuel cell system costs about $52/kW.

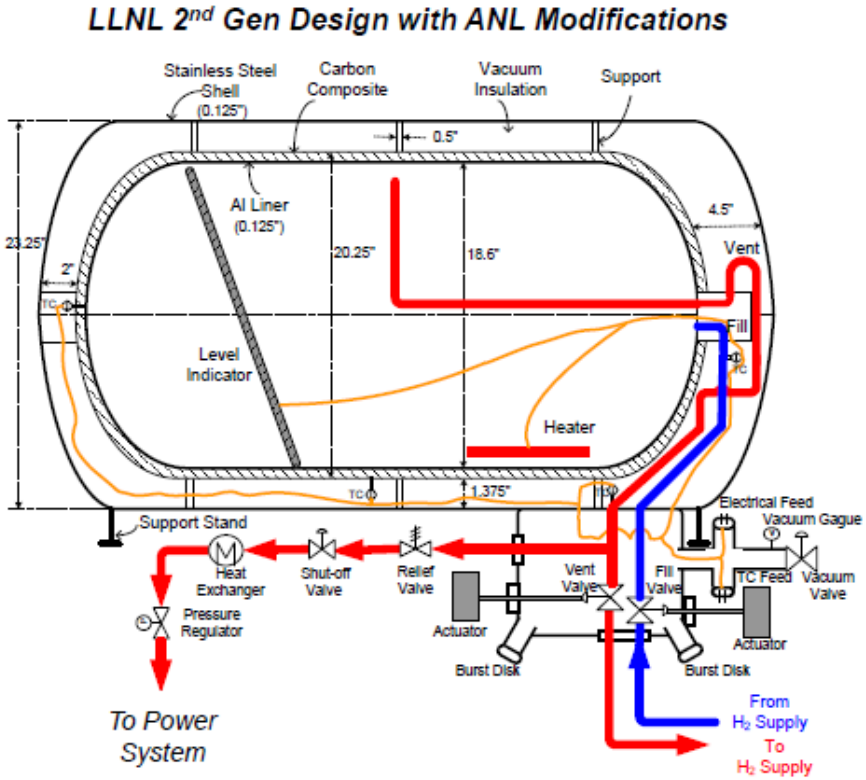
System Components	Class4 Truck System Cost ($/kW)	Mid-size Light Duty Vehicle System Cost ($/kW)	Comments
Stack	$42.6	$22.2	
Water management	$2.4	$1.6	Cathode side humidifier, etc.
Thermal management	$8.8	$5.0	HX, coolant pump, etc.
Air management	$17.9	$10.1	CEM, etc.
Fuel management	$8.9	$4.8	H2 pump, etc.
Balance of system	$3.9	$3.9	Sensors, controls, wire harness, piping, etc.
System assembly	$4.0	$3.9	
Total system[1, 2]	$88.6	$51.5	

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



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

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

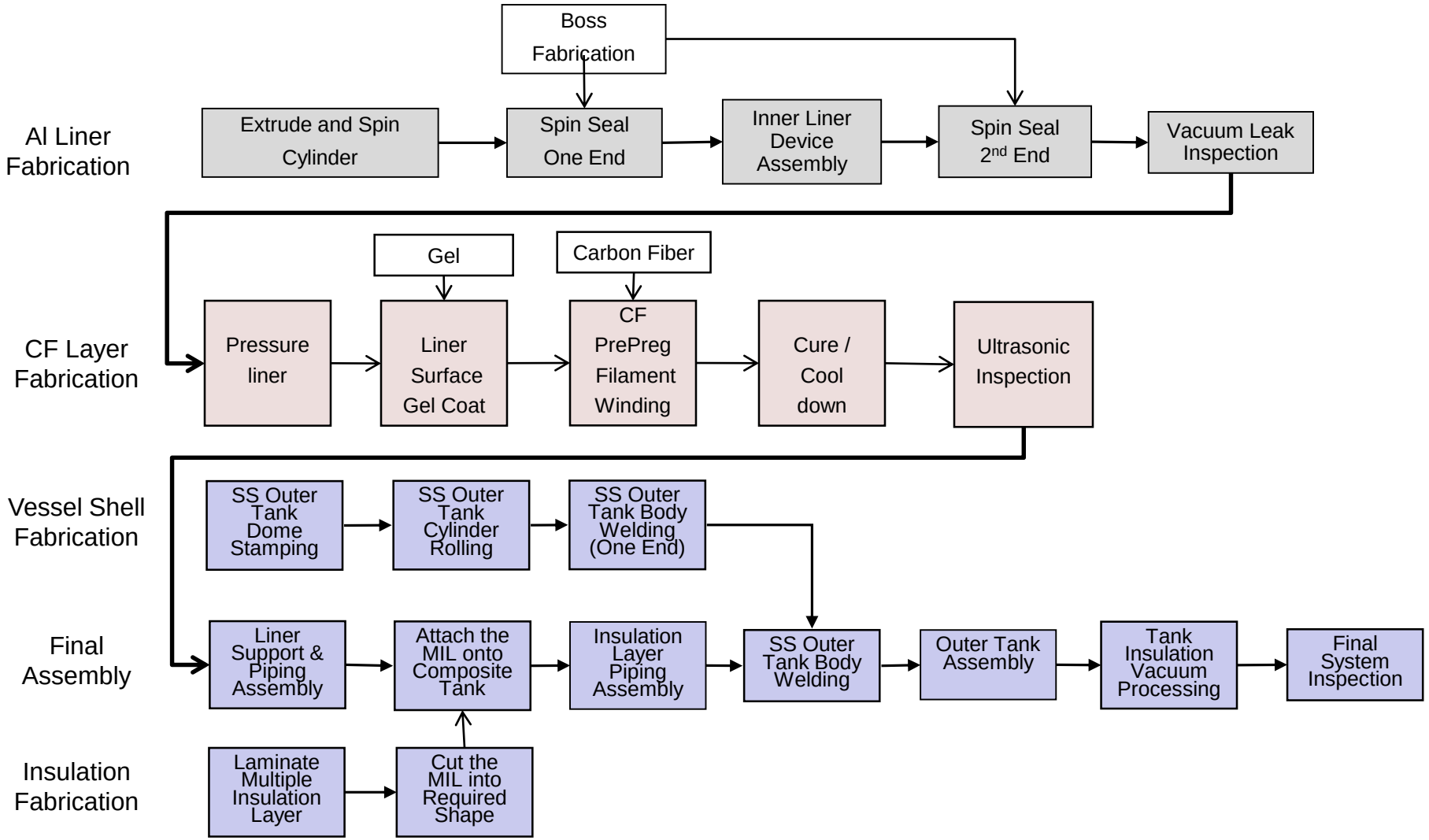
1. S. Lasher and Y. Yang, “Cryo-compressed and Liquid Hydrogen System Cost Assessments”, DOE Merit Review, 2008
2. R.K. Ahluwalia, i.e. “Cryo-compressed hydrogen storage: performance and cost review” Februrary, 2011

