Direct Hydrogen PEM Fuel Cell Powertrain Manufacturing Cost Analysis for Heavy Duty Truck Applications

AustinPower
Engineering

Yong Yang

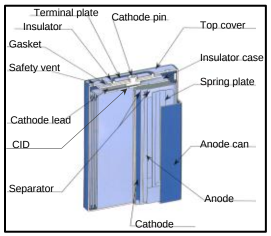
President

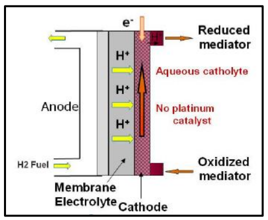
November 7, 2019

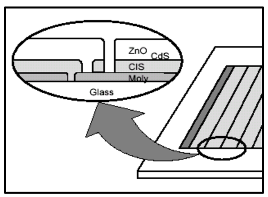
Austin Power Engineering LLC
1 Cameron St
Wellesley, MA 02482
USA

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

Austin Power Engineering LLC is an independent technology consulting company that focuses mainly on bottom-up technical cost modeling.





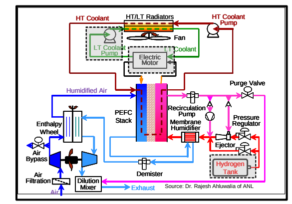


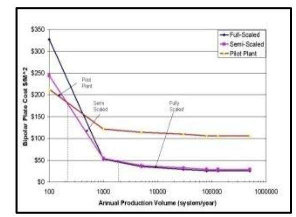
Fuel Cell

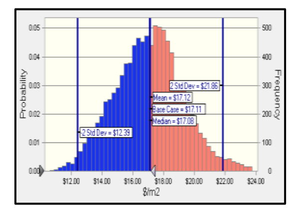
Hydrogen Storage

Hydrogen Electrolysis

Battery







Hydrogen & Fuel Cell Manufacturing Cost Modeling

2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019

Arthur D Little / TIAX

Austin Power Engineering

Have been working on various EV 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

Onboard **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 8 truck fuel cell power system.

	Class and Vocation	PHA Vehicle Class Definaion	ANL Analysis Assumption/Results		
			Test Wt.	Fuel Cell	Battery
			lbs	kW	kW
Light Duty	Class 1	Class 1: < 6,000 lbs	Not eval.	Not eval.	Not eval.
	Class 2 Van	Class 2: 6,001 - 10,000 lbs	7588	147	6
Medium Duty	Class 3 Service	Class 3: 10,001 - 14,000 lbs	11356	165	4
	Class 3 School Bus	Class 3: 10,001 - 14,000 lbs	11512	180	76
	Class 3 Enclosed Van	Class 3: 10,001 - 14,000 lbs	12166	149	62
	Class 4 Walk-in, Multi-Stop	Class 4: 14,001 - 16,000 lbs	15126	166	59
	Class 5 Utility	Class 5: 16,001 - 19,500 lbs	16860	253	8
	Class 6 Construction	Class 6: 19,501 - 26,000 lbs	22532	170	30
Heavy Duty	Class 7 School Bus	Class 7: 26,001 - 33,000 lbs	[illegible]	[illegible]	56
	Class 8 Constrction	Class 8: >33,001 lbs	37429	139	57
	Class 8 Refuse		45291	273	94
	Class 8 Nikola One		50870	300	446
	Class 8 Tractor Trailer		[illegible]	[illegible]	95
	Class 8 Line Haul		70869	363	47

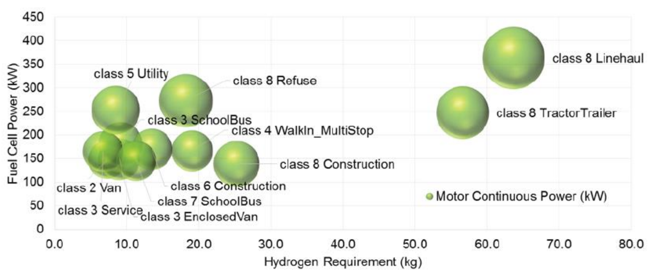
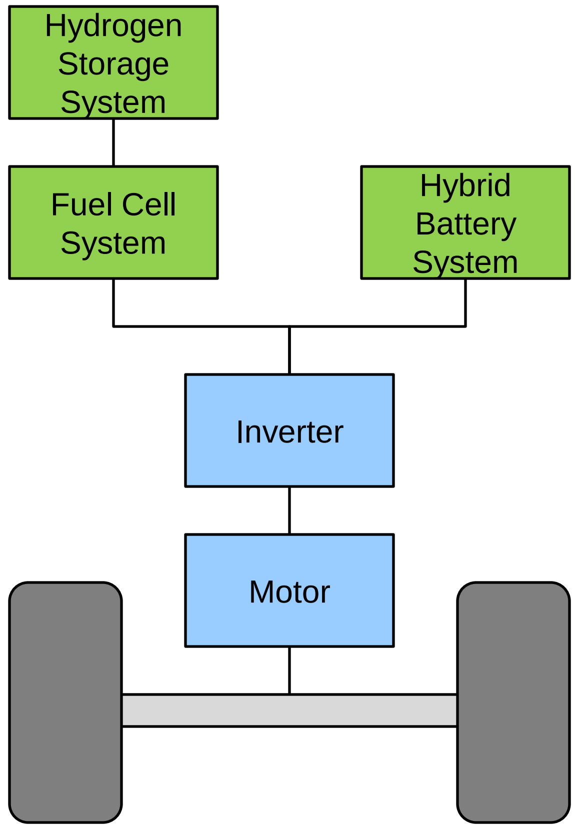


FIGURE 1. Fuel Cell and Hydrogen Tank Sizing Result for FCETs



Class 8 Fuel Cell Truck

Fuel cell power: 160 kW_{net} / 197kW_{Gross}

Battery power: 350 kW

Battery energy: 16 kWh

Motor power: ~500 kW

H2 storage: 60 kg (Six tanks)

