PEM Fuel Cell System Manufacturing Cost Analysis for Automotive Applications

Yong Yang

President

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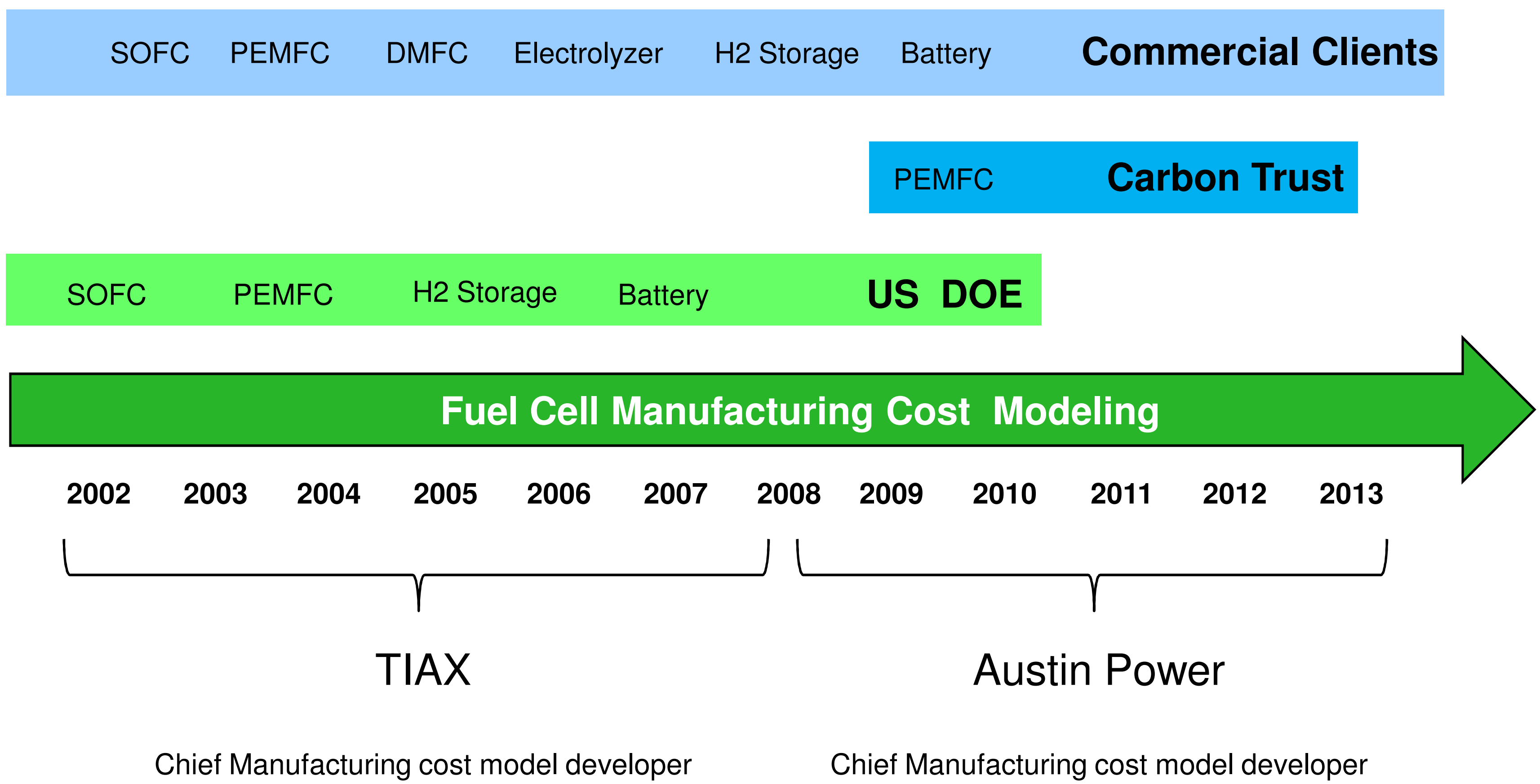
Austin Power Engineering LLC
2310 W 9th ST UNIT 1
Austin, TX 78703
USA

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

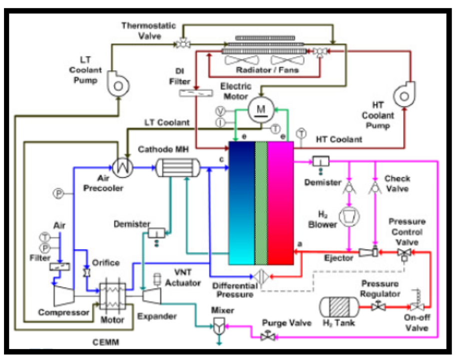
Have been working on fuel cell manufacturing cost modeling for US DOE, UK Carbon Trust, and commercial clients since 2002.

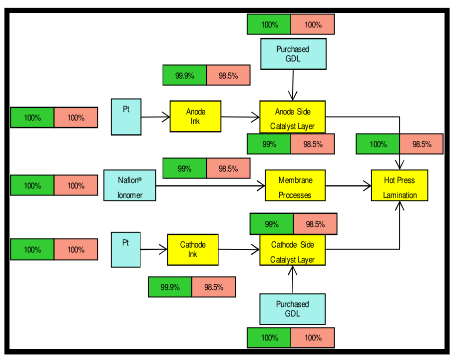


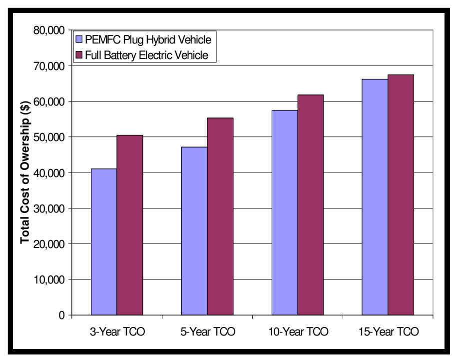
Approach Manufacturing Cost Modeling Methodology

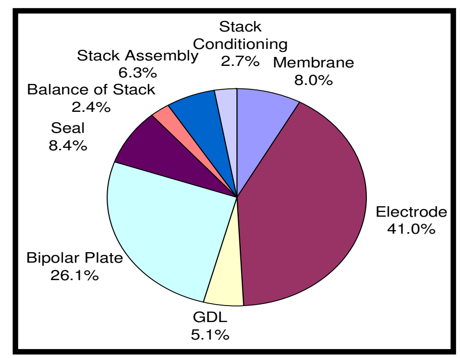
This approach has been used successfully for estimating the cost of various technologies for commercial clients and the DOE.

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



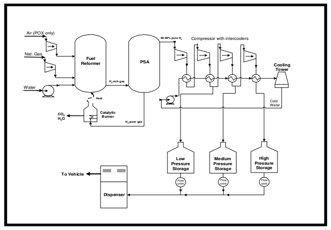






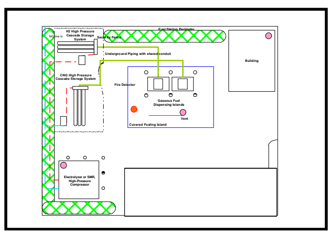
Combining performance and cost model will easily generate cost results, even when varying the design inputs.

Conceptual Design



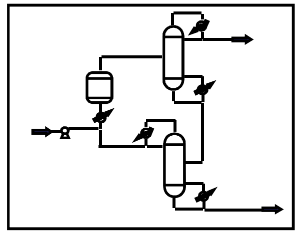
- System layout and equipment requirements

Site Plans



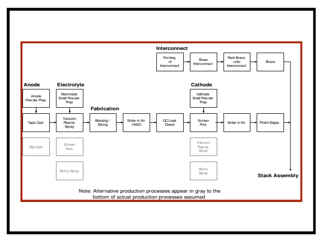
- Safety equipment, site prep, land costs

Process Simulation



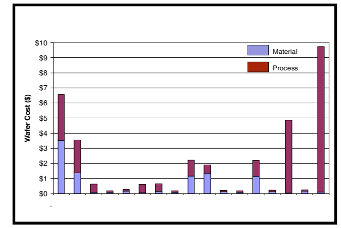
- Energy requirements
- Equipment size/ specs

