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Manufacturing Cost Analysis of Fuel Cells for Material Handling Applications

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Battelle

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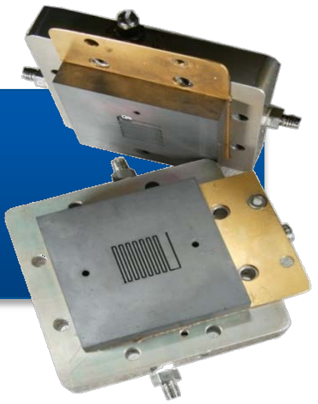
Presentation Outline

- Background
- Approach
- System Design
- Fuel Cell Stack Design
- Stack, BOP and System Cost Models
- System Cost Summary
- Results Summary

Background



5-year program to provide feedback to DOE on evaluating fuel cell systems for stationary and emerging markets by developing independent models and cost estimates

- Applications - Primary (including CHP) power, backup power, APU, and material handling
- Fuel Cell Types - 80°C PEM, 180°C PEM, SOFC technologies
- Annual Production Volumes - 100, 1K, 10K, and 50K (only for primary production systems)
- Size - 1, 5, 10, 25, 100, 250 kW

In fiscal year 2012

- 10 and 25 kW PEM Fuel Cells for Material Handling Equipment (MHE) applications

Manufacturing Cost Analysis Methodology

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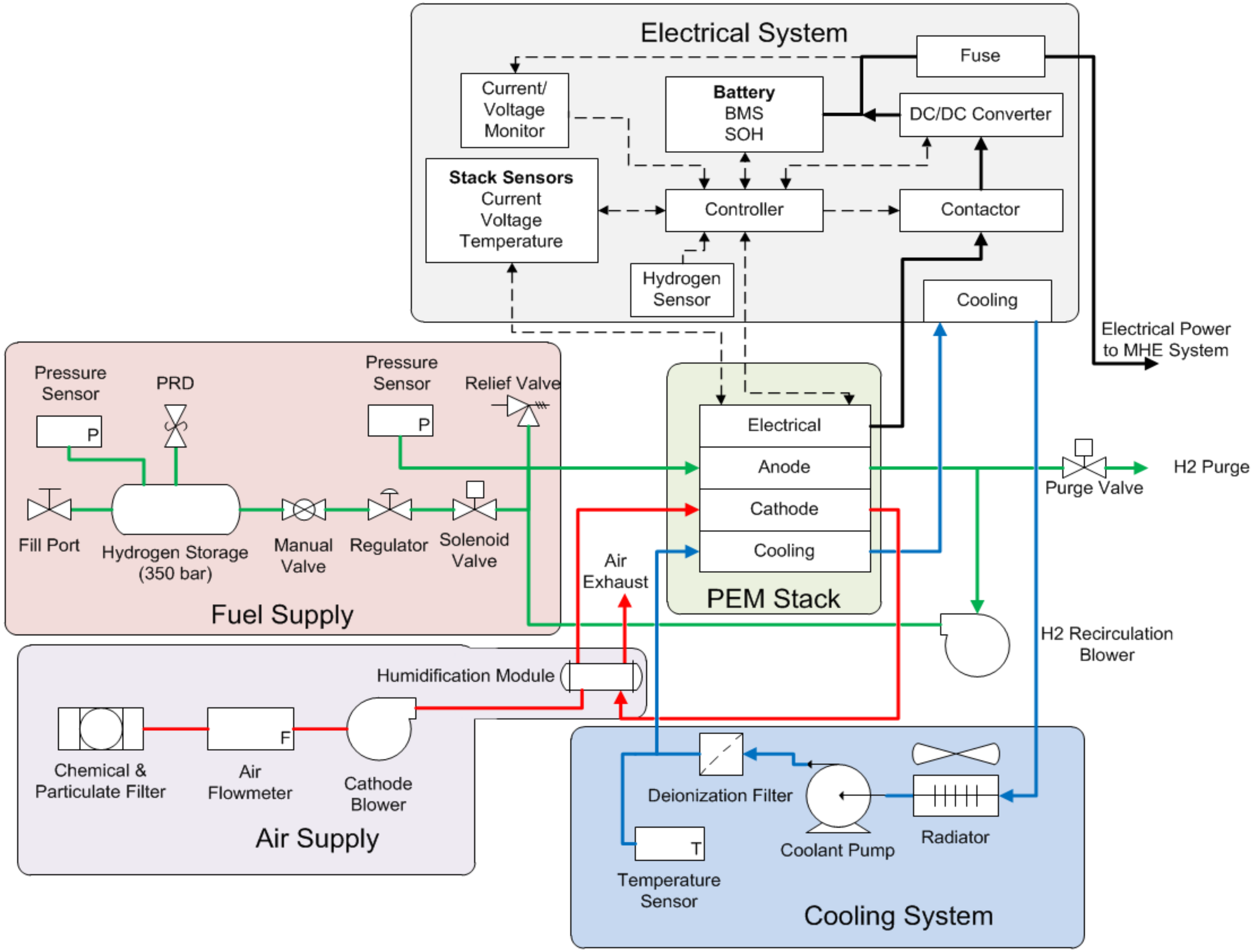
Market Assessment	System Design	Cost Modeling	Sensitivity & Lifecycle Cost Analysis
• Characterization of potential markets • Identification of operational and performance requirements • Evaluation of fuel cell technologies relative to requirements • Selection of specific systems for cost modeling	• Conduct literature search • Develop system design • Gather industry input • Size components • Gather stakeholder input • Refine design • Develop BOM • Define manufacturing processes • Estimate equipment requirements	• Gather vendor quotes • Define material costs • Estimate capital expenditures • Determine outsourced component costs • Estimate system assembly • Develop preliminary costs • Gather stakeholder input • Refine models and update costs	• Sensitivity analysis of individual cost contributors • Lifecycle cost analysis to estimate total cost of ownership