H2 storage tank: Cryo-compressed

Range: 300 miles

Not included in the analysis

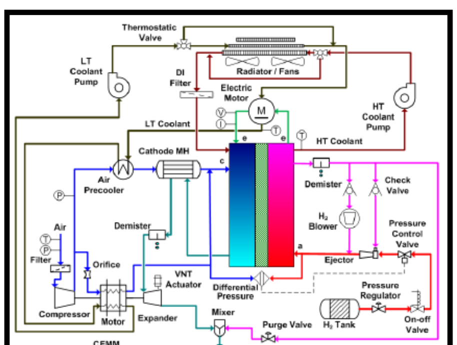
Included in the analysis

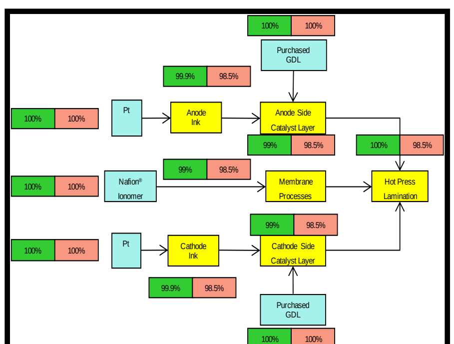
* Data from Argon National Lab research papers, 21st Century Truck, DOE

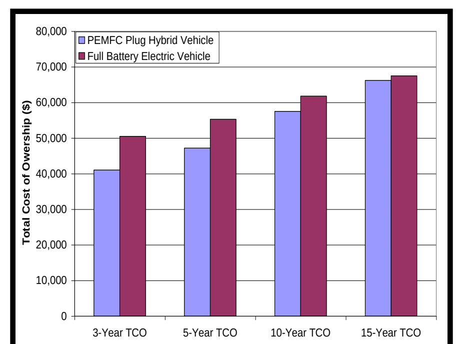
Approach Manufacturing Cost Modeling Methodology

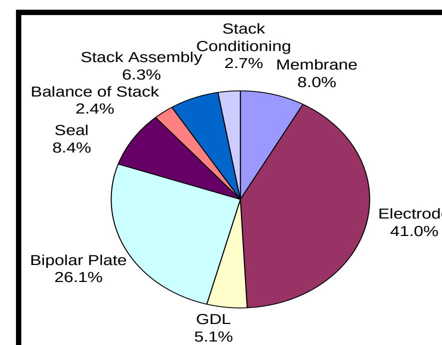
This approach has been used successfully for estimating the cost of various technologies for commercial clients and the DOE.

Technology Assessment	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





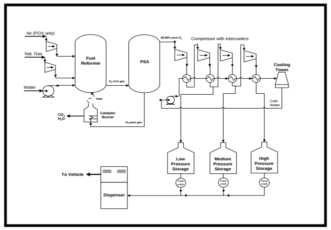




Approach Manufacturing Cost Modeling Methodology

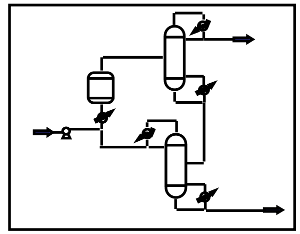
Combining performance and cost model will easily generate cost results, even when varying the design inputs.

Conceptual Design



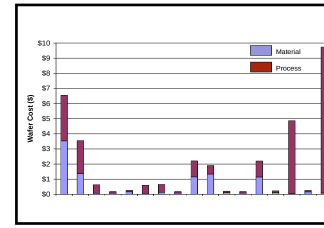
- System layout and equipment requirements

Process Simulation



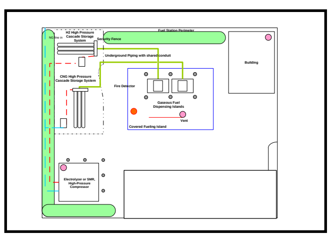
- Energy requirements
- Equipment size/ specs

Process Cost Calcs



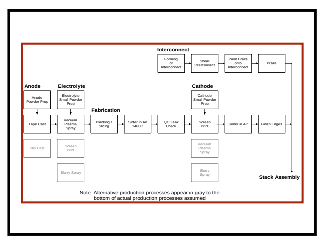
- Process cost
- Material cost

Site Plans



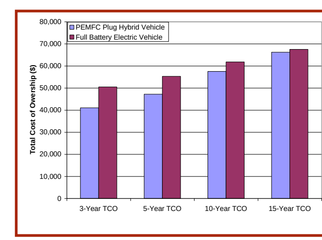
- Safety equipment, site prep, land costs

Capital Cost Estimates



- High and low volume equipment costs

Product Costs



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

Approach In-depth Analysis

Stack and system component in-depth analysis on technology progress and supply chain optimization:

Stack and BOP components

- MEA
- GDL/MPL
- Bipolar plates
- Compressor/expender
- H2 circulation pump
- Humidifier
- Radiator

In-depth analysis

Technology progress

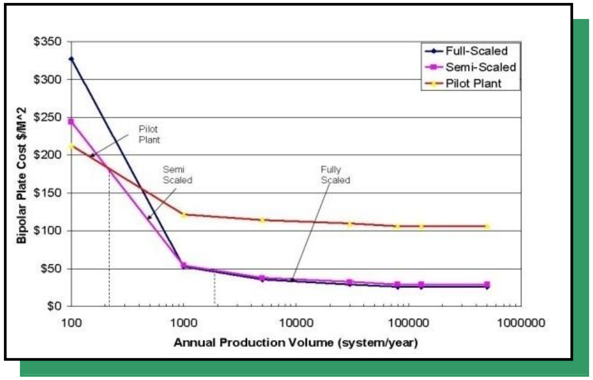
- Breakthrough innovation
- Technology improvement in short and long term
- Design simplification