Capital Cost Estimates



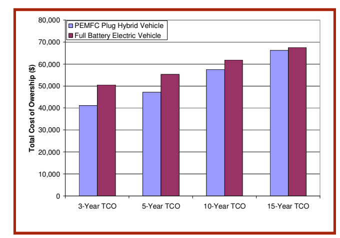
- High and low volume equipment costs

Process Cost Calcs



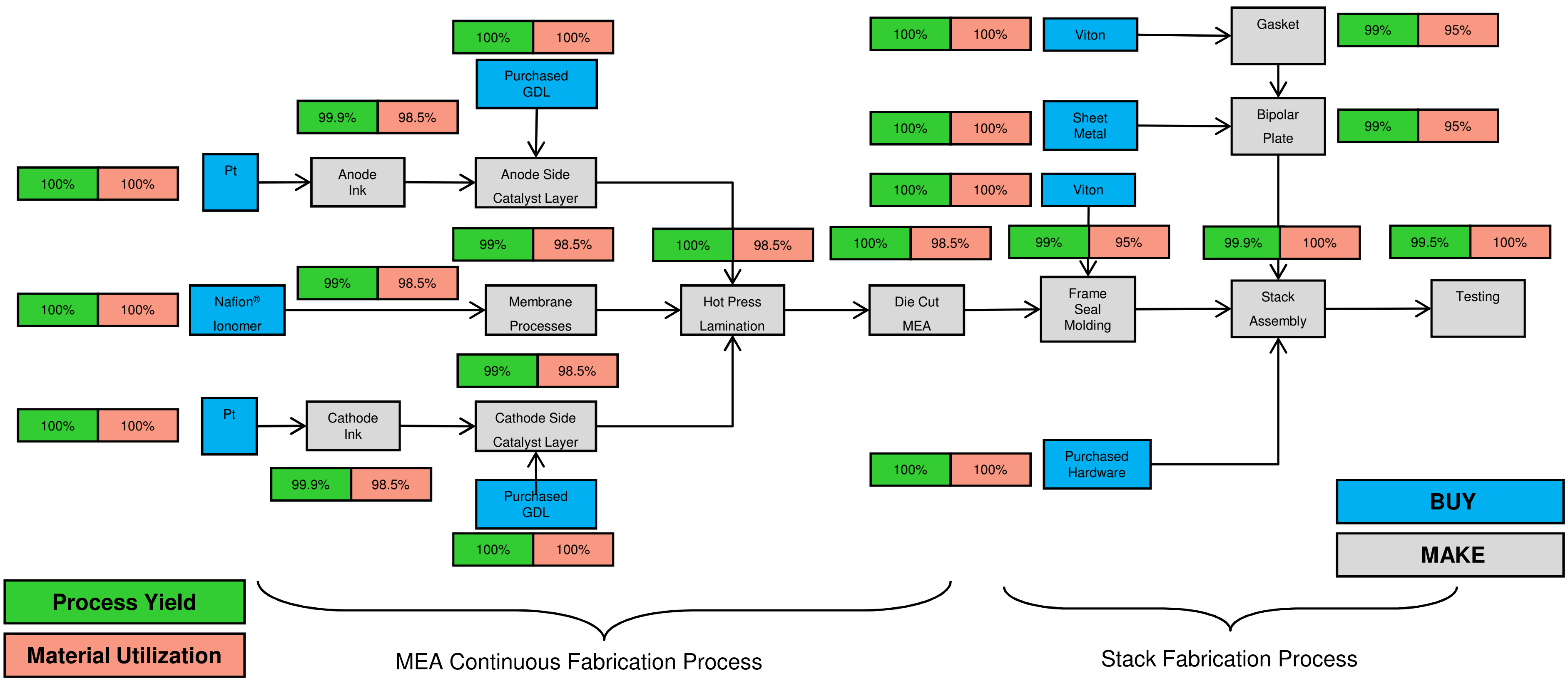
- Process cost
- Material cost

Product Costs



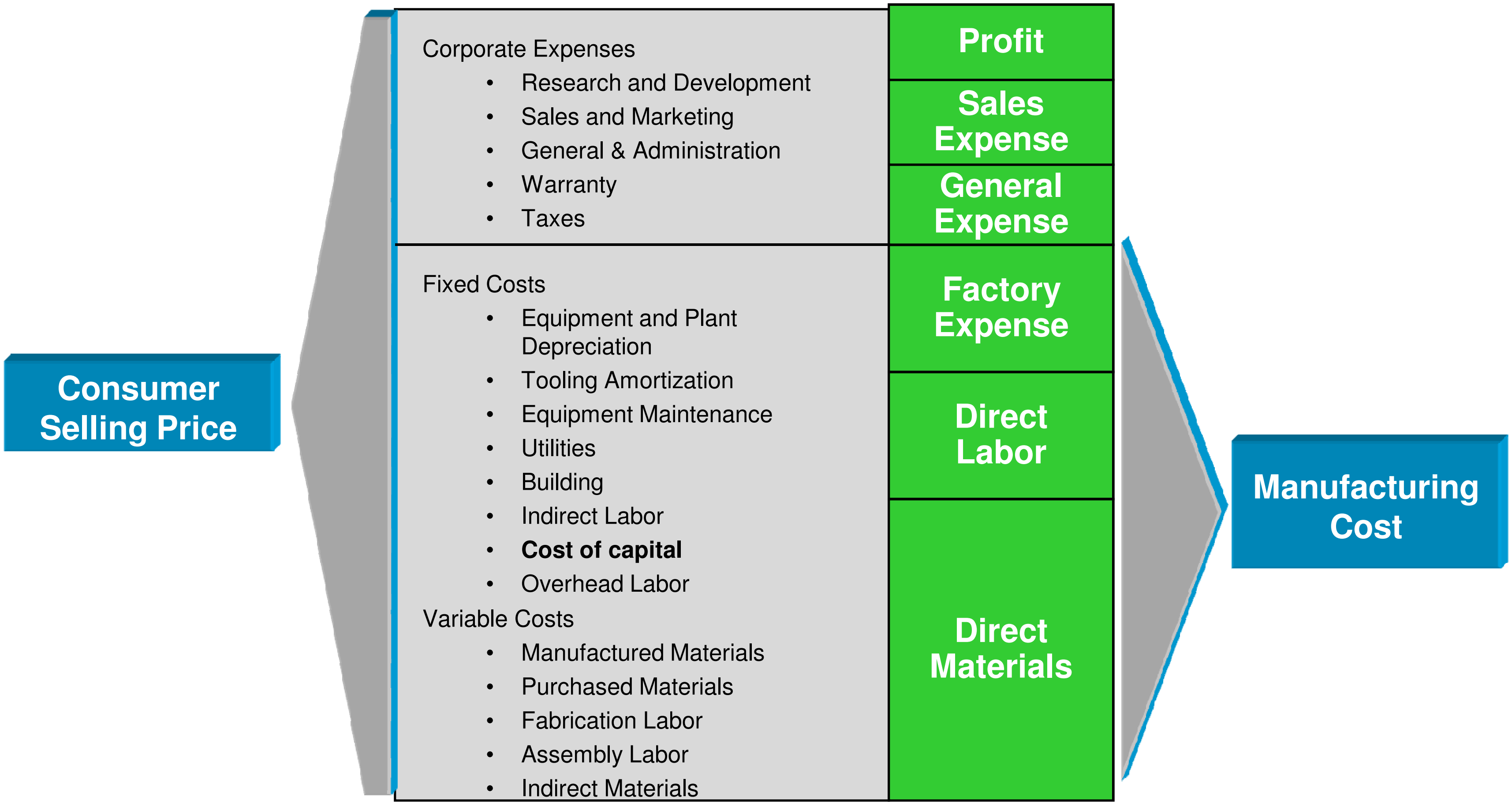
- Product cost (capital, O&M, etc.)

The bottom-up cost approach will be used to capture accurately 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.

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, a 25-year building life, and three months working capital.

Approach Scope

Our cost assessment includes a fuel cell system, an on-board H2 storage, and a hybrid battery pack which is for a middle size passenger vehicle.

PEMFC System

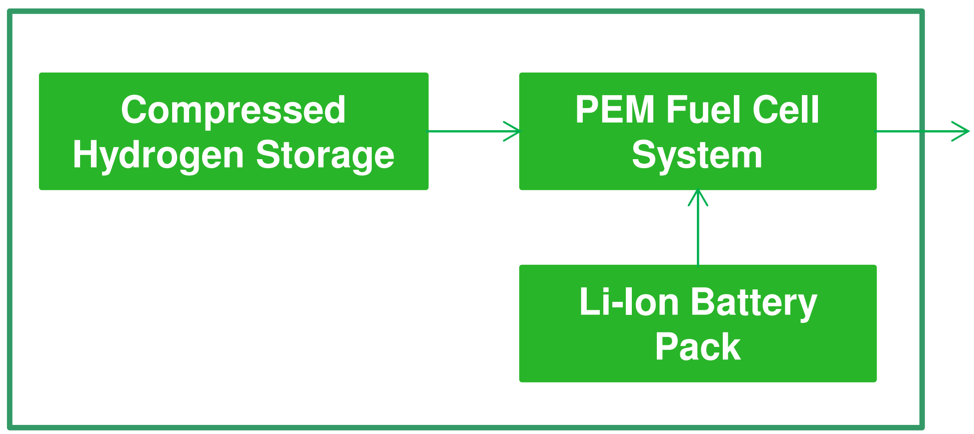
- *80 kW$_{net}$ Stack*
  - *Membrane*
  - *Electrode*
  - *GDL/MPL*
  - *Bipolar Plate*
  - *Seal & Gasket*
  - *Balance of Stack*
- *BOP*
  - *Fuel Management*
  - *Thermal Management*
  - *Air Management*
  - *Water Management*
- *Balance of System*
  - *Control Board*
  - *Valves & Sensors*
  - *Fittings & Piping*
  - *Wire Harness*
  - *Others*
- *Assembly, QC, and Conditioning*

On-board H2 Storage

- *Type IV Composite Tank*
- *Fill Port*
- *High Pressure Regulator*
- *Valves & Sensors*
- *Fittings & Piping*
- *Assembly & Inspection*

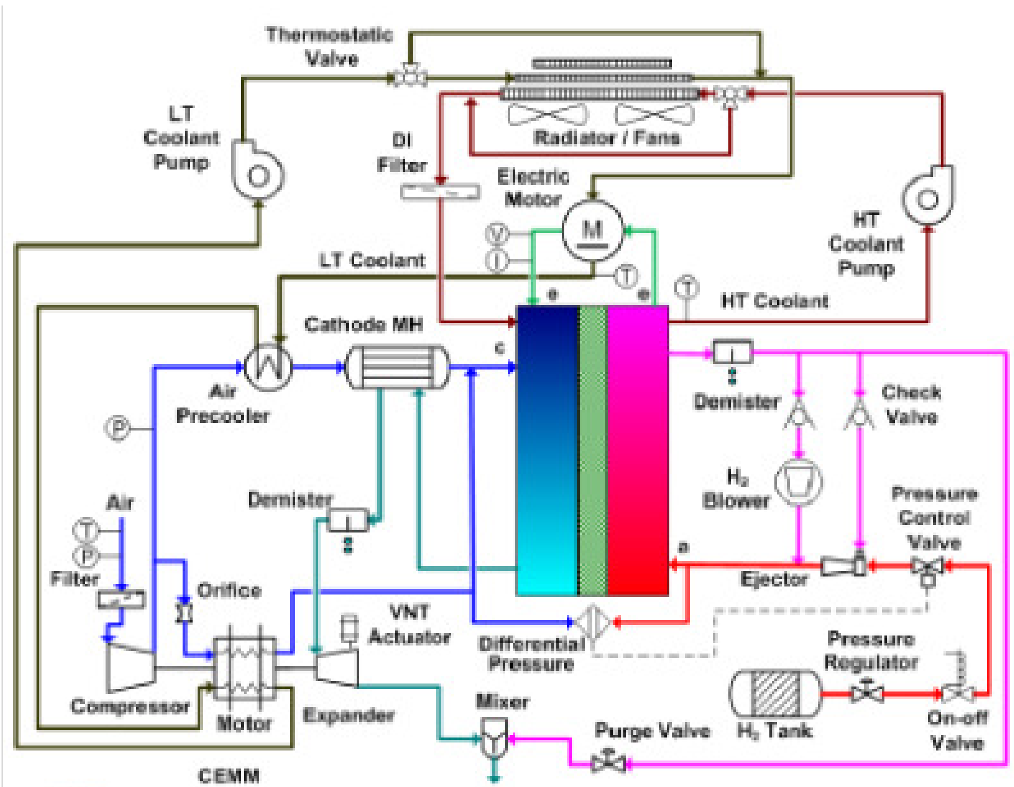
Hybrid Battery

- *Li-Ion hybrid battery (40kW, 1.2kWh)*



Fuel Cell Hybrid Electric Vehicle Power System

The 80 kW_{net} direct hydrogen PEM fuel cell system configuration was referenced in previous and current studies conducted by Argon National Laboratory (ANL).