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

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

Stack Components	Unit	Class4 Truck	Mid-size Light Duty Vehicle
Production volume	systems/year	5,000	500,000
Usable hydrogen	Kg	20.2	10.1
Total H2 in the tank	Kg	21.4	10.7
Tank type		III	III
Tank max pressure	PSI	5,000	5,000
# of tanks	Per System	2	1
Safety factor		2.25	2.25
Tank length/diameter ratio		3:1	3:1
Liner material		Al	Al
Liner thickness	mm	3	3
Carbon fiber type		Toray T700S	Toray T700S
Carbon fiber cost	$/lbs	12	12
Carbon fiber vs. resin ratio		0.68:0.32	0.68:0.32
Carbon fiber translational Strength factor		81.5%	81.5%
Carbon fiber composite layer thickness	mm	12	12
Vacuum gap	mm	40	40
# of MLVI layer		40	40
Outer layer		SS304	SS304
Outer layer thickness	mm	3	3

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

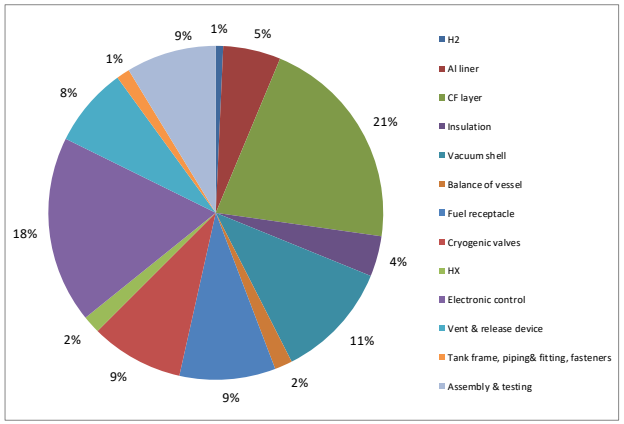


Compressed H2 Storage System Cost

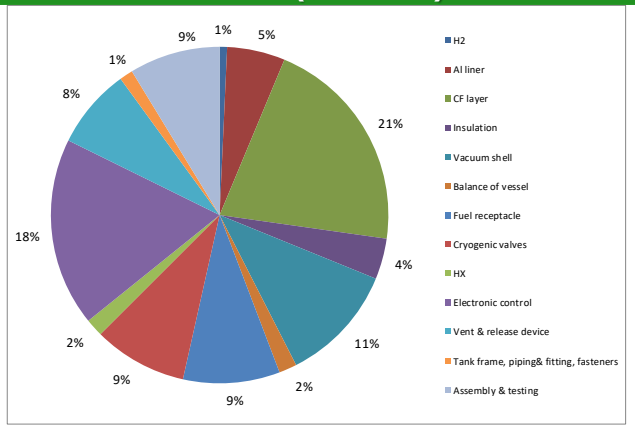
In the cryo-compressed hydrogen storage system, the carbon fiber composite layer , cryogenic valves, system control valves are the top three cost drivers.