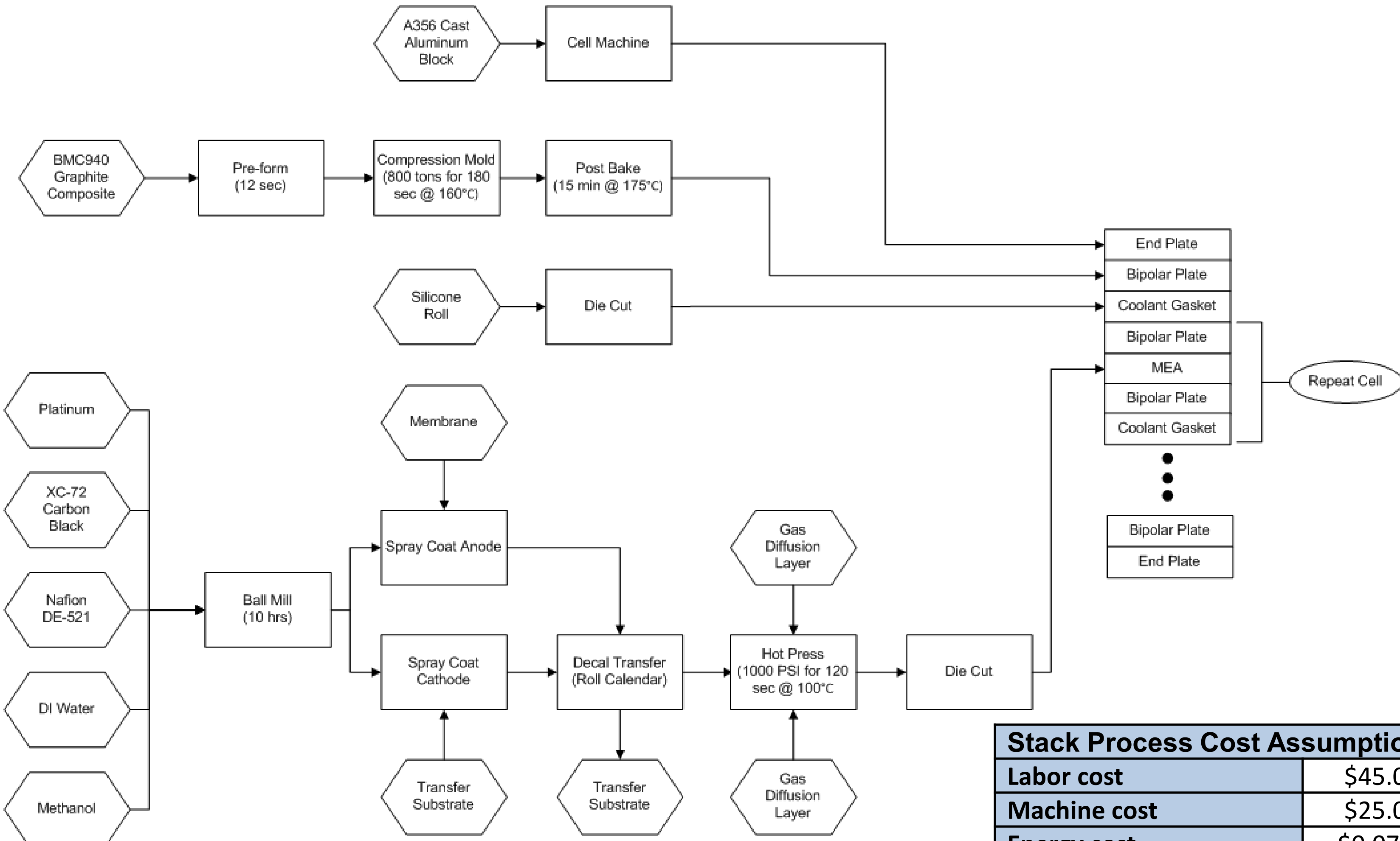
PEM Fuel Cell System Design for MHE Applications



Material Handling PEM Fuel Cell System Specification

Parameter	10 kW System	25 kW System
Power Density (W/cm^2)	0.65	
Current Density (A/cm^2)	1.0	
Cell Voltage (VDC)	0.65	
Active Area Per Cell (cm^2)	200	400
Net Power (kW)	10	25
Gross Power (kW)	11	27.5
Number of Cells (#)	85	106
Full Load Stack Voltage (VDC)	55	69
Membrane Base Material	PFSA, 0.2mm thick, PTFE reinforced	
Catalyst Loading	0.6 mg Pt/cm^2 (total) Cathode is 2:1 relative to Anode	
Catalyst Application	Catalyst ink prepared, sprayed deposition, heat dried, decal transfer	
Gas diffusion layer (GDL) Base Material	Carbon paper 0.2 mm thick	
GDL Construction	Carbon paper dip-coated with PTFE for water management	
Membrane electrode assembly (MEA) Construction	Hot press and die cut	
Seals	1 mm silicone, die cut	
Stack Assembly	Hand assembled, tie rods	
Bipolar Plates	Graphite composite, compression molded	
End Plates	Machined cast aluminum	

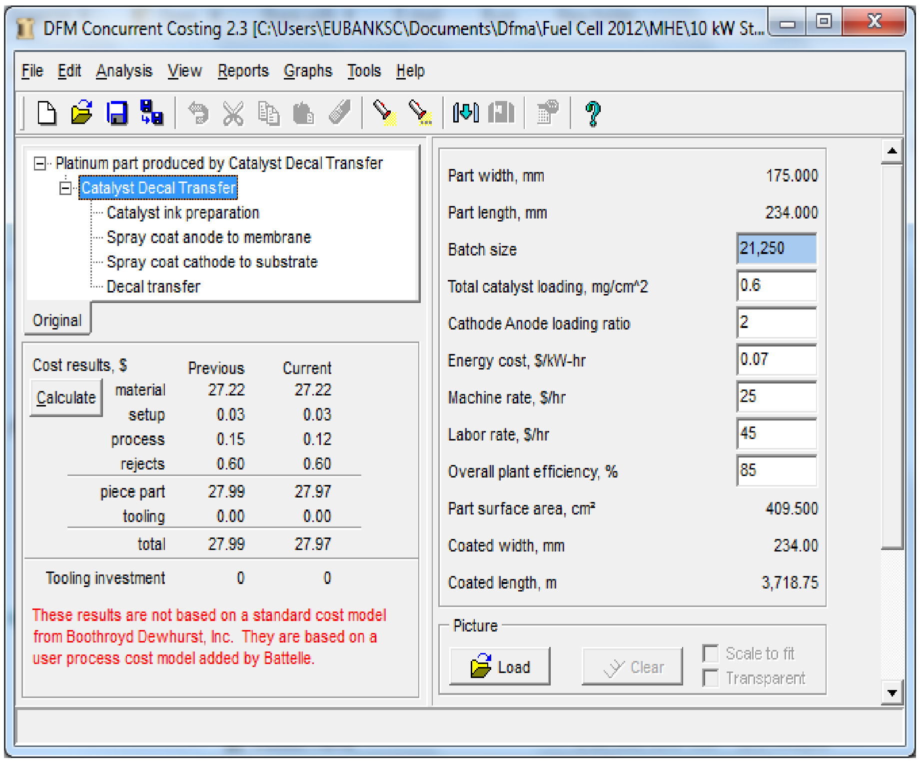
PEM Fuel Cell Stack Manufacturing Process Overview



Stack Process Cost Assumptions	
Labor cost	$45.00/hr
Machine cost	$25.00/hr
Energy cost	$0.07/kWh
Overall plant efficiency	85.00%

Methodology for Calculating Manufacturing Costs

- Use the Boothroyd-Dewhurst estimating software
- Employed standard process models whenever they exist
- Developed custom models as needed



- Custom Model Development Process
  - Develop model approach and process flow
  - Perform preliminary model analysis
    - Inputs and calculations required to produce cost outputs
    - Independent verification of viability and accuracy
  - Implement model in Boothroyd Dewhurst DFMA tool
    - Develop model code
    - Validate model results against preliminary cost analysis results

Major Stack Material and Process Assumptions for MHE Applications

Material	Cost ($)	Measure
Platinum	1,390	troy oz
Nafion NR50	2,750 – 1,100	kg
Carbon powder	18	kg
Membrane	250 - 180	m^2
GDL	95 - 60	m^2
BMC 940 for Bipolar Plate	2.43	kg
A-356 Cast Aluminum	2.54	kg

Process Assumptions	Value
Scrap rate	Varies
Inspection steps included in processing	None
Labor cost	$45/hr
Machine cost*	$25/hr
Energy cost	$0.07/kW-h
Overall plant efficiency	85%
Operators per line	1

*note that energy cost of high power machines is included in processing cost

- Catalyst ink composition
  - 32% platinum
  - 48% carbon powder
  - 20% Nafion
- Catalyst loading
  - Anode: 0.2 mg/cm^2
  - Cathode: 0.4 mg/cm^2
- Scrap rates
  - Bipolar plates: 2.5%
  - Catalyst application: 2.5%
  - MEA hot pressing: 3.0%
  - Gasket die cutting: 0.5%
  - End plates: 0.5%