80 kW_{net} Fuel Cell System Schematic[1]

1. DOE Fuel Cell Technologies Program Record , "Fuel Cell System Cost -2012"
2. R. K. Ahluwalia, X. Wang, and R. Kumar, "Fuel cells systems analysis," 2012 DOE Hydrogen Program Review, Washington DC, May 14-18, 2012.

Key Parameters

Stack
- 3M NSTFC MEA
- 25 µm supported membrane
- 0.196 mg/cm² Pt
- Power density: 984 mW/cm²
- 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 ejector / pump hybrid

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

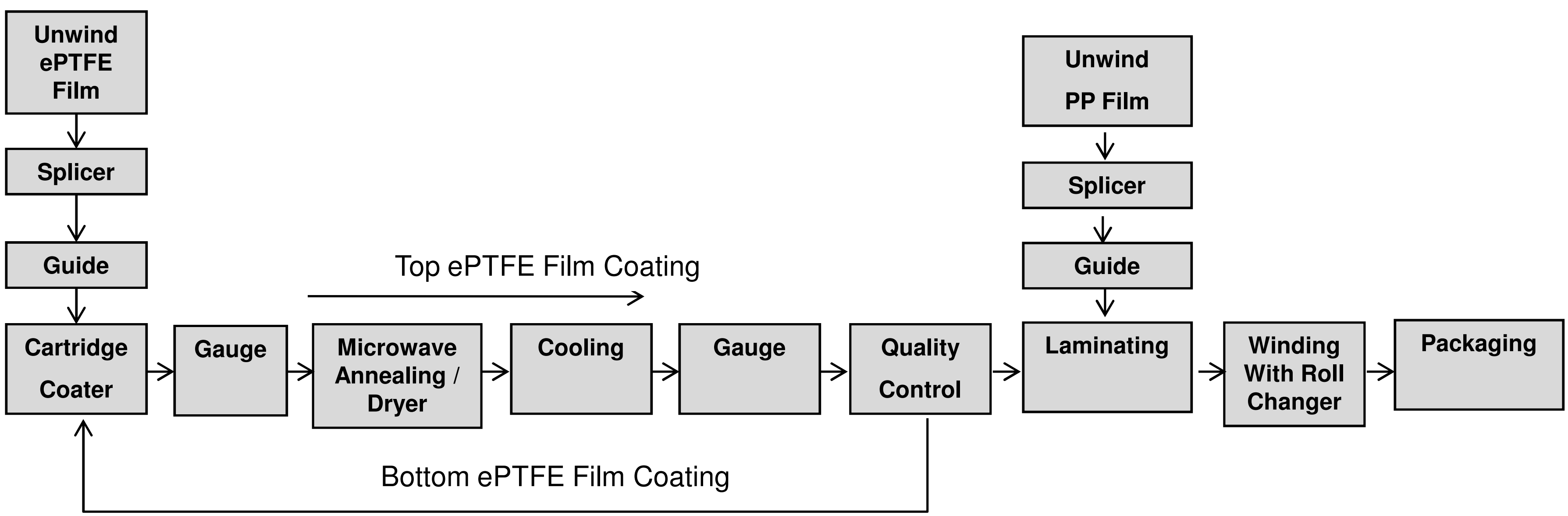
Stack Components	Unit	Current System	Comments
Production volume	systems/year	500,000	High volume
Stacks' net power	kW	80	DOE 2012
Stacks' gross power	kW	88	DOE 2012
Cell power density	mW/cm^2	984	DOE 2012
Peak stack temp.	Degree C	87	DOE 2012
Peak stack pressure	Bar	2.5	DOE 2012
System Voltage (rated power)	Volt	300	DOE 2012
Platinum price	$/tr.oz.	$1,100	DOE 2012
Pt loading	mg/cm^2	0.196	DOE 2012
Membrane type		Reinforced 3M PFSA	
Membrane thickness	micro meter	25	
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 $1,100/tr.oz. for the baseline, which was consistent with other DOE cost studies.

We assumed a double-side dispersion coating process (US 2008/0269409) to an ePTFE-supported membrane process.

	ePTFE	3M PFSA Supported Membrane
Thickness (µm)	25	25
Porosity (%)	95%	-
Bulk Density (g/cm^3)	0.098	1.97
Material Cost	$5/m^2	3M Ionomor:$80/lbs*

* DOE FCTT feedback

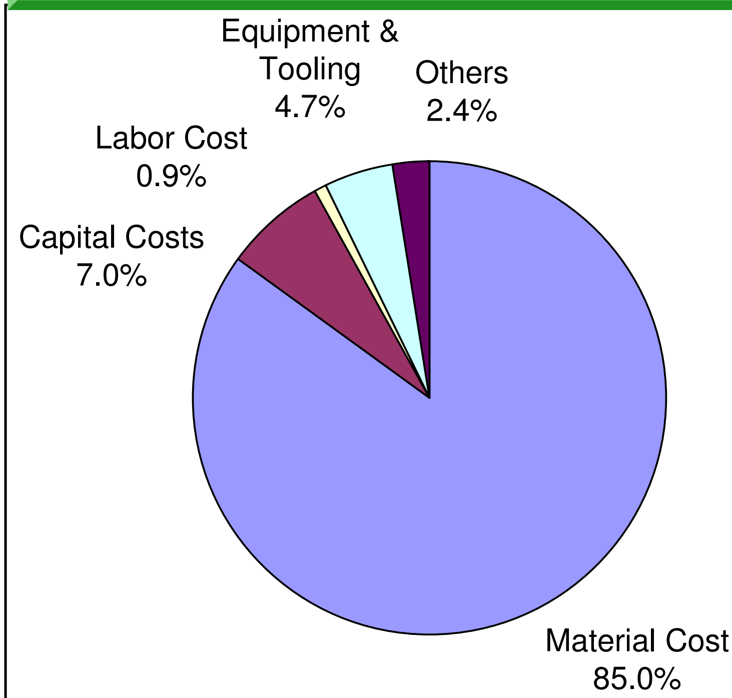


The reinforced 25 µm 3M PFSA membrane is estimated to cost ~$19/m² on an active area basis, with materials representing ~85% of the cost.

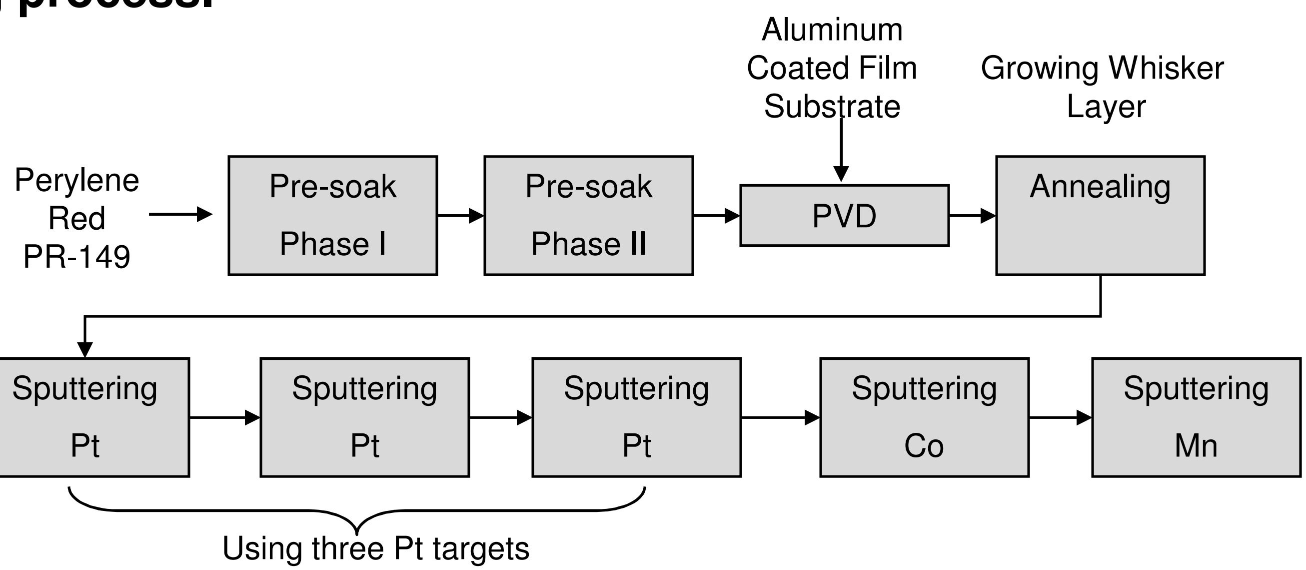
Membrane Manufactured Cost[1]				
Component	Material		Process	
	($/m²)	($/kg)	($/m²)	($/kg)
Film Handling	$6.33	$107.64	$0.34	$5.78
Coating	$10.07	$171.11	$0.44	$7.42
Drying & Cooling	$0.00	$0.00	$1.98	$33.64
Quality Control	$0.00	$0.00	$0.04	$0.60
Laminating	$0.00	$0.00	$0.05	$0.93
Packaging	$0.03	$0.43	$0.03	$0.46
Subtotal	$16.42	$279.19	$2.87	$48.83
Total	**19.30 ($/m²)**			
	328.02 ($/kg)			

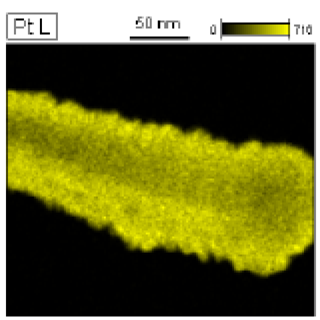
[1] Manufactured cost on an active area basis or per kg of finished membrane basis (accounts for scrap and yield)
[2] 3M PFSA ionomer cost assumed to be $80/lb based on FCTT feedback.
[3] ePTFE cost assumed to be $5/m²

Membrane Manufactured Cost ($19/m²)

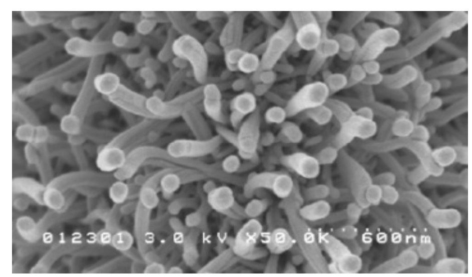


Organic whisker support was fabricated by physical vapor deposition (PVD) with vacuum annealing process. Catalysts were coated to this layer via vacuum sputtering process.