Supply chain optimization

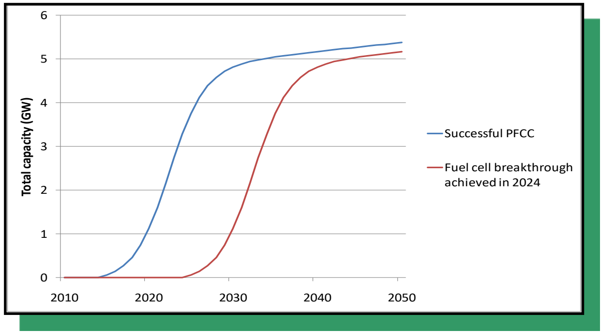
- Raw material
- Off-the-shelf Component
- Fabrication process
- Utilization in other industry
- Challenges

OEM evaluation

- Market share
- Production capacity
- Annual revenue
- Product cost



Economies of Scale Analysis



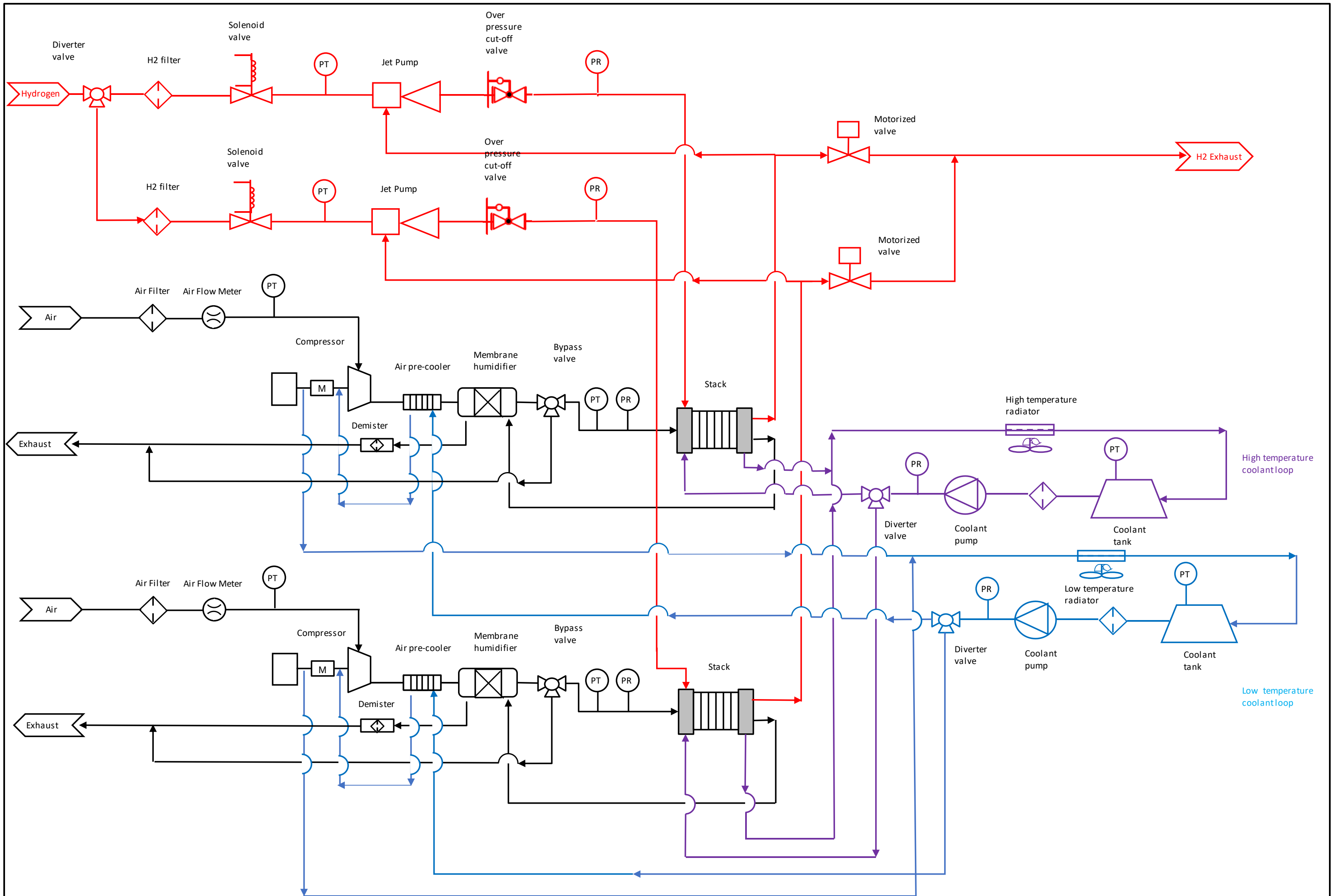
Bass Diffusion Model Analysis

Manufacturing Assumptions

We assume class 8 truck has an annual production volume of 10,000 units.

System Components	Class 8 Truck
Vehicle production volume (unit/year)	10,000
Stack source	Assume two 80 kWnet stacks at the annual production volume of 20,000 units
H_2 storage system production volume	10 kg x 6 cryo-compressed H_2 tanks at the annual production volume of 60,000 units
Battery source	16 kWh lithium-ion battery pack at the annual production volume of 10,000 units