Capital Cost Assumptions

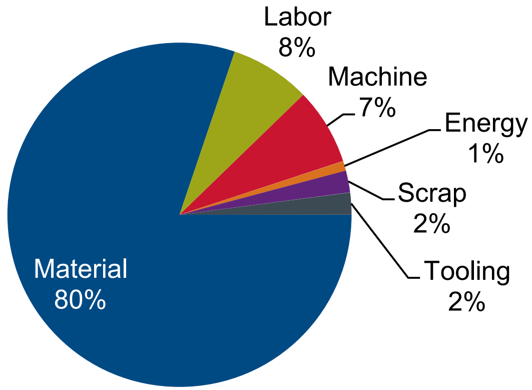
Capital Cost	Unit Cost	Units	Total Cost (2010$)	Assumption/Reference
Factory Total Construction Cost	250	$/sq.ft	855,750 to 5,545,000	• Includes Electrical Costs ($50/sq.ft.). Total plant area based on line footprint plus 1.5x line space for working space, offices, shipping, etc. • Varies with anticipated annual production volumes of both 10 kW and 25 kW stacks.
Production Line Equipment Cost	Varies by component		1,492,270 to 12,327,330	• Varies with anticipated annual production volumes of both 10 kW and 25 kW stacks.
Forklifts	25,000	$/lift	50,000	• Assumes 2 forklifts with extra battery and charger.
Cranes	66,000	$/crane	198,000	• 5 ton crane, 20' wide per line
Real Estate	125,000	$/acre	125,000	• Assumes 1 acre of vacant land, zoned industrial Columbus, OH
Contingency	10% CC		272,102 to 1,871,833	• Construction estimation assumption
Total			**2,993,122 to 20,590,163**	• Varies with anticipated annual production volumes of both 10 kW and 25 kW stacks

10 kW MHE PEM Fuel Cell Stack Manufacturing Cost Summary

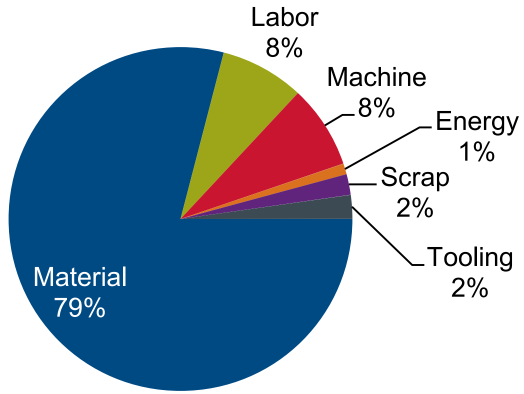
Stack Component	100 Units ($)	1000 Units ($)	10,000 Units ($)
Bipolar plates	726	725	724
MEA	3,333	2,964	2,415
Cooling gasket	139	139	139
Tie rods and hardware	40	40	40
End plates	54	54	54
Stack assembly	65	52	50

Note: All costs include manufacturing scrap

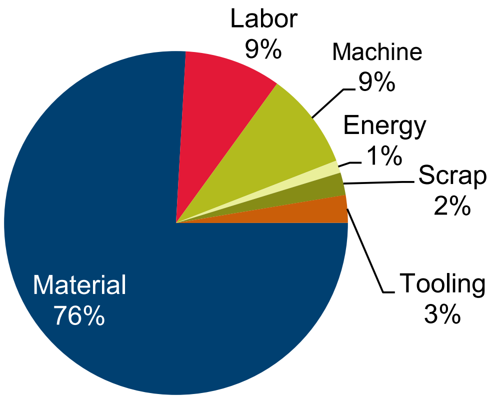
10 kW Stack Costs
100 units/year



10 kW Stack Costs
1000 units/year

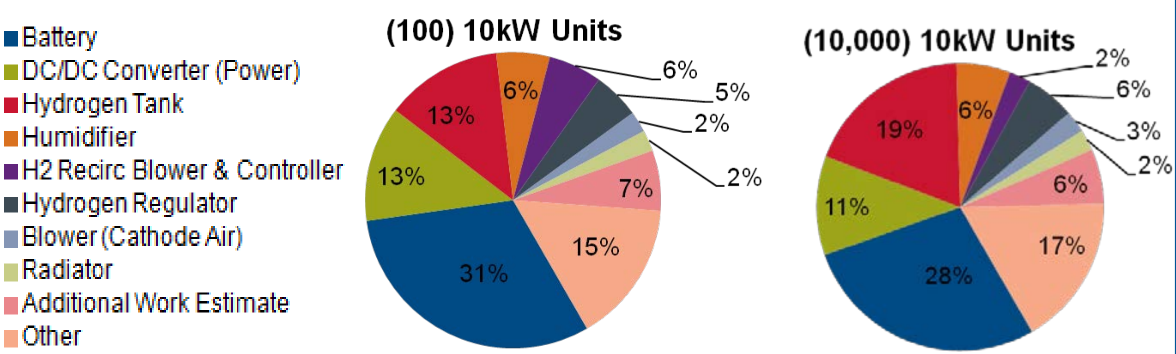


10 kW Stack Costs
10,000 units/year



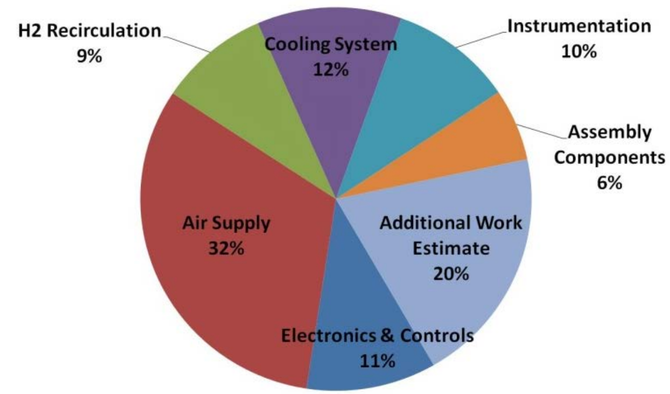
10 kW MHE PEM Fuel Cell BoP Manufacturing Cost Summary

BOP Component	100 Units ($)	1,000 Units ($)	10,000 Units ($)
Battery	8,500	6,000	5,000
Hydrogen Tank	3,494	3,373	3,373
DC/DC Converter (Power)	3,450	2,900	1,996
H2 Recirc Blower & Controller	1,595	469	431
Humidifier	1,595	1,276	1,085
Hydrogen Regulator	1,400	1,200	1,000
Radiator	625	500	425
Blower (Cathode Air)	629	503	440
Other Components	4,184	3,458	3,006
Additional Work Estimate	1,800	1,400	1,100
System Assembly	58	46	45



BOP of (10,000) 10kW Units

Note: Battery , DC/DC Converter ,H2 Storage & Fittings Not Included



10 kW MHE PEM Fuel Cell System Cost Summary

Description	100 Units	1,000 Units	10,000 Units
Total stack manufacturing cost, with scrap	$4,357	$3,974	$3,422
Stack manufacturing capital cost	$2,825	$283	$74
BOP	$27,272	$21,079	$17,856
System assembly, test, and conditioning	$279	$267	$266
Total system cost, pre-markup	**$34,733**	**$25,603**	**$21,618**
System cost per gross KW, pre-markup	**$3,158**	**$2,328**	**$1,965**
Sales markup	50.0%	50.0%	50.0%
Total system cost, with markup	**$52,100**	**$38,405**	**$32,427**
System cost per gross KW, with markup	$4,736	$3,491	$2,948