Pt Whisker Distribution[1]



Nanostructured Thin Film Catalyst before transfer to a PEM[2]

[1] M. K. Debe, Advanced Cathode Catalysts and Supports for PEM Fuel Cells, DOE Merit Review, May 2012

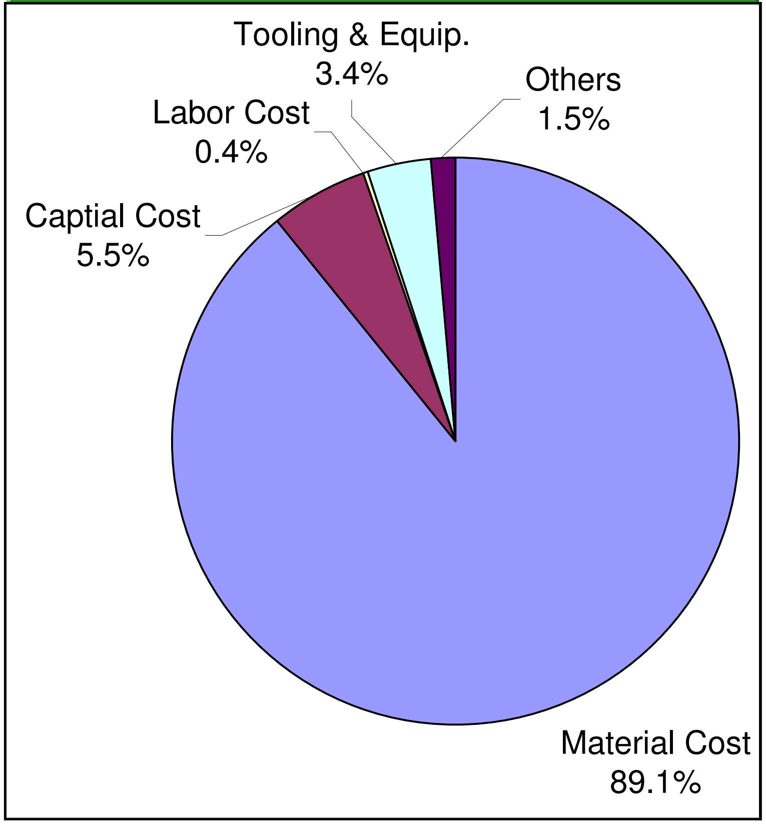
[2] M. K. Debe, Durability Aspects of Nanostructured Thin Film Catalysts for PEM Fuel Cells, ECS Transactions, 1(8) 51-66 (2006)

The 2012 electrode cost estimate of $86/m² which was dominated by Platinum price. We have assumed Pt price to be $1,100/tr.oz. or $35.4/g.

Manufactured Cost	Anode[1] ($/m²)	Cathode[1] ($/m²)	Total[1] ($/m²)
Material	$25.97	$50.33	$76.30
Capital Cost	$1.79	$2.94	$4.73
Labor	$0.16	$0.19	$0.35
Tooling	$1.18	$1.75	$2.93
Other[2]	$0.53	$0.76	$1.29
Total	$29.63	$55.97	$85.60

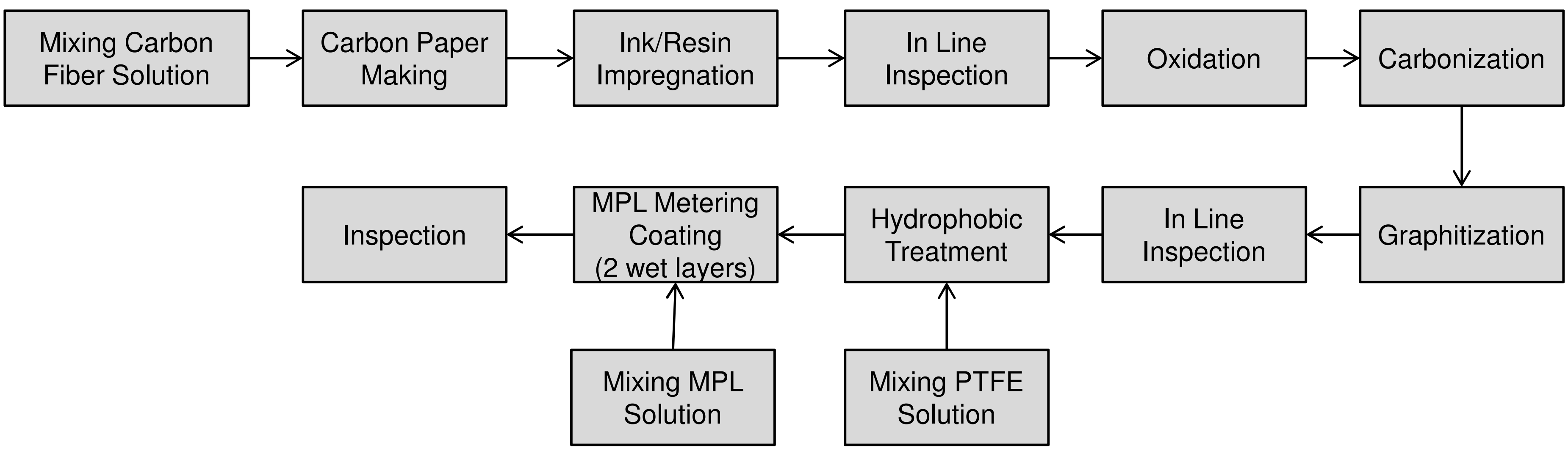
[1] m² of active area
[2] Other costs include utilities, maintenance, and building

Electrode Manufactured Cost ($86/m²)



We cost a non-woven carbon paper GDL with MPL based on discussions with formerly Ballard Material Products on their AvCarb® GDS3250 for automotive applications.

Material	Pressure (kPa)	Bare GDL	GDL with PTFE Treatment	GDL with PTFE Treatment + MPL
Thickness (µm)	50	185		225
Porosity (%)	250	90%	88%	80%
Areal Weight (g/m^2)		40	44	75
Materials		Carbon Fiber loading: 15 /m^2 Ink/Resin loading: 25 g/m^2	10 wt% PTFE; 4 g/m^2	PTFE loading: 15 g/m^2 Carbon black loading: 16 g/m^2

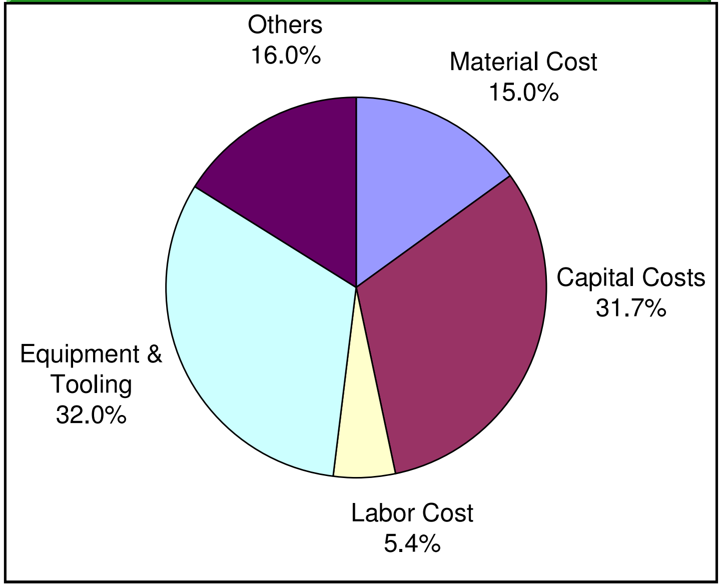


The non-woven carbon paper GDL (for *both* anode and cathode) cost about $12/m^2, on an active area basis.