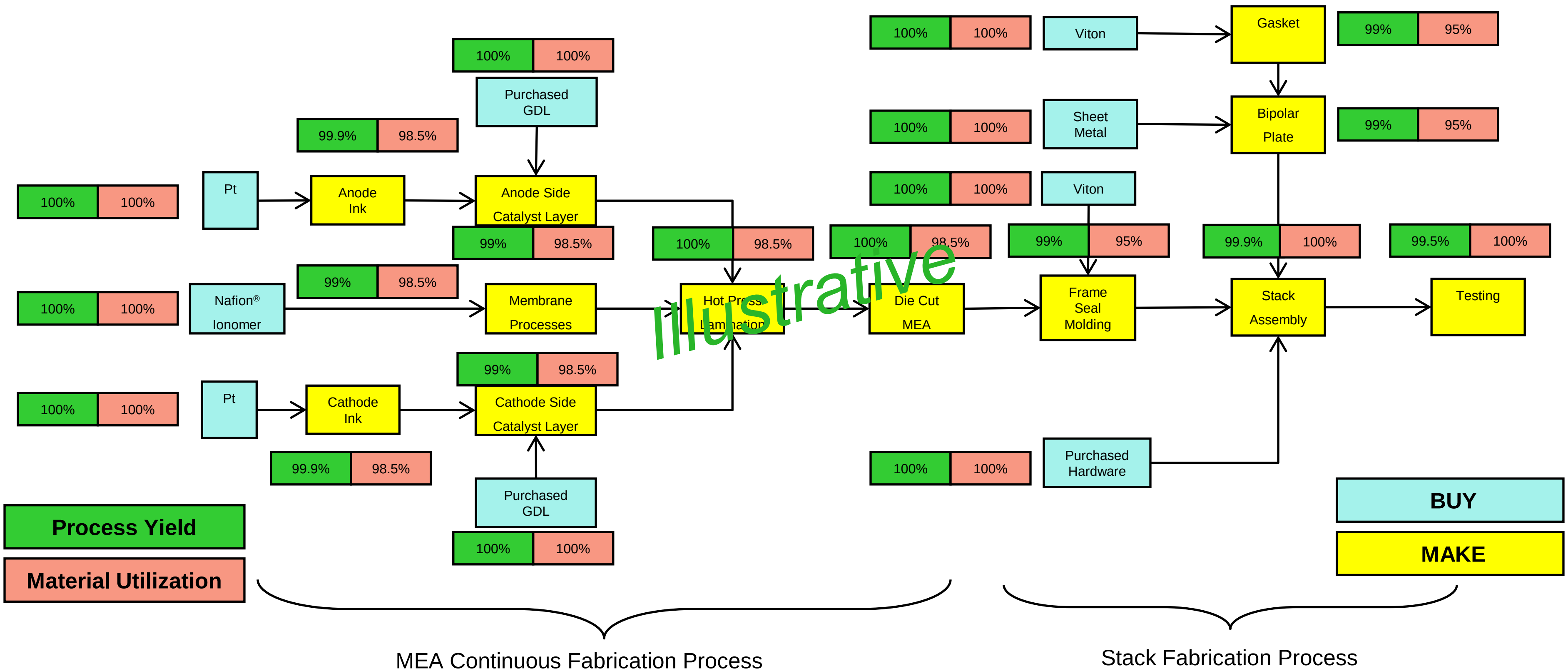
The 160 kW$_{net}$ direct hydrogen PEM fuel cell system configuration:



System and material assumptions for the cost estimation:

Stack Components	Unit	Current System	Comments
Production volume	systems/year	10,000	Baseline
System net power	kW	160	
System gross power	kW	197	
# of stacks in the system	#	2	
Stack' net power	kW	80	
Stacks' gross power	kW	98.5	
Cell power density	mW/cm^2	1,200	DOE 2018
System Voltage (rated power)	Volt	250	
Platinum price	$/tr.oz.	$1,500	Estimated, DOE 2018
Pt loading	mg/cm^2	0.35	DOE 2018
Membrane type		Reinforced PFSA	
Membrane thickness	micro meter	14	
GDL layer		Non-woven carbon paper with MPL layer	
GDL thickness	micro meter	110	@50 kPa pressure
MPL layer thickness	micro meter	45	
MEA gasket material		PET	
MEA gasket thickness	micro meter	100	
Bipolar plate type		Gold dot coated SS316	Treadstone; Near term
Bipolar plate base material Thickness	micro meter	100	
Seal material		EPDM	

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

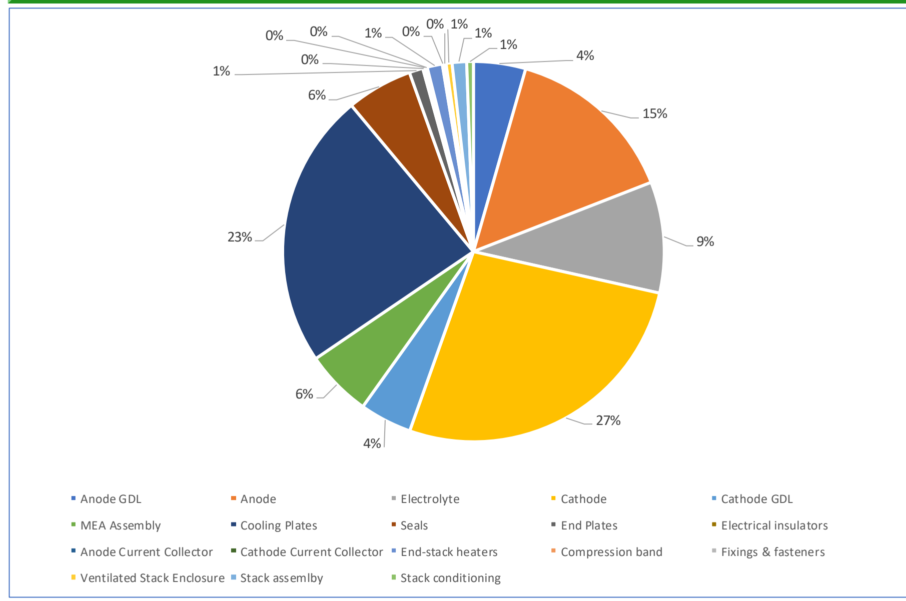


True-value-mapping analysis virtualizes costs in each fabrication step, which breaks down costs into materials, labor, capex, utility, maintenance, etc.

The class 8 truck fuel cell stack costs approximately $64/kW.