Comparison to Automotive Studies

2010 DTI Automotive Update – Key Characteristics		
Active cells per stack	369	cells
Cell voltage at max power	0.676	V/cell
Membrane power density at max power	0.833	W/cm^2
Active area per cell	285.84	cm^2
Total area per cell	357.3	cm^2
Ratio of active area to total area	0.80	
Catalyst loading	0.15	mg/cm^2
Gross power per stack	87.91	kW
Net power per stack	80	kW

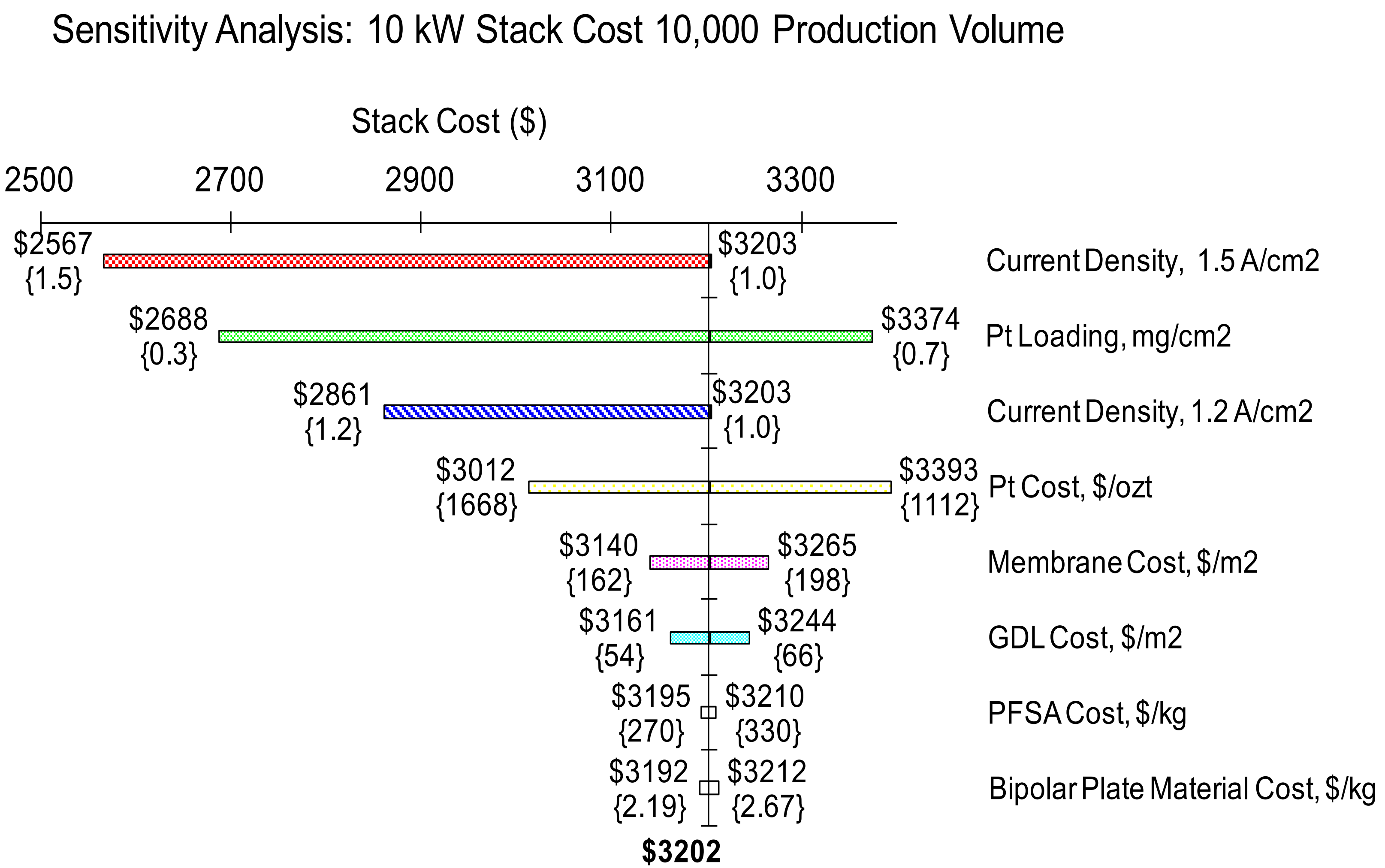
Battelle MHE – Key Characteristics		
Active cells per stack	66	cells
Cell voltage at max power	0.65	V/cell
Membrane power density at max power	0.65	W/cm^2
Active area per cell	200	cm^2
Total area per cell	409.5	cm^2
Ratio of active area to total area	0.49	
Catalyst loading	0.6	mg/cm^2
Gross power per stack	11	kW
Net power per stack	10	kW

- The lowest automotive manufacturing volume in the 2010 DTI report is 1,000 systems which requires the manufacture of 369,000 cells. This is equivalent to Battelle MHE system annual production volumes of: (369 / 66) × 1,000 = 5,591 systems

Material Cost/Assumptions Adjusted for Comparison Purposes		
Material/Assumption	Cost	
Platinum	$1,100	/tr.oz.
Platinum loading	0.15	mg/cm^2
Nafion	$2,000	/kg
Membrane	$224.45	$/m^2$
GDL	$71.83	$/m^2$

	Battelle MHE	DTI Automotive
Stack cost per kW_{gross}	$158	$145
Stack cost per kW_{net}	$174	$159

Sensitivity Analysis of 10 kW MHE PEMFC Stack



X-axis is cost of fuel cell stack. Numbers in brackets are the values of the cost drivers.