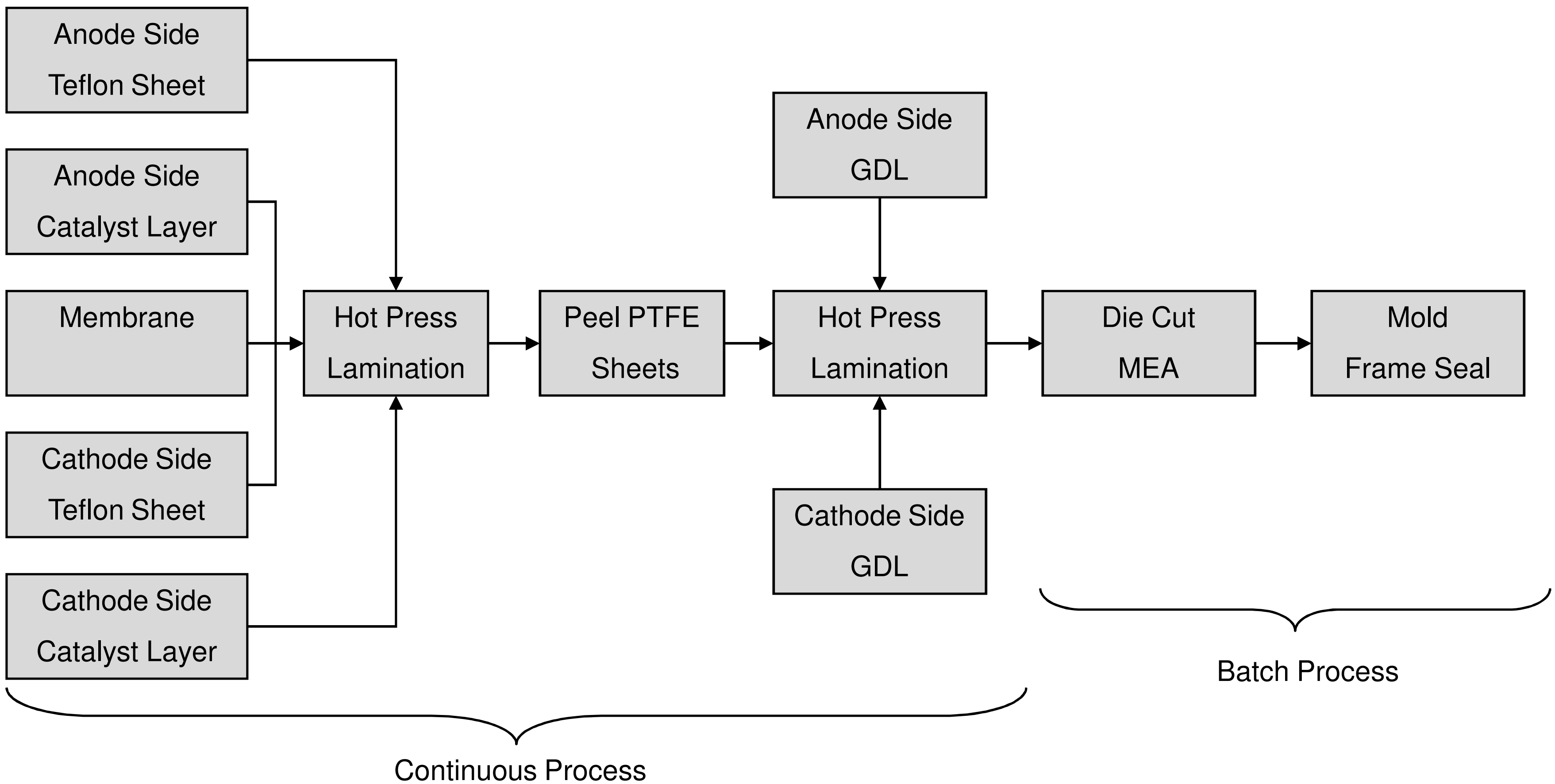
Manufactured Cost[1]	GDL ($/m^2)	GDL (Anode + Cathode) ($/m^2)
Material	$0.88	$1.76
Capital Cost	$1.86	$3.71
Labor	$0.31	$0.63
Tooling	$1.88	$3.76
Other[2]	$0.94	$1.88
Total	$5.87	$11.73

[1] Manufactured cost on an active area basis
[2] Other costs include utilities, maintenance, and building

GDL Manufactured Cost ($12/m^2)



The anode and cathode organic whisker layers were hot pressed to the membrane with Teflon® backing sheets. GDL layers were laminated to the coated membrane and were formed an MEA in roll good form. The MEA was cut into sheets and molded with a frame seal.

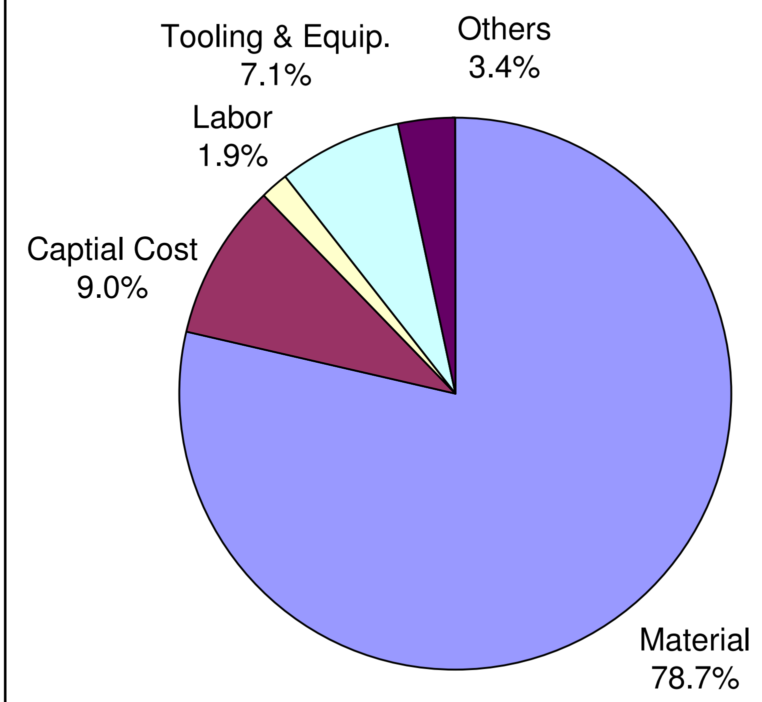


The MEA with frame seal together were estimated to cost about $128/m².

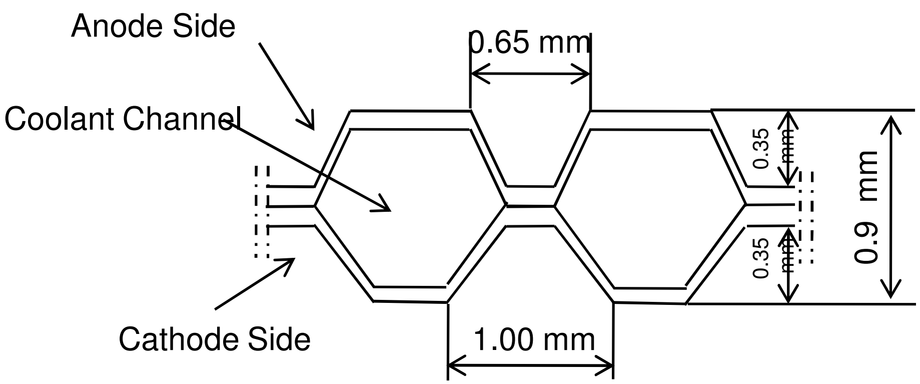
Manufactured Cost[1]	MEA ($/m²)	Frame Seal ($/m²)
Material *- Membrane* *- Electrode* *- GDL*	94.48 - 16.42 - 76.30 - 1.76	$6.07
Capital Cost	$9.80	$1.71
Labor	$1.15	$1.24
Tooling & Equipment	$7.60	$1.46
Other[2]	$3.63	$0.70
Subtotal	$116.65	$11.17
Total	**127.83**	

[1] Manufactured cost on a per m² of active area basis
[2] Other costs include utilities, maintenance, and building
[3] Active area to Total area ratio reduced from 85% to 75%, based on feedback from OEMs and FCTT

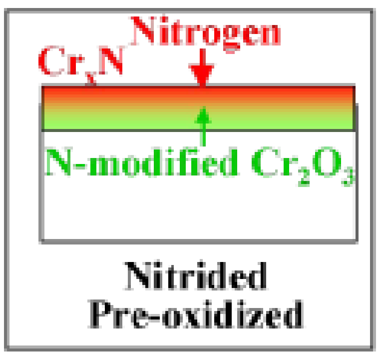
MEA & Seal Manufactured Cost ($128/m²)



The metal bipolar plate cost was based on discussions with ORNL on their thermal nitriding process[1] for specific alloys, e.g. Fe-20Cr-4V.



Parameter	Specifications
Base Material Thickness (mm)	0.1
Base Material	76Fe-20Cr-4V
Base Material Surface Treatment	Pre-oxidation + Thermal Nitridation
# of Tiles in a Pair of Bipolar Plate	2
Cooling Channel	Yes
Joint Method	Spot + Edge Laser Welding



Ref.1

$Fe_{20}Gr_4V$ Foil
100 micro meter
Assume $5/lbs
→ Stamping Half Plate → Laser Welding Whole Plate → Thermal Nitridation[4]

Seven-Stage Progressive Die[2,3]

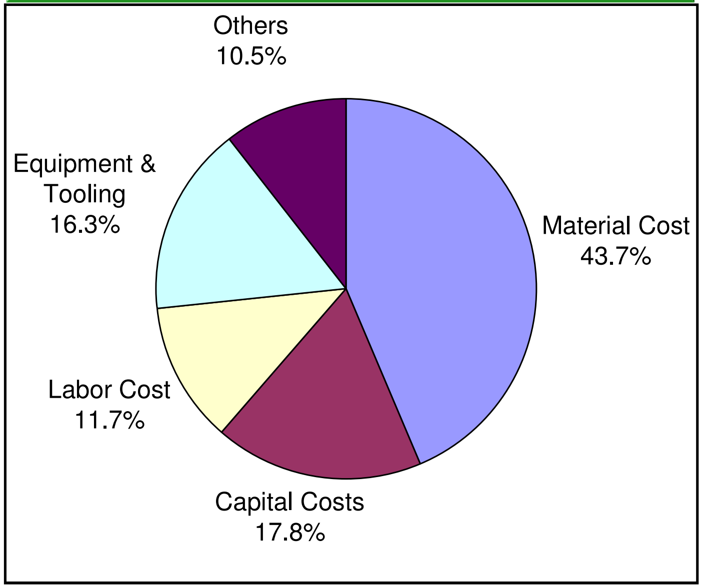
1. Nitrided metallic bipolar plates, M.P. Brady, et al., ORNL, DOE Merit Review presentation, May 2009
2. US 20090081520 (Hitachi)
3. Discussion with Minster Press Inc., April 2010
4. Preferential thermal nitridation to form pin-hole free Cr-nitrides to protect proton exchange membrane fuel cell metallic bipolar plates, M.P. Brady, et al., Scripta Materialia 50 (2004) 1017-1022

The cost of the nitrided Fe-20Cr-4V metal bipolar plates was estimated to be ~$57/m² or ~$6/kW.