Stack Components	Class 8 Truck Stack Cost ($/kW)[1,2]
Anode GDL	$2.8
Anode	$9.3
Electrolyte	$6.0
Cathode	$17.1
Cathode GDL	$2.8
MEA Assembly	$3.6
Cooling Plates	$14.9
Seals	$3.6
End Plates	$0.7
Electrical insulators	$0.1
Anode Current Collector	$0.1
Cathode Current Collector	$0.1
End-stack heaters	$0.8
Compression band	$0.1
Fixings & fasteners	$0.1
Ventilated Stack Enclosure	$0.3
Stack assemlby	$0.8
Stack conditioning	$0.4
Stack Total Cost ($/kW)	$63.6

Class 8 Truck Stack Cost ($64/kW$_{net}$)



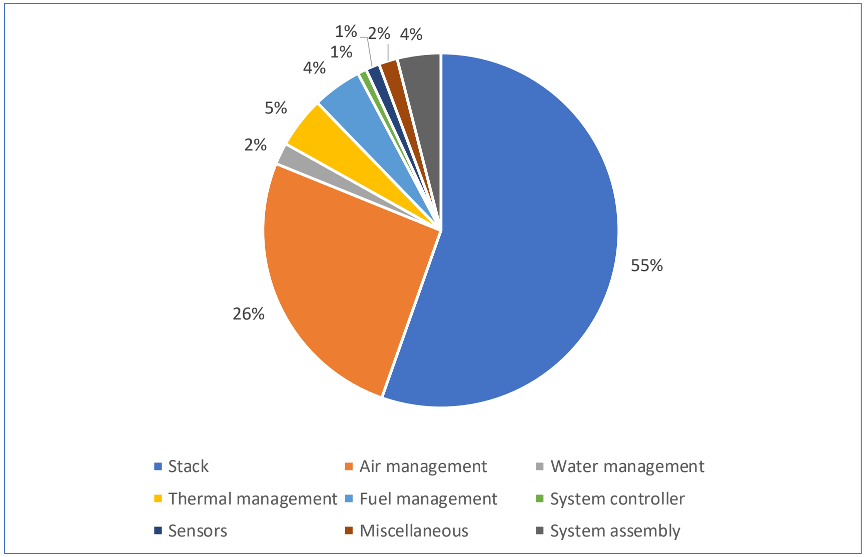
1. Results may not appear to calculate due to rounding of the component cost results.
2. Actual stack production volume: 20,000 stacks/yr.

PEMFC System Costs

The class 8 truck fuel cell system costs approximately $115/kW at the production volume of 10,000 systems/year.

System Components	Class 8 Truck System Cost ($/kW)
Stack	$63.58
Air management	$29.56
Water management	$2.27
Thermal management	$5.35
Fuel management	$5.16
System controller	$0.93
Sensors	$1.44
Miscellaneous	$1.94
System assembly	$4.55
Total:	$114.78

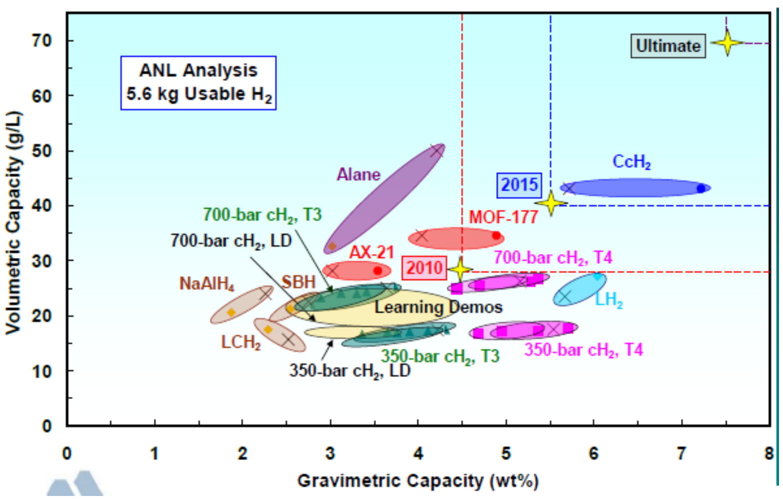
Class 8 Truck System Cost ($115/kW$_{net}$)