System Components	Class4 Truck System Cost ($/kWh)	Mid-size Light Duty Vehicle System Cost ($/kWh)
H2	0.10	0.10
Al liner	0.78	0.42
CF layer	2.94	2.86
Insulation	0.55	0.37
Vacuum shell	1.59	0.53
Balance of vessel	0.24	0.24
Fuel receptacle	1.30	1.27
Cryogenic valves	1.26	1.23
HX	0.24	0.24
Electronic control	2.54	2.52
Vent & release device	1.08	1.05
Tank frame, piping& fitting, fasteners	0.18	0.18
Assembly & testing	1.22	1.10
Total:	14.02	12.11

Class 4 Truck H2 Storage System Cost ($14/kWh)

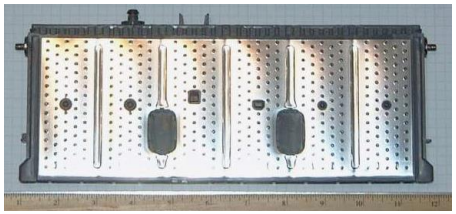


Mid-size Light Duty Vehicle H2 Storage System Cost ($12/kWh)



We use a 1.6 kWh NiMH hybrid battery pack in both systems, which is current widely used in various Toyota hybrid vehicles, such as Camry hybrid, etc.

Battery Pack



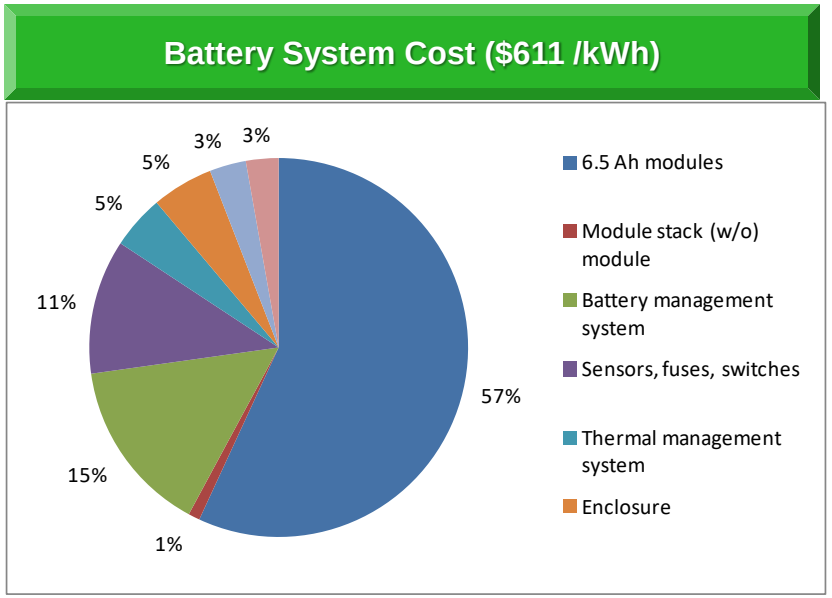
Battery Module

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	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 $24,593 and $9,174 for class 4 FC truck and mid-size light duty FC vehicle, respectively.

Cost Category	Class4 FC Truck	Mid-size Light Duty FC Vehicle
Fuel Cell System	$14,176	$4,120
H2 Storage system	$9,439	$4,077
Hybrid Battery Pack	$978	$978
Total:	$24,593	$9,174
Comments	Production volume: 5,000/yr	Production volume: 500,000/yr

- Class 4 truck production volume: 5,000/yr; 160kW FC; 20.2 kg H2 storage; 1.6 kWh battery pack
- Mid-size light duty vehicle production volume: 500,000/yr; 80kW FC; 10.1 kg H2 storage; 1.6 kWh battery pack

The sale prices for class 4 FC truck and mid-size light duty FC vehicle are $55,718 and $26,593, respectively.

Component Category		Class 4 FC Truck ($/unit)	Mid-size Light Duty Vehicle ($/unit)	Comments
Glider	**Glider**	***$10,000***	***$7,000***	Class 4 truck and mid-size passenger vehicle
Power Chain	**PEMFC**	$14,176	$4,120	Bottom-up costing
	H2 storage	$9,439	$4,077	Bottom-up costing
	Battery system	$978	$978	Bottom-up costing
	Traction motor[1]	$2,100	$1,200	Motor + controller + transmission
	Power electric[1]	$1,470	$840	Main inverter, auxiliary inverter, etc
	Power chain sub-total	***$28,163***	***$11,214***	
Total vehicle manufacturing cost		***$38,163***	***$18,214***	
Markup[2]		46%	46%	Corporation cost & profit, dealer cost, shipping cost, tax
Purchase price for consumer		***$55,718***	***$26,593***	

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

Thank You!

Contact: Yong Yang

Austin Power Engineering LLC

1 Cameron St,
Wellesley, MA 02482

+1 781-239-9988
+1 978-263-0397
yang.yong@austinpowereng.com
www.austinpowereng.com