	Bipolar Plate Manufactured Cost[1] ($/m²)		Bipolar Plate Manufactured Cost[2] ($/kW)	
Component	**Material**	**Process**	**Material**	**Process**
Stamping	$25.02	$11.06	$2.78	$1.23
Laser Welding	$0.00	$8.73	$0.00	$0.97
Nitridation	$0.00	$12.47	0.00	$1.39
Subtotal	$25.02	$32.26	$2.78	$3.58
Total	**$57.28**		**$6.36**	

[1] Manufactured cost on an active area basis
[2] Manufactured cost on a kW_{net} basis

Bipolar Plate Manufactured Cost ($57/m²)

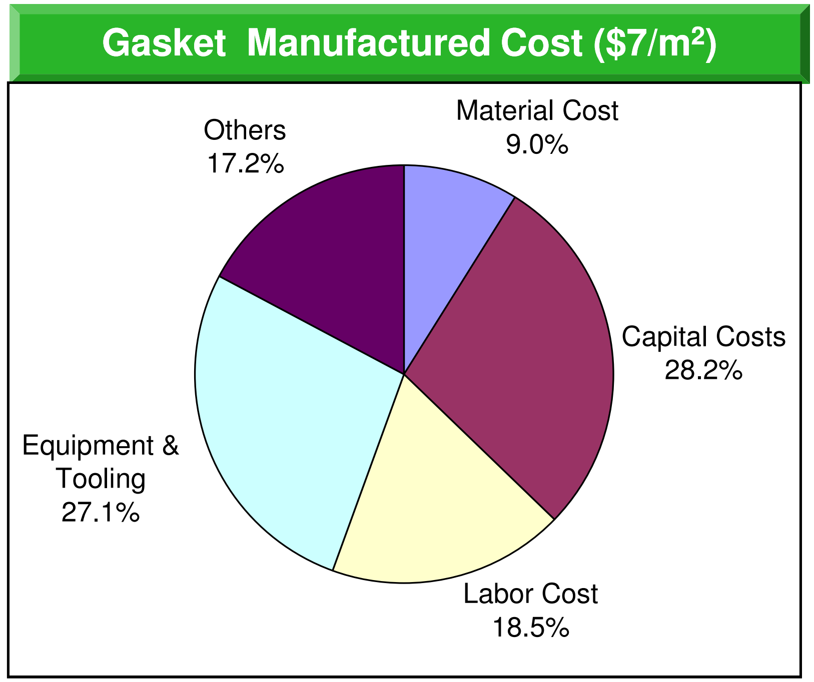


As a based material, Fe-20Cr-4V is a specialty metal and could have higher price than the conventional base materials, such as SS316, etc.

The cost of the gasket was estimated to be ~$7/m².

Manufactured Cost[1]	Gasket ($/m²)
Material	$0.62
Capital Cost	$1.93
Labor	$1.26
Tooling	$1.86
Other[2]	$1.18
Total	$6.85

[1] Manufactured cost on an active area basis
[2] Other costs include utilities, maintenance, and building

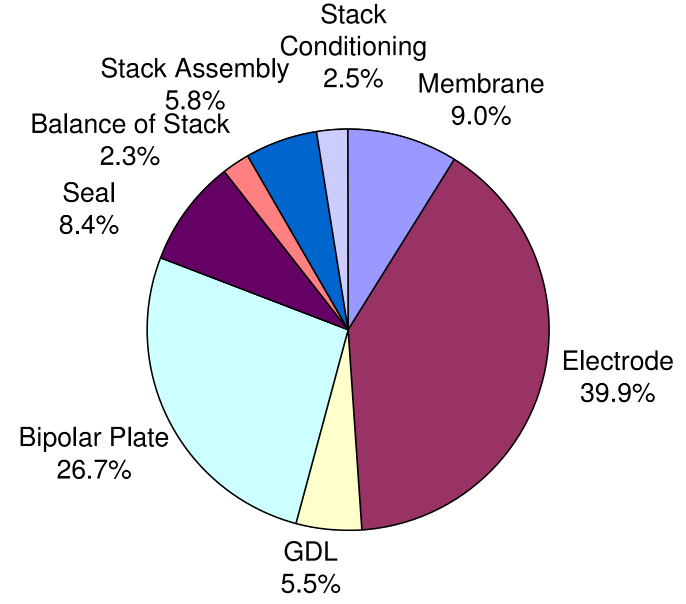


Transfer molding was used to fabricate the seals between the MEA and bipolar/cooling plate. The seal material is Viton® which costs ~$20/lb.

The 80 kW$_{net}$ PEM fuel cell stack cost $24/kW. Electrodes, bipolar plates, and membranes were the top three cost drivers.

Stack Components	Stack Manufacturing Cost ($/kW)	Comments
Membrane	$2.14	PFSA ionomer ($80/lb)
Electrode	$9.51	3M NSTFC
GDL	$1.30	No-Woven carbon paper
Bipolar Plate	$6.36	Nitrided metallic plates
Seal	$2.00	Viton
BOS	$0.55	Manifold, end plates, current collectors, insulators, tie bolts, etc.
Final Assembly	$1.40	Robotic assembly
Stack Conditioning	0.60	2 Hours
Total stack[2]	23.85	

80 kW$_{net}$ PEM Fuel Cell Stack Cost ($23.9/kW$_{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.

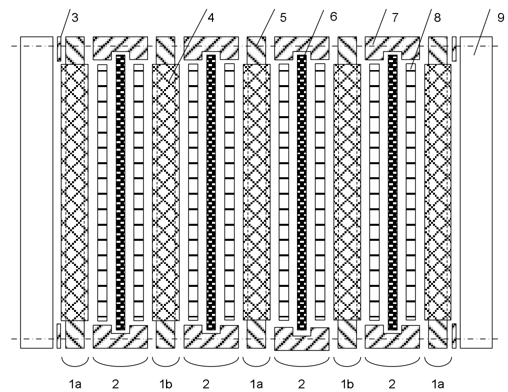
The water management system OEM cost[1,2] was projected to be $128.

Component	Factory Cost[1]	OEM Cost[1,2]
Cathode Planar Membrane Humidifier	112	128

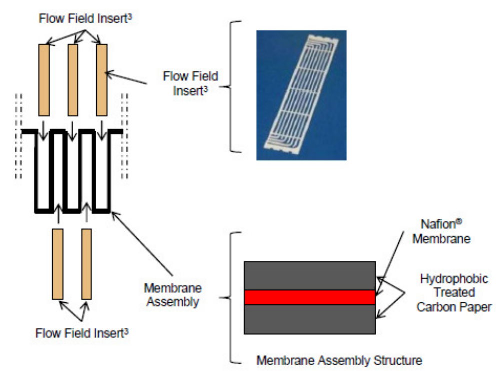
[1] R. K. Ahluwalia and X. Wang, Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading, July 21, 2009

[2] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

[3] Assumes 15% markup to the automotive OEM for BOP components



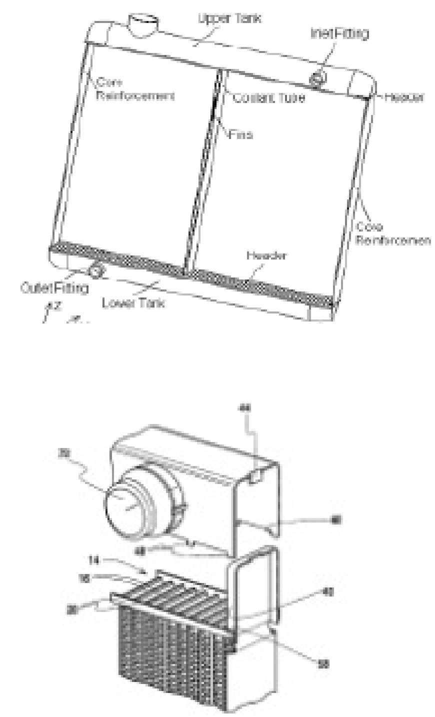
1a: Frame and foam unit to deliver air from fuel cell
1b: Frame and foam unit to deliver air to fuel cell
2: Gasket-GDL-Membrane unit
3: Endplate gasket
4: Metal/Carbon Foam
5: Frame
6: Membrane
7: Seal/Gasket
8: GDL
9: Endplate



The cathode planar membrane humidifier cost was estimated using bottom-up costing tools.

The thermal management system OEM cost[1,2] was projected to be $404.

Component	Factory Cost[1]	OEM Cost[1,2]
HT Radiator	86	99
LT Radiator	21	25
Air Precooler	-	20
HT/LT Radiator Fan	-	75
- Motor	-	- 60
- Fan	-	- 15
HT Coolant Pump	-	150
- Motor	-	- 95
- Pump	-	- 55
LT/Air Precooler Coolant Pump	-	30
Other	-	5
Total	**387**	**404**



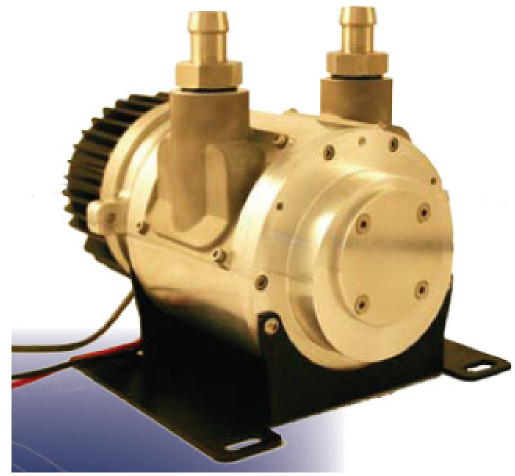
Radiator Structure
US Patent 7,032,656

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
[2] Assumes 15% markup to the automotive OEM for BOP components

The air precooler, radiator fan, coolant pumps, and their motors were assumed to be purchased components; hence their price included a markup.

The fuel management system OEM cost[1,2] was projected to be $382.