MHE PEM Fuel Cell Balance of Plant Cost Comparison

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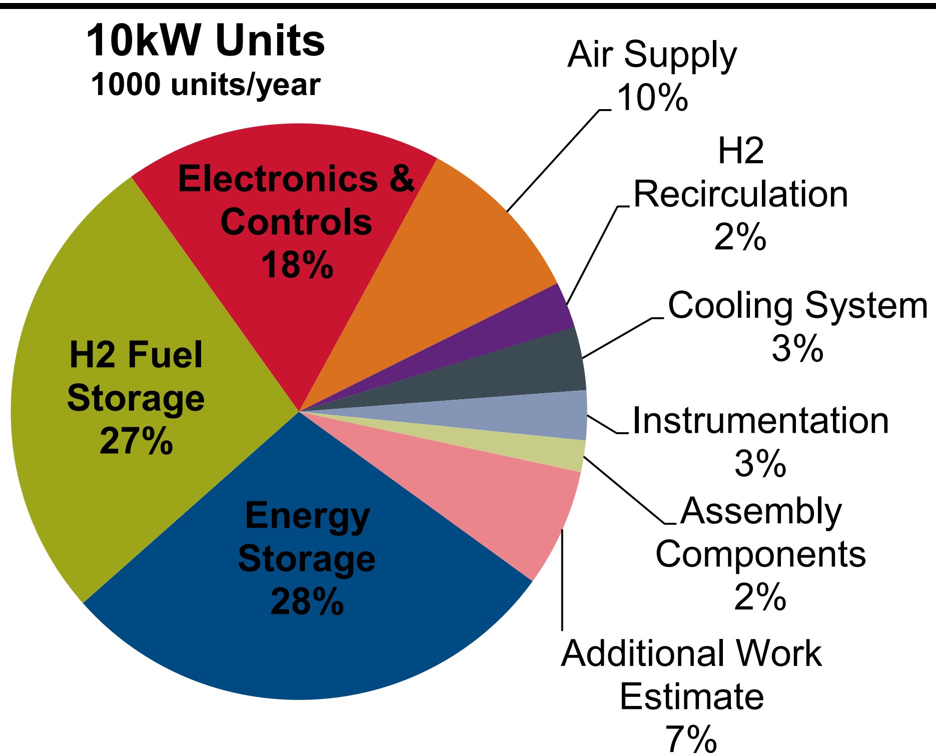
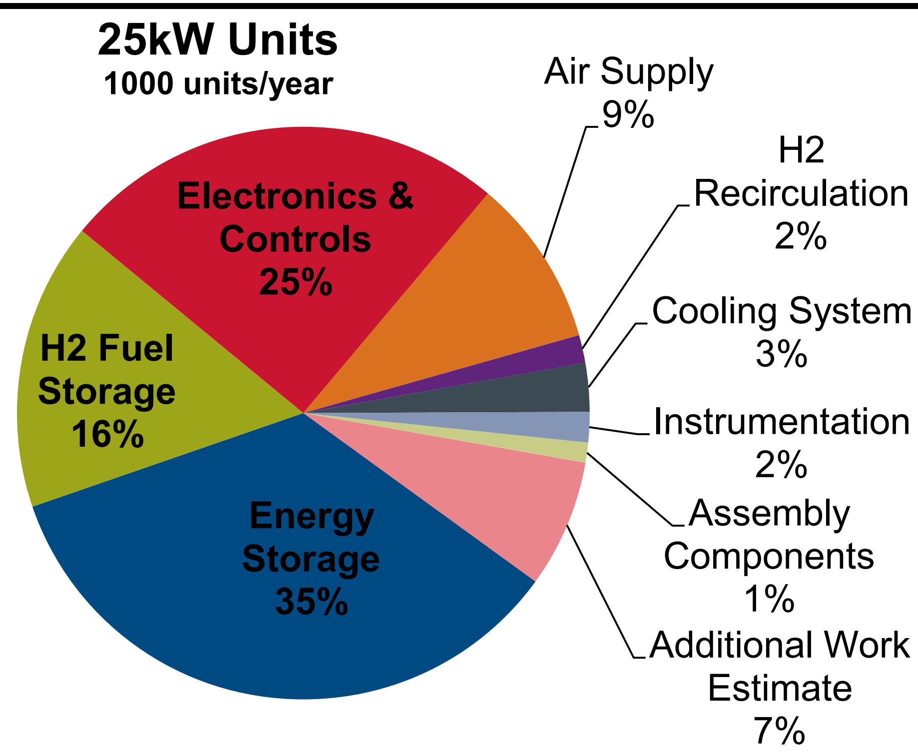
- 3 Dominant Cost Drivers
  1. Energy Storage
  2. H2 Fuel Storage
  3. Electronics & Controls





MHE PEMFC System BOP Cost Drivers

1. Energy Storage
2. H2 Fuel Storage
3. Electronics & Controls

Avenues for BOP Cost Reductions:

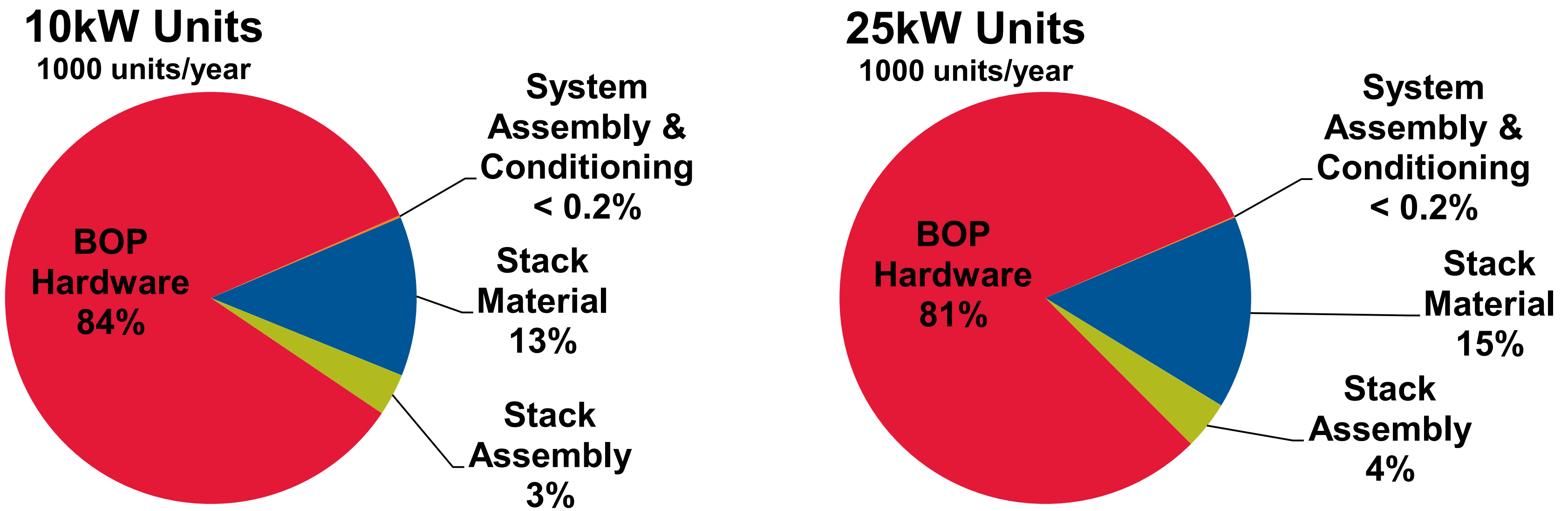
- Alternative hydrogen storage (i.e. All steel tank)
- Eliminate DC/DC converter
- Battery improvements
- Cathode humidification redesign or complete elimination

Opportunity for Cost Reduction – Use of All Steel Tank for H2 Storage

Component Description	Annual Production Rate			
	(1)	(100)	(1,000)	(10,000)
Composite H_2 Tank	$4,000	$3,494	$3,373	$3,373
All-Steel H_2 Tank	$846	$804	$754	$731
Savings	**$3,154**	**$2,690**	**$2,619**	**$2,642**

MHE System Cost Comparison

- Largest System Expense = Balance of Plant (BOP) Hardware
- Avenues for BOP Cost Reductions:
  - Alternative hydrogen storage (i.e. All steel tank)
  - Eliminate DC/DC converter
  - Battery improvements
    - Further cost reductions, increased power density, complete forklift redesign, etc
  - Cathode humidification redesign or complete elimination