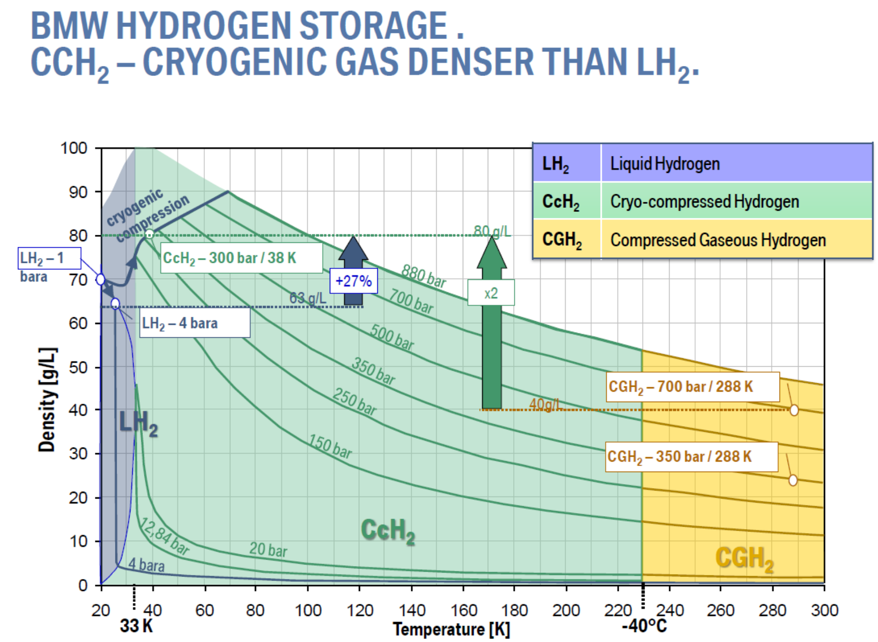


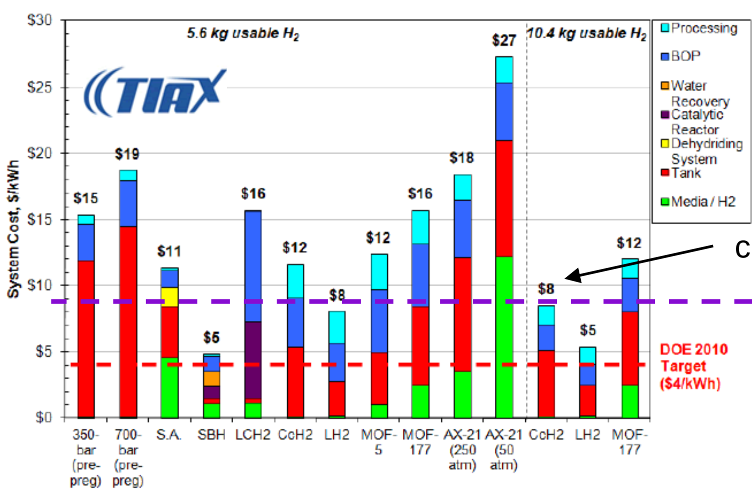
1. Assumed 15% markup to the automotive OEM for BOP components
2. Results may not appear to calculate due to rounding of the component cost results.

Cryo-Compressed H2 Storage System Configurations

The cryo-compressed hydrogen tank has advantages in gravimetric density, volumetric density, and cost.





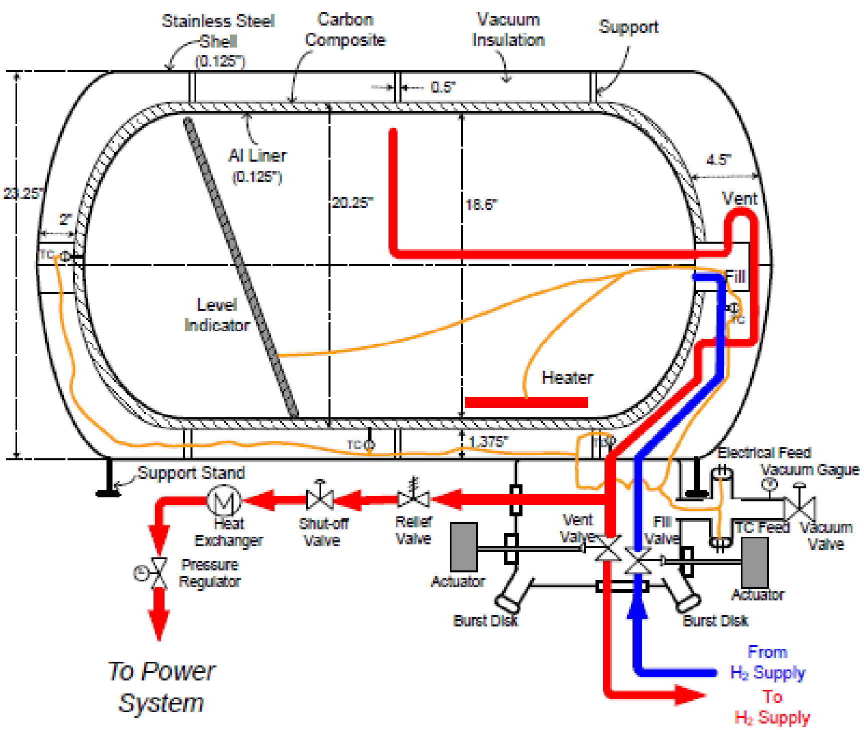


Cryo-compressed H2 Tank

- US Department of Energy Hydrogen Storage Cost Analysis, 2013, TIAX; Cost is based on 500,000 units/year
- System level analysis of hydrogen storage options, R. K. Ahluwalia, 2010
- Cryo-compressed hydrogen storage, BMW 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

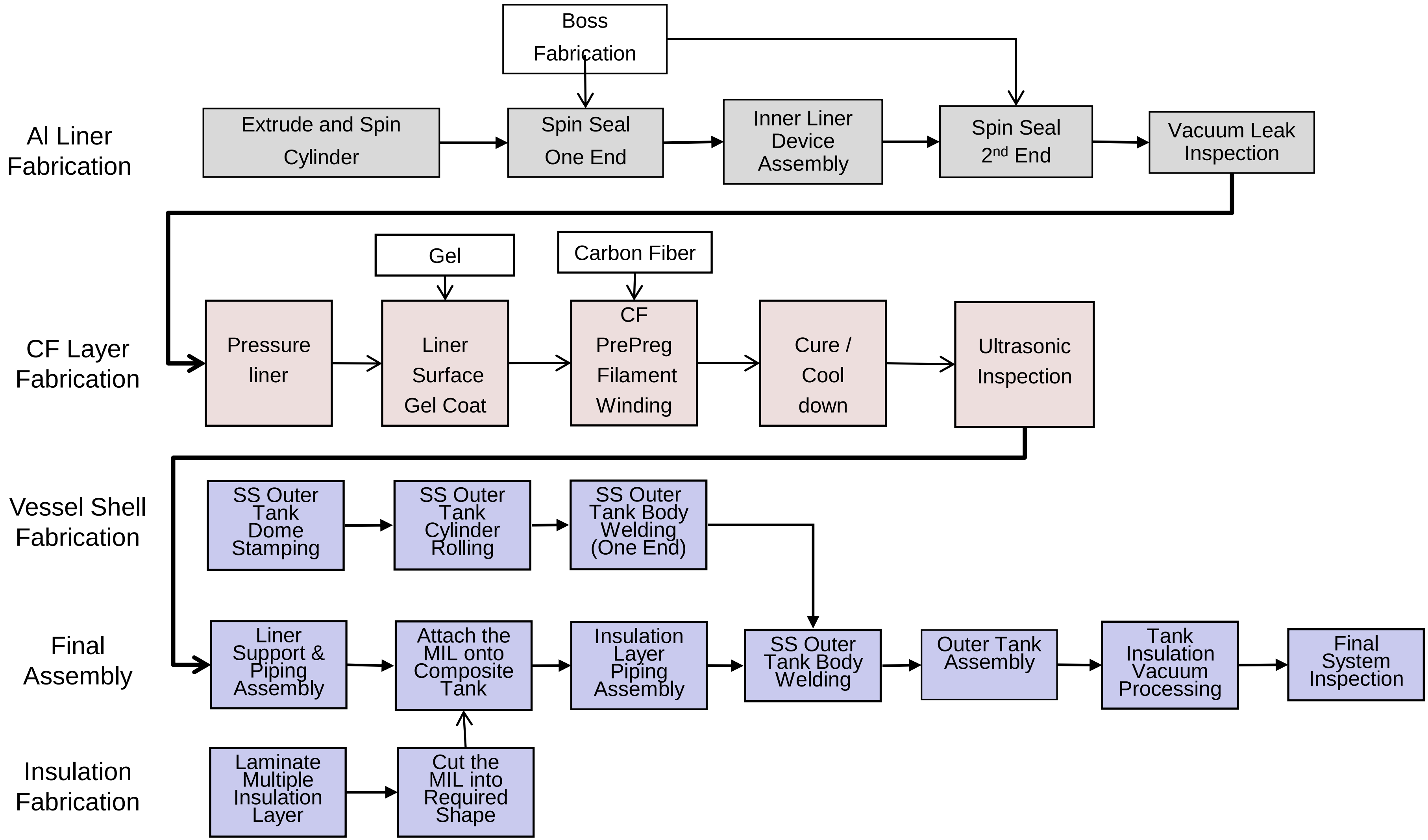
Tank
- Carbon fiber: Toray T700S
- Carbon fiber / resin ratio: 0.68 : 0.32 (weight)
- Translational strength factor: 81.5%
- Safety factor: 2.25
- Carbon fiber composite layer thickness: 12 mm
- Liner: 3mm Al
- Vacuum gap: 40 mm with 40 layers of MLVI
- Outer Shell: 3 mm thick SS304
- Gravimetric capacity: 7.1 wt%
- Volumetric capacity: 44.5 kg/m³