Component	Factory Cost[1]	OEM Cost[1,2]
H_2 Blower	219.5	252
H_2 Ejectors	-	20
H_2 Demister	-	61
Solenoid Valves	-	23
Purge Valve	13	15
Check valve	9	10
Total	**346**	**382**



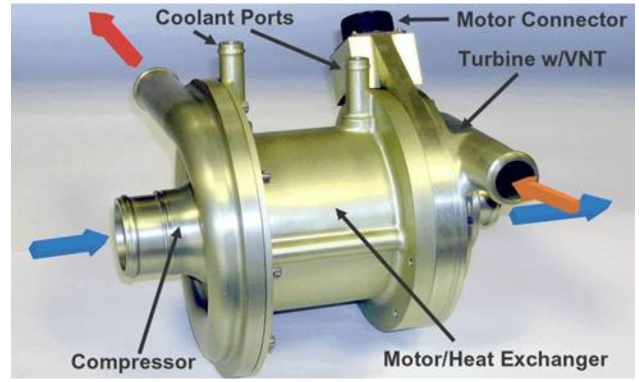
Parker Hannifin Brochure for Model 55 Univane™ Compressor

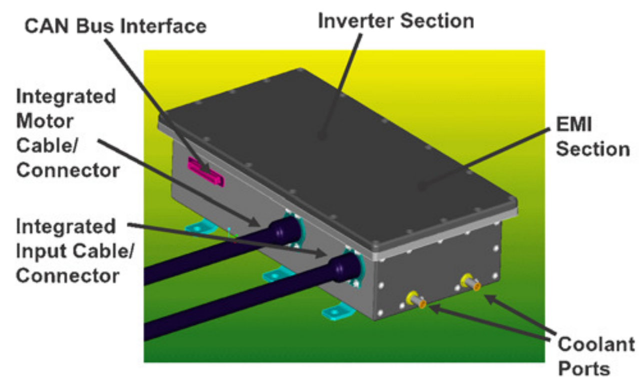
[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
[2] Assumes 15% markup to the automotive OEM for BOP components

The H_2 ejectors, H_2 demister, and solenoid valves were assumed to be purchased components; hence their price included a markup.

The air management system OEM cost[1,2] was projected to be $936.

Component	Factory Cost[1]	OEM Cost[1,2]
CEM (Compressor, Expander, Motor, Motor Controller	**535**	**615**
Air demister	-	156
Air/H_2 mixer	-	27
Flow orifice	-	5
Air filter	-	4
Total	**-**	**936**





CEM: Honeywell, DOE Program Review, Progress Report & Annual Report, 2005

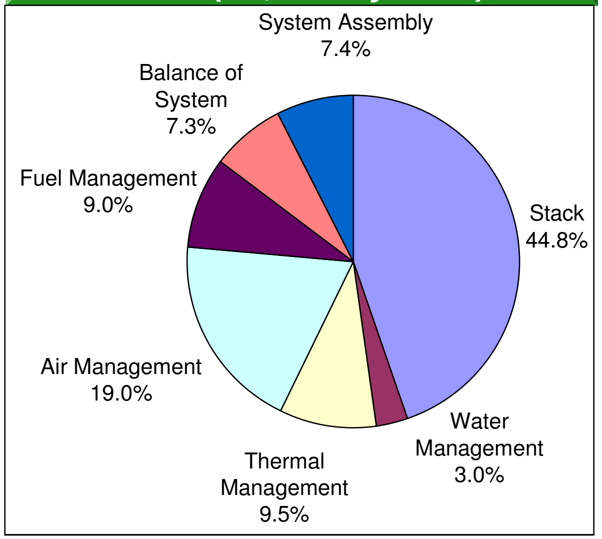
[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
[2] Assumes 15% markup to the automotive OEM for BOP components

The air demister, air/H_2 mixer, flow orifice, and air filter were assumed to be purchased components; hence their price included a markup.

The 80 kW$_{net}$ PEM fuel cell system cost $53/kW at the mass production volume. Stack, air management, and thermal management were the top three cost drivers.

System Components	System Manufacturing Cost ($/kW)	Comments
Stack	$23.87	
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]	**$53.2**	

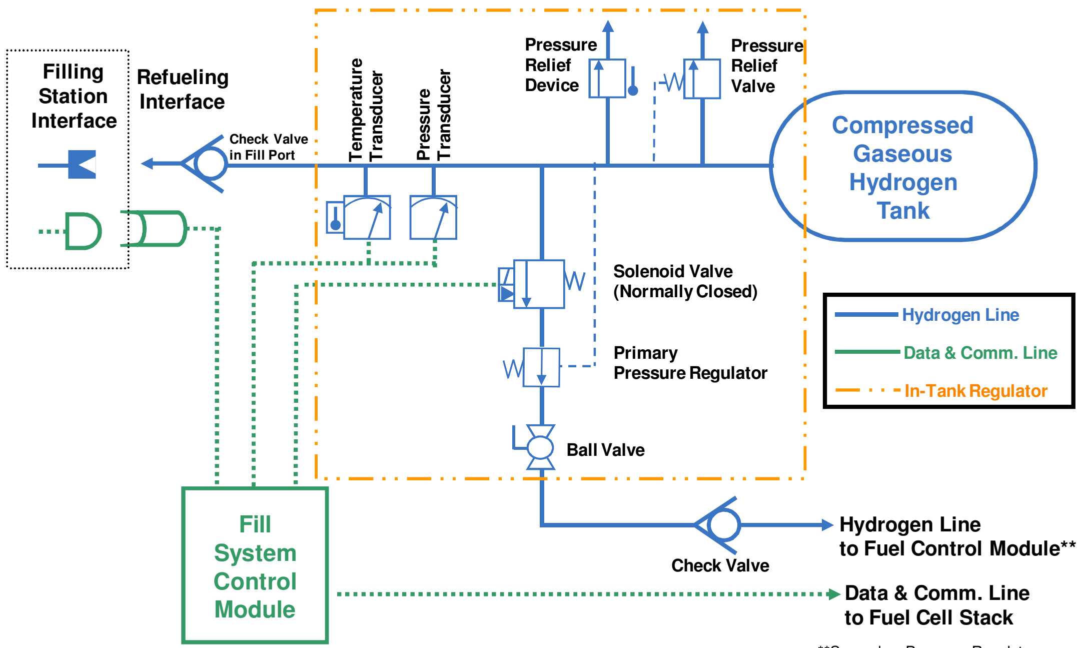
80 kW$_{net}$ PEM Fuel Cell System Cost ($4,256/system)



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 80 kW$_{net}$ direct hydrogen PEM fuel cell system cost $4,256 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].



*Schematic based on both the requirements defined in the draft European regulation for "Hydrogen Vehicles: On-board Storage Systems" and US Patent 6,041,762.

**Secondary Pressure Regulator located in Fuel Control Module.

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

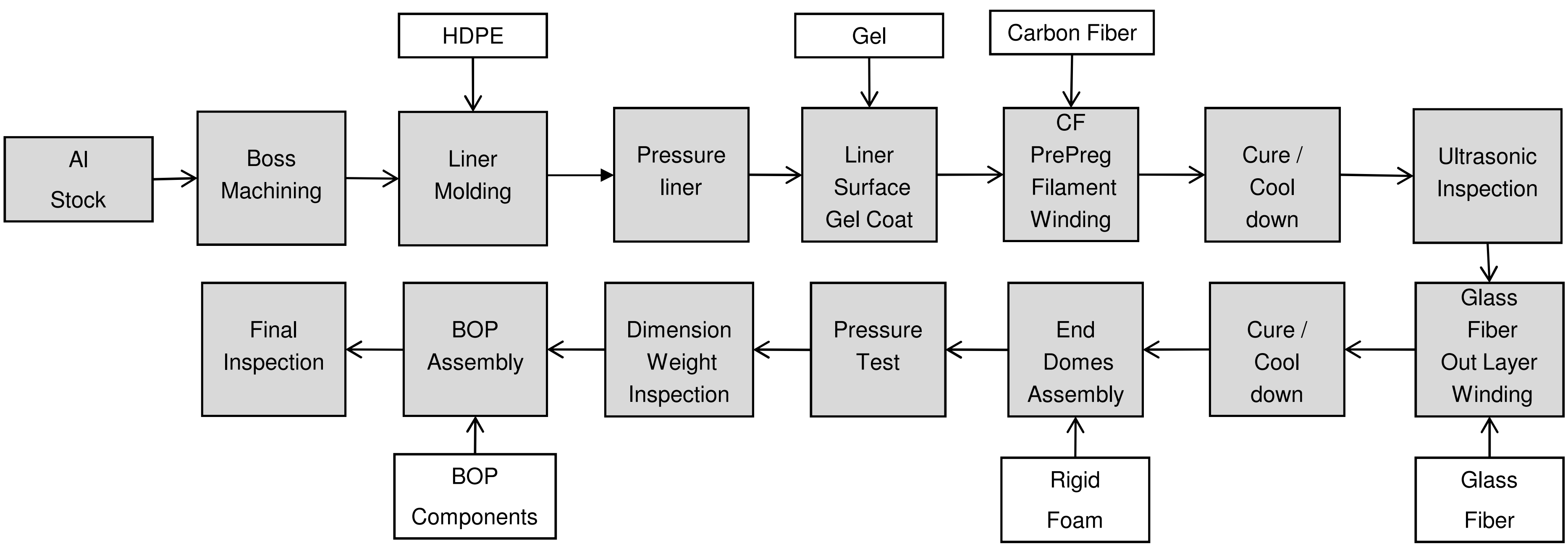
The single tank design had a usable hydrogen storage capacity of 5.6 kg.

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	

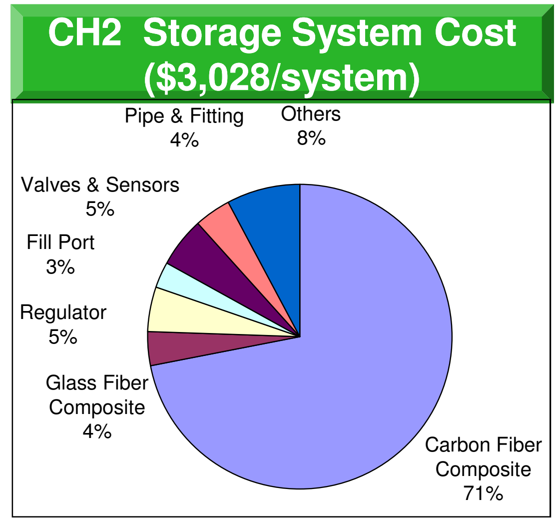
A vertically integrated manufacturing process was assumed for the tank and BOP components.

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 - Liner - Carbon fiber layer - Glass fiber layer - Foam	12.69 - 0.09 - 11.79 - 0.59 - 0.22	Pre-preg carbon fiber cost $36/kg
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	



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

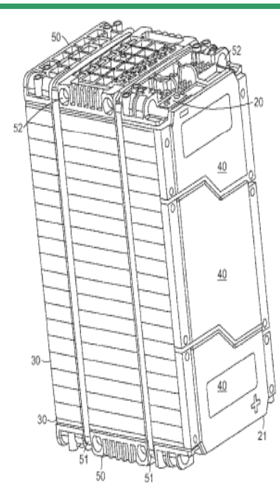
A lithium-ion battery pack will provide hybridization of a fuel cell vehicle which will improves fuel economy as well as having the function as a startup battery.