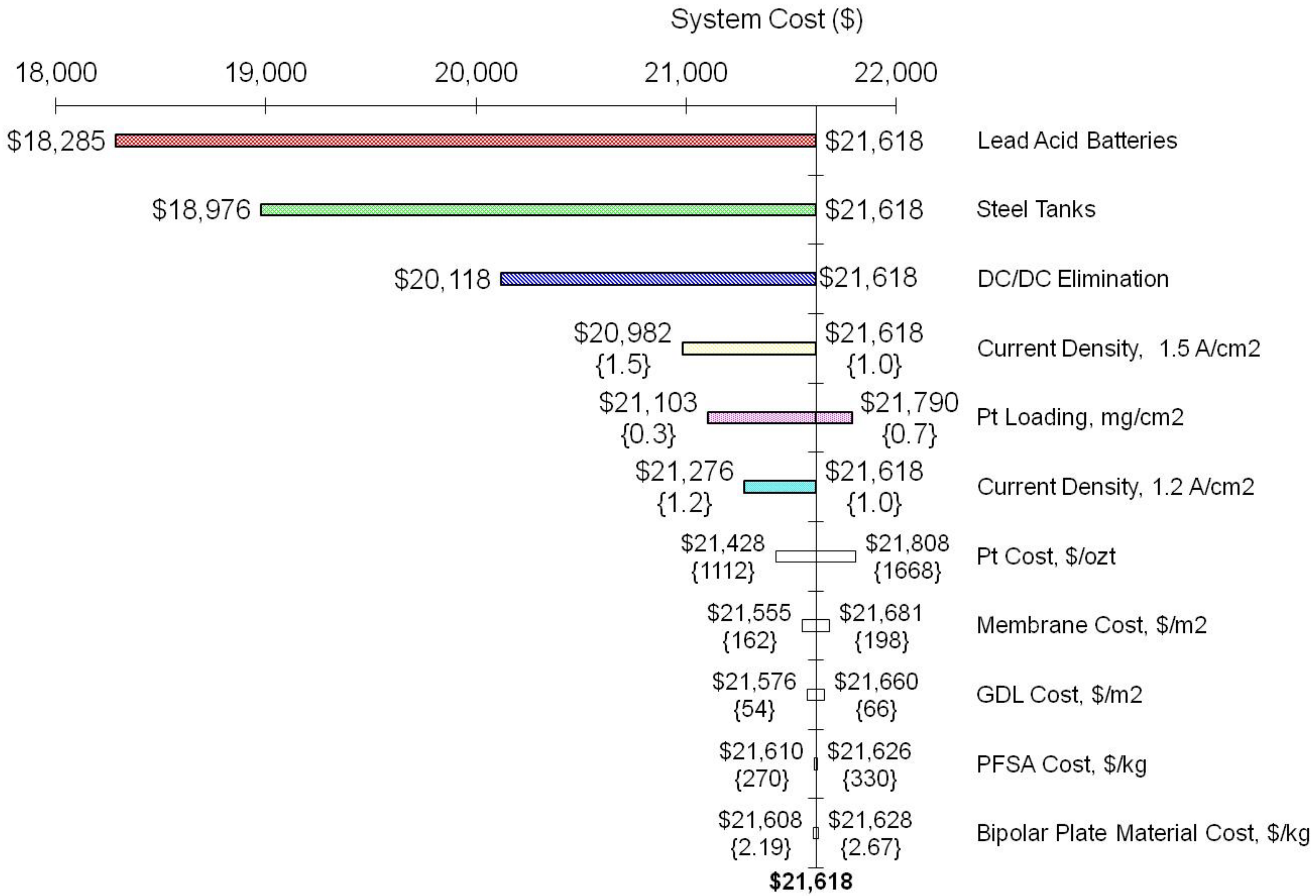
Results Summary

- BoP component costs driving total system cost
  - Potentially eliminate DC/DC converter
  - Potentially eliminate stack humidification
    - Required for operation at higher temperature and wider operating range
    - May require change of membrane material
  - Use all steel hydrogen storage tank
- Production volume has negligible effect on stack cost
  - Precious metal, graphite composite and commodity cost constant across all volumes
  - Material processing requirements limit throughput

Proposed Future Work

FY13	FY14, FY15, FY16
• Complete assessment 1 and 5 kW of SOFC systems for APU applications • Update assessment of Backup Power applications	• Complete additional new analyses • Revisit and update previous analyses based upon technological advancements

Sensitivity Analysis: 10 kW System Cost 10,000 Production Volume



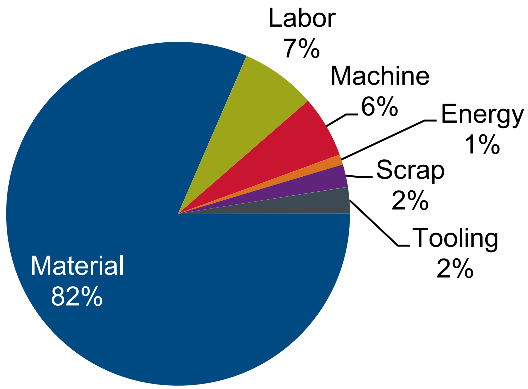
X-axis is total cost of fuel cell system (pre-markup). Numbers in brackets are the values of the cost drivers.

25 kW MHE PEM Fuel Cell Stack Manufacturing Cost Summary

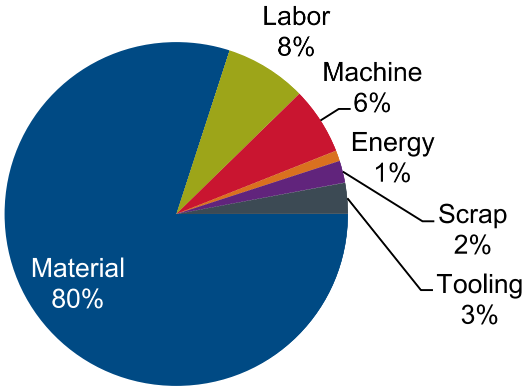
Stack Component	100 Units ($)	1000 Units ($)	10,000 Units ($)
Bipolar plates	1,461	1,475	1,457
MEA	6,887	6,138	4,941
Cooling gasket	280	280	280
Tie rods and hardware	40	40	40
End plates	80	80	80
Stack assembly	68	54	53