The single tank design has 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	Class 8 Truck
Production volume	tanks/year	60,000
Usable hydrogen	Kg	10.1
Total H2 in the tank	Kg	10.7
Tank type		III
Tank max pressure	PSI	5,000
# of tanks	Per System	6
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
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

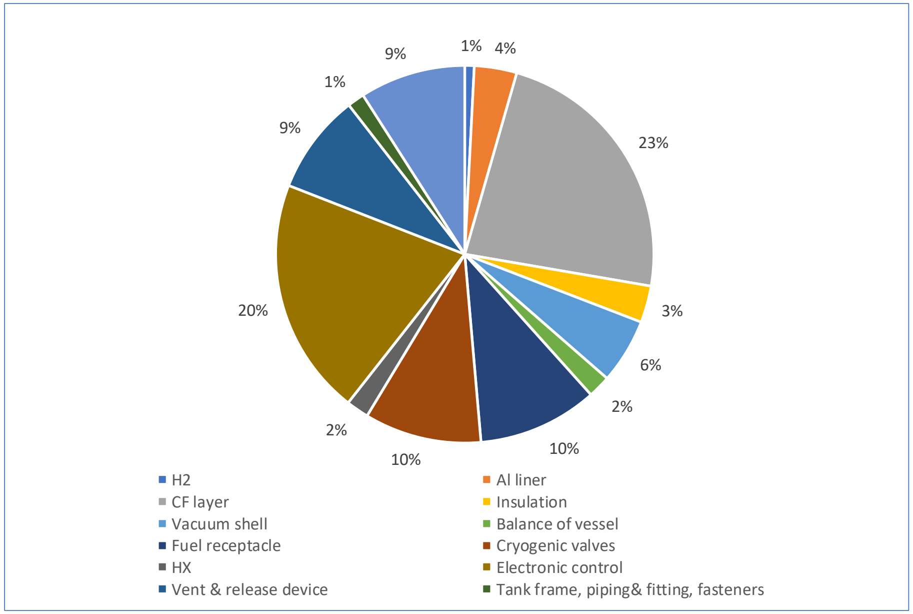
A vertically integrated manufacturing process is assumed for the tank and BOP components.



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

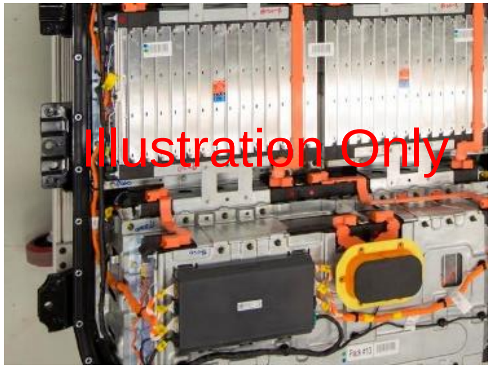
System Components	Class 8 Truck System Cost ($/kWh)
H2	0.10
Al liner	0.45
CF layer	2.88
Insulation	0.39
Vacuum shell	0.69
Balance of vessel	0.24
Fuel receptacle	1.27
Cryogenic valves	1.24
HX	0.24
Electronic control	2.52
Vent & release device	1.06
Tank frame, piping& fitting, fasteners	0.18
Assembly & testing	1.12
Total:	12.37

Class 8 Truck H2 Storage System Cost ($12.4/kWh)



- Cryo-compressed H2 tank production volume: 60,000 tanks/year (10,000 systems/year)

We use a 16 kWh lithium ion hybrid battery pack in the fuel cell truck powertrain.