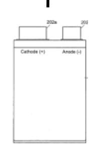
Lithium-ion Battery Pack

Battery Management Systems (BMS)

- Low Voltage Monitoring
- High Voltage System

Battery Modules





Battery Cells[2]

Thermal Management System

BOP

Key Parameters

System

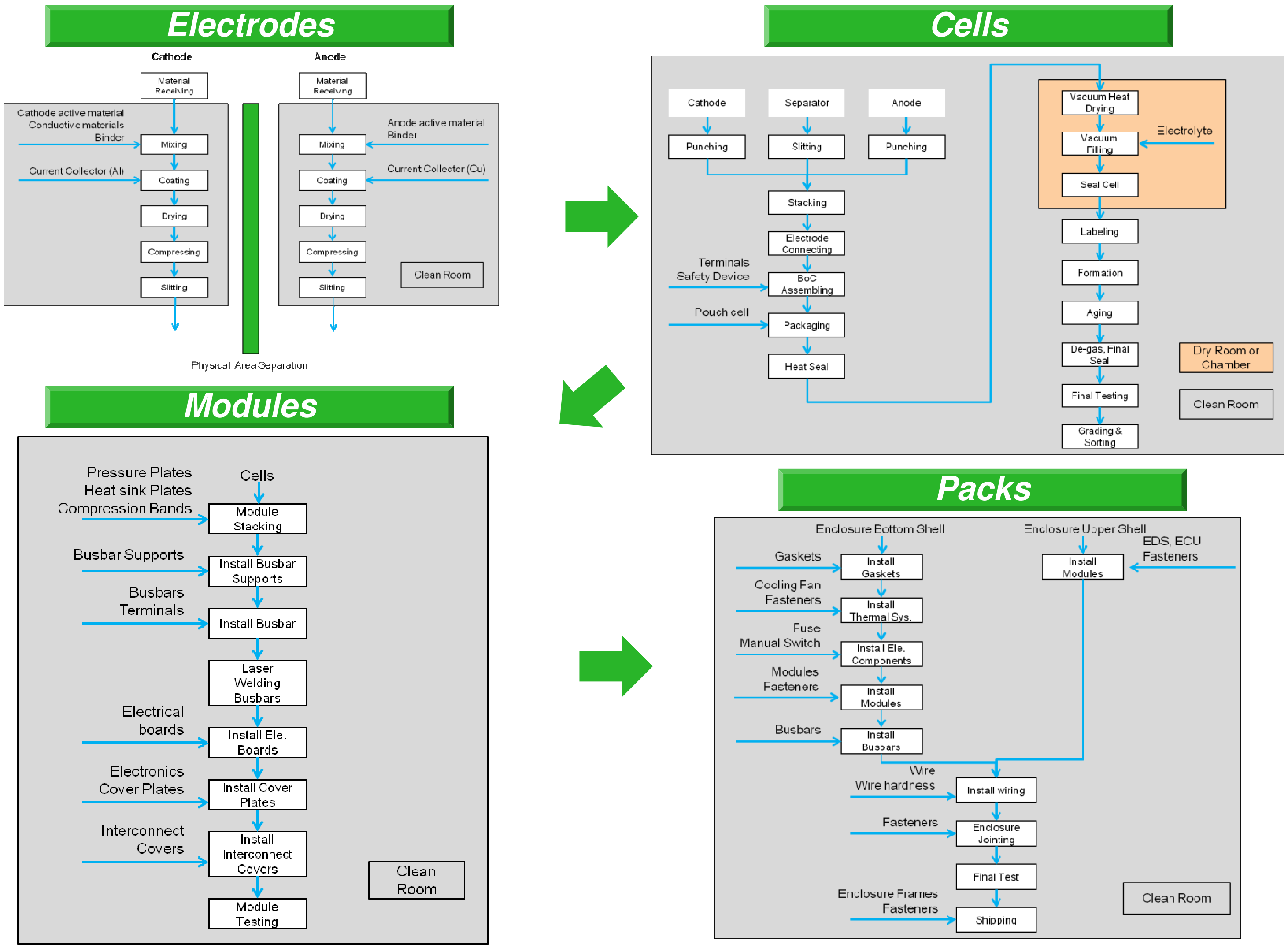
- Power: 40 kW
- Energy capacity: 1.2 kWh usable
- Power to energy ratio: 33:1
- Percent SOC: 80%
- Fade: 20%

Cell

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

1. US patent 20100247999
2. US patent 20090169990

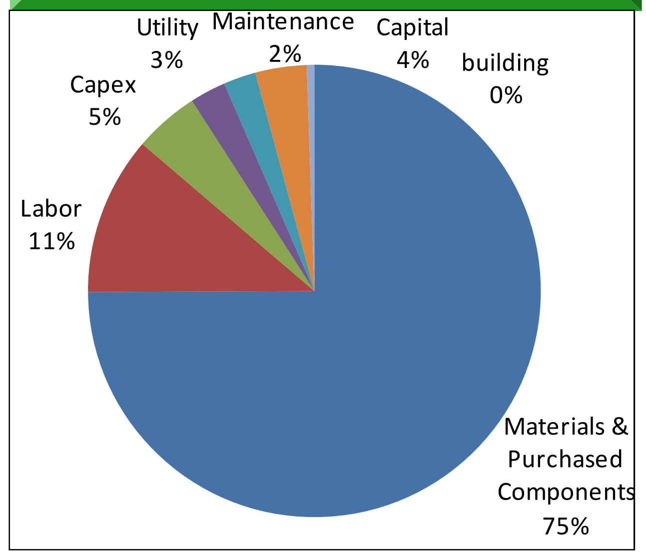
A vertically integrated manufacturing process was assumed for the four-level battery pack fabrication: electrode, cell, module, and pack.



The lithium-ion battery system cost $862 /kWh. Battery management system and packaging have higher cost contributions.

Cost Category	Cell Cost ($/cell)	Pack Cost ($/pack)
Material	$7.88	$775
Labor	$1.51	$116.96
Equipment & tooling	$1.38	$48.03
Utility	$0.79	$26.76
Maintenance	$0.67	$23.79
Capital cost	$1.18	$37.85
Building	$0.15	$5.72
Total	**$13.56**	**$1,033.83**
Total ($/kWh)*	**$327.63**	**$861.52**

Battery System Cost ($862 /kWh)

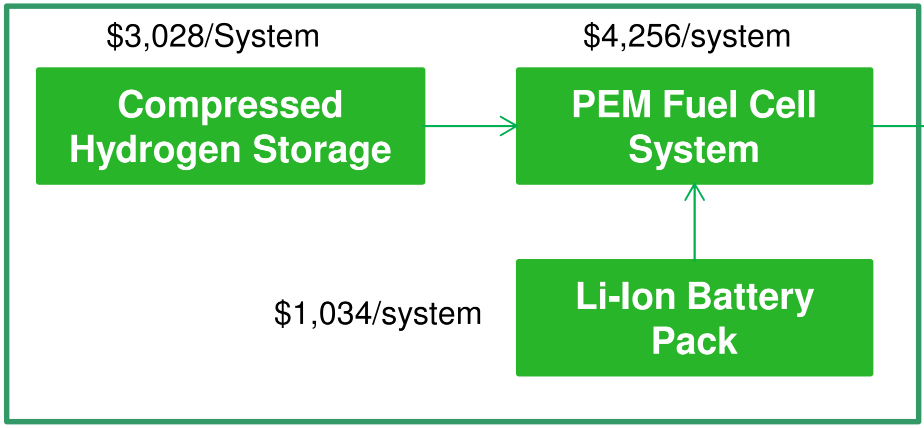


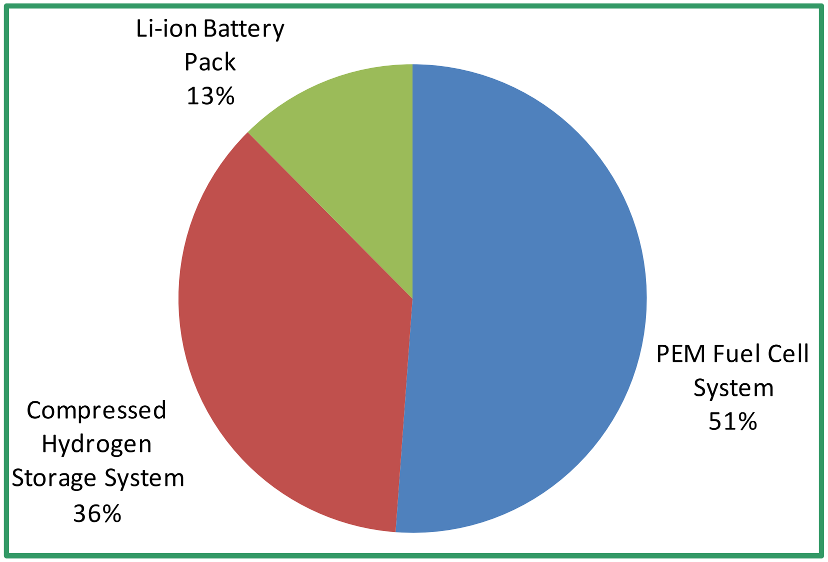
* Based on usable energy (1.88 kWh x 0.8 x0.8 = 1.2 /kWh)

The 1.2 kWh lithium-ion battery system cost $1,034 per pack at the mass production volume.

Conclusion

The overall PEM fuel cell system, onboard hydrogen storage, and hybrid battery costs are approximately $8,318 per vehicle.





- The mass production manufacturing cost of the 80 kW_{net} PEMFC stack was estimated to be $23.8/kW.
- The mass production OEM cost of the 80 kW_{net} PEMFC system was estimated to be $53.2/kW
- The 5.6kg compressed on-board hydrogen storage system was estimated to be $16.4/kWh at the mass production.
- The hybrid lithium-ion battery (40kW, 1.2kWh) costs $1,034 per pack.

Thank You!

Contact: Yong Yang
Austin Power Engineering LLC
2310 W 9th ST #1, Austin TX 78703
512-469-0138
yang.yong@austinpowereng.com