Note: All costs include manufacturing scrap

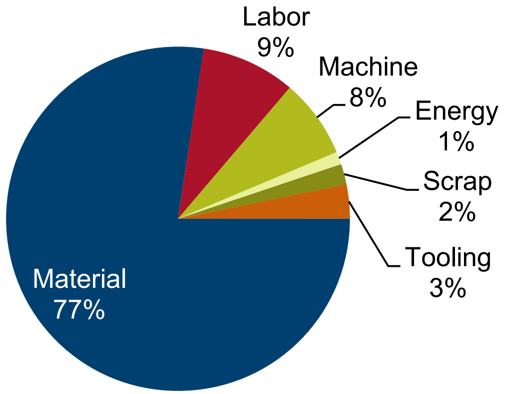
25 kW Stack Costs
100 units/year



25 kW Stack Costs
1000 units/year

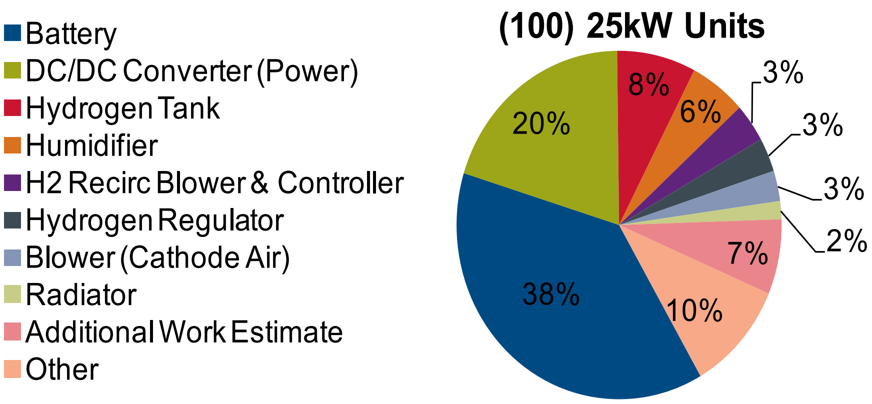


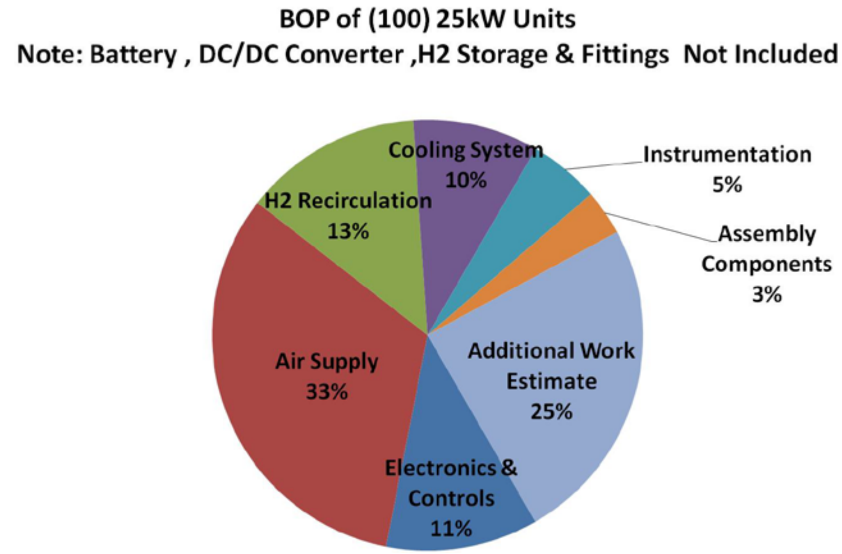
25 kW Stack Costs
10,000 units/year



25 kW MHE PEM Fuel Cell BoP Manufacturing Cost Summary

BOP Component	100 Units ($)	1,000 Units ($)	10,000 Units ($)
Battery	17,000	12,000	10,000
DC/DC Converter (Power)	8,915	7,718	6,024
Hydrogen Tank	3,494	3,373	3,373
Humidifier	2,500	2,000	1,700
H2 Recirc Blower & Controller	1,595	469	431
Hydrogen Regulator	1,400	1,200	1,000
Blower (Cathode Air)	1,260	1,010	885
Radiator	750	591	503
Other Components	4,503	3,710	3,198
Additional Work Estimate	3,100	2,500	2,000
System Assembly	58	46	45





25 kW MHE PEM Fuel Cell System Cost Summary

Description	100 Units	1,000 Units	10,000 Units
Total stack manufacturing cost, with scrap	$8,815	$8,068	$6,851
Stack manufacturing capital cost	$2,825	$307	$121
BOP	$44,517	$34,571	$29,114
System assembly, test, and conditioning	$279	$267	$266
Total system cost, pre-markup	**$56,436**	**$43,213**	**$36,352**
System cost per gross KW, pre-markup	**$2,052**	**$1,571**	**$1,322**
Sales markup	50%	50%	50%
Total system cost, with markup	**$84,654**	**$64,820**	**$54,528**
System cost per gross KW, with markup	**$3,079**	**$2,357**	**$1,983**

STRATEGIC ANALYSIS INC

Application of Manufacturing Cost Analysis Methodology to Automotive Fuel Cell Systems

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16 April 2013

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Presentation Outline

- Purpose/Goals
- SA's Cost Analysis Philosophy
- General Steps in Cost Analysis
- Overview of 80kW Automotive System
- Cost Results
- Application to Other Systems

Purpose and Goals

- Estimate of total cost of system when produced in quantity
  - Understanding of how cost changes with manufacturing rate
- Identify key parameters that drive system cost
  - Understand cost sensitivity each parameter (Tornado charts)
- Discern cost differences between different design or manufacturing processes
  - Use as tool to pick design/process that leads to lowest cost
- Use as “proof” that cost claims are not just wishful thinking
  - Assumptions must be transparent and in adequate detail
- Force identification of changes between “lab design” and “mass-production design”
  - One-off design might be radically different than mass-produced design
  - Inventive team may not be best group to assess mass-produced design
  - Applies to both design and manufacturing methods

SA's Design for Manufacturing & Assembly (DFMA)® - Style Costing Methodology

- DFMA® (Design for Manufacturing & Assembly) is a registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Company (Ford) design/costing method for the past 20+ years
- SA practices are a blend of:
  - "Textbook" DFMA®, industry standards and practices, DFMA® software, innovation, and practicality
- DFMA® is Process-Based analysis
  - Mimics actual manufacturing & assembly processes and part dimensions/materials
  - Reflects manufacturing cost factors:
    - Material costs
    - Manufacturing methods
    - Machine Rate
    - Tooling Amortization

Estimated Cost = (Material Cost + Processing Cost + Assembly Cost) x Markup Factor

Cost Factors Included in Estimates

Not Included in Cost Analysis

- Markup for primary manufacturer/assembler (G&A, scrap, R&D, profit)
- Non-recurring RD&E costs
- Warranty
- Advertising
- Taxes

Profit

One-Time Costs

General Expenses

→ Cost Excluded from SA Analysis

Included in Cost Analysis

Fixed Costs
- Equipment depreciation
- Tooling amortization
- Utilities
- Maintenance

Variable Costs
- Direct Materials used in manufacturing
- Direct Materials purchased from suppliers
- Manufacturing scrap
- Manufacturing labor
- Assembly labor

Factory Expenses

Direct Materials

Direct Labor

→ Cost Included in SA Analysis

Original Equipment Manufacturer's (OEM) Price

Basic Cost Modeling Work Flow

1. Obtain or create system design
   - Create system schematic to ensure full functionality/system-completeness
   - Mimic existing designs, project new configurations, speak with developers
2. Develop Bill of Materials (BOM) & physical embodiment of each component
   - Materials, scaling, dimensions, design embodiment
   - Sources: patents, existing products, conv. with inventors, own imagination
3. Model the manufacturing & assembly process
   - Specify process for each component and production stage
   - Manufacturing methods based on SA experience, industry input, analogy to similar products
4. Compute cost results and conduct sensitivity analysis
   - Tornado Charts, Monte Carlo analysis
5. Vet results with experts and incorporate feedback

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Strategic Analysis Inc. Rules to Cost Analysis (Guidelines of Governing Philosophy)

- It's process-based cost analysis: break down complex systems into understandable simple steps.
- Quotes are for commodities (with multiple sellers & buyers). Use process-based analysis for everything else.
- Its about specifying the details (and knowing which details to specify)
  - detailed input leads to higher accuracy results, but takes longer
- Make many small assumptions, rather than a few big ones.
- Estimate….then do sensitivity studies.
- Be inventive: if you can imagine it, chances are someone can build it.
  - Factories are filled with custom machinery
- Apply principal of Kaizen (continuous improvement)
  - keep iterating until you are not longer able to improve.
- Factory robots are becoming commonplace
  - They are surprisingly inexpensive and very fast

Strategic Analysis Inc. Rules to Cost Analysis
(Guidelines of Governing Philosophy)