Pack

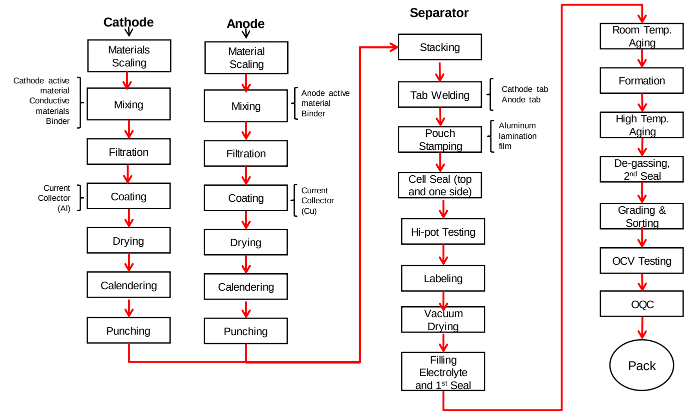
Specifications	
Battery pack energy	16 kWh
Battery module Output	350 kW
Cell size (Ah)	55
# of cells in pack	80
# of cells in module	20
# of modules in pack	4
Anode active material	Graphite/Si
Cathode active material	NMC622

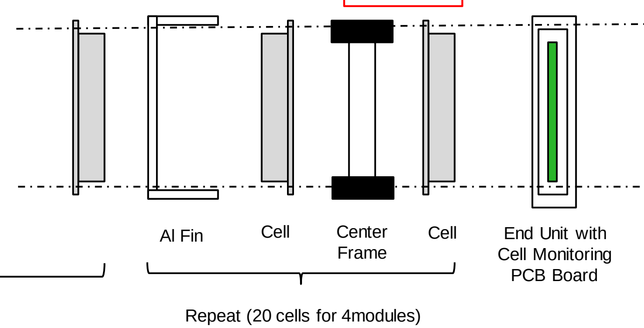
We analyze the cells, modules, and pack cost using bottom-up approach.

Cell

Module

Pack

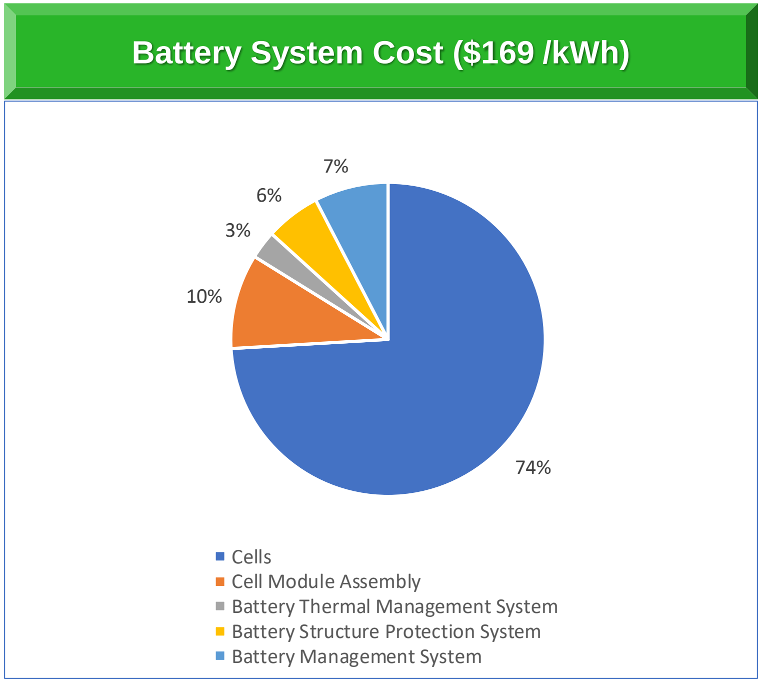




Thermal Management System	+	Structure Protection System	+	Battery Management System

The hybrid lithium ion battery pack costs $169/kWh. Cells, cell module assembly, and battery management system have higher cost contributions.

Cost Category	Pack Cost ($/kWh)
Cells	$125.00
Cell Module Assembly	$16.50
Battery Thermal Management System	$4.89
Battery Structure Protection System	$9.54
Battery Management System	$12.84
Total ($/kWh)	$168.76



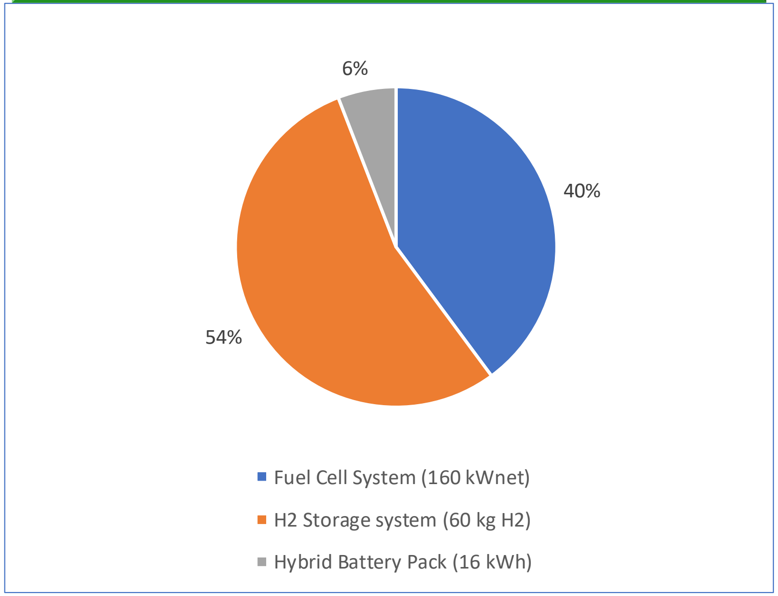
The 16 kWh lithium-ion battery system costs $2,700 per pack at the annual production volume of 10,000 packs.

Conclusions

PEM fuel cell system, onboard hydrogen storage, and hybrid battery cost approximately $46,050 for class 8 fuel cell truck.

Cost Category	Class 8 Fuel Cell Truck
Fuel Cell System (160 kWnet)	$18,365
H2 Storage system (60 kg H2)	$24,985
Hybrid Battery Pack (16 kWh)	$2,700
Total:	$46,050
Comments	Production volume: 10,000/yr

Fuel Cell + H2 Tank + Battery Cost ($169 /kWh)



Thank You!

Contact: Yong Yang

Austin Power Engineering LLC

1 Cameron St,
Wellesley, MA 02482

+1 781-239-9988
+1 401-829-9239
yang.yong@austinpowereng.com
www.austinpowereng.com