- Only pay workers for the time they work.
  - Base on use of fractional/part-time works to reduce costs
- When unsure, model both/all pathways, and let cost results guide you to lowest cost pathway.
- Consult vendors frequently
  - They possess a wealth of information and are often very happy to help even if there is no immediate payback to them.
- Full time labor is 14 hours/day, 240 days/year (based on auto industry protocol).
  - i.e. 2 shifts of 7 hours (productive)
  - 5 days/week minus 2 weeks at Christmas plus 1 extra week in summer for maintenance
- There is a large difference between cost and price.
  - Price includes mark-up, non-recurring R&D costs, eng. design costs, warranty, advertising, marketing, taxes, etc.
- The three most important costing parameters are:
  - cycle time
  - capital cost
  - machine/line utilization

Example of Machine Rate Computation

Methodology Reflects Cost of Under-utilization:

Processing Cost =

Machine Rate X Cycle Time

$$\frac{\text{Annual Capital Repayment} + \text{Annual Operating Payments}}{\text{Annual Minutes of Equipment Operation}} = \text{Machine Rate (\$/min)}$$

Maintenance/Spares: 10% of capital cost per year
Miscellaneous Exp.: 8% of capital cost per year
Labor Costs:

- 0.1 full time equivalent (FTE) per machine
- Labor rate: $45/hour

Utilities:

- 3.6 kWe per machine
- $0.08/kWh electricity


Fanuc LR 200

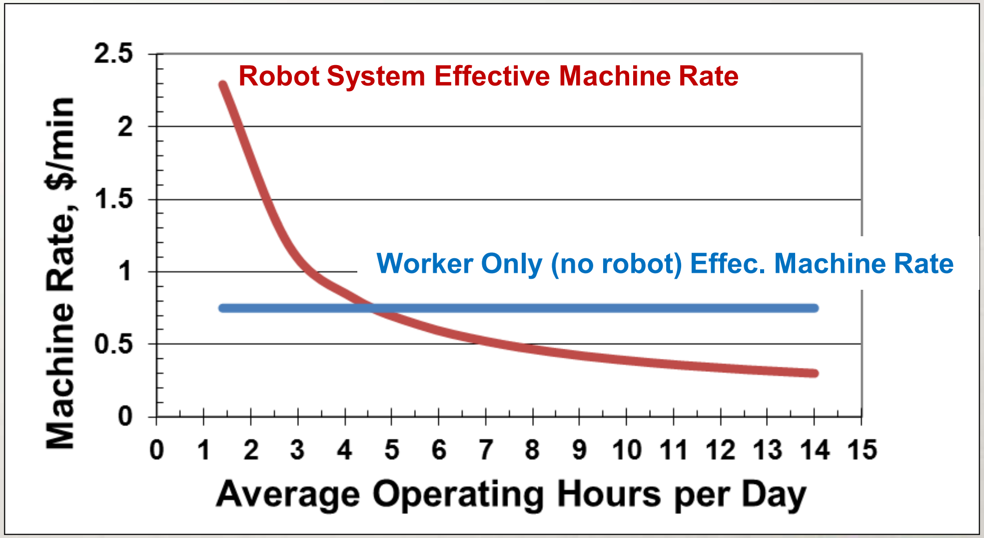

Motoman HP-20

Total Installed Capital Cost: $147k

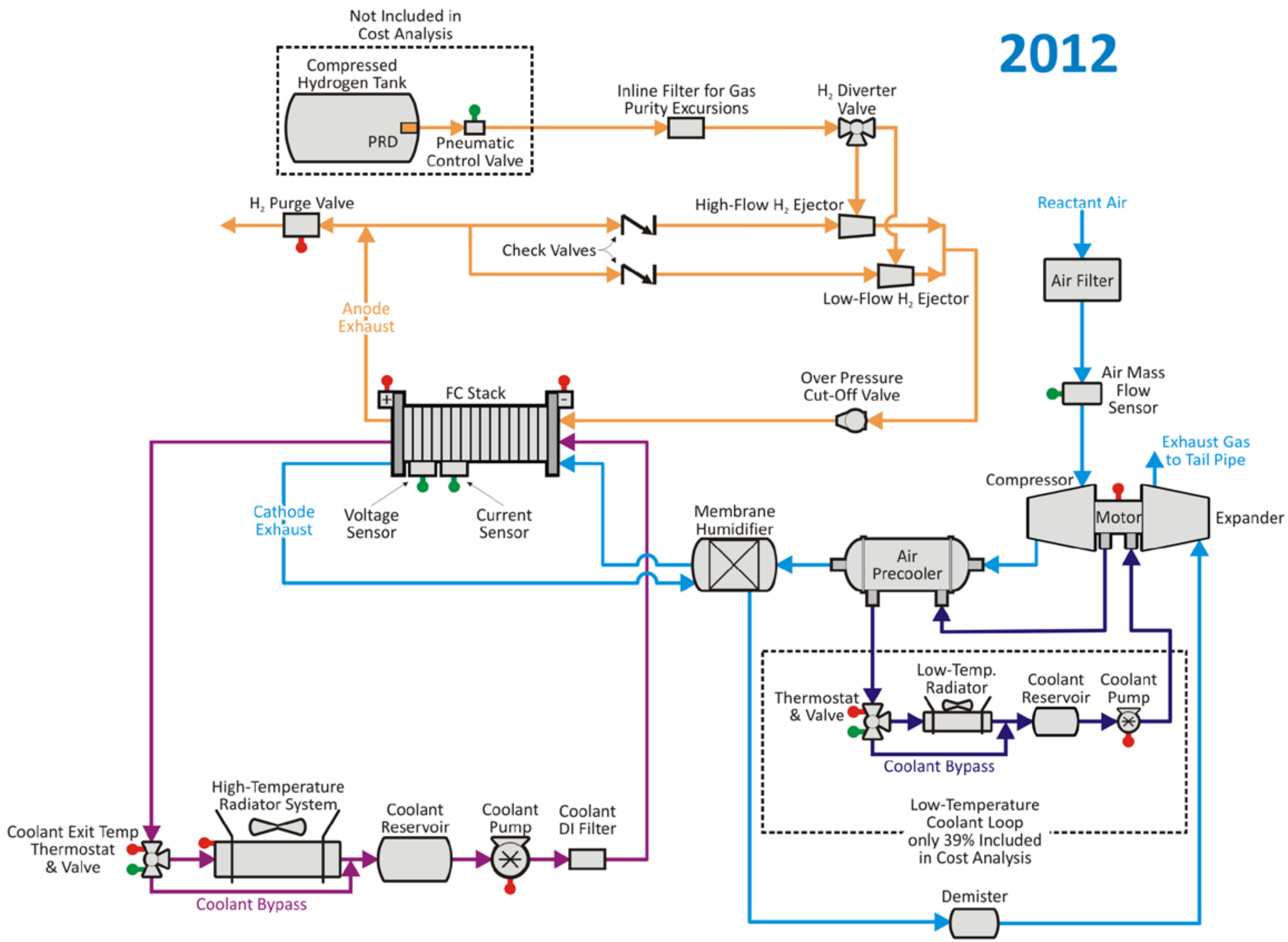
- $85k base robot
- $20k custom gripper
- 40% adder for installation

Capital Recovery Factor (CRF)

- CRF is % of capital cost that must be repaid each year to repay investment
- Discount Rate: 10%
- Corp. Income Tax Rate: 40%
- Equip. Lifetime: 15 years
- CRF computed to be 0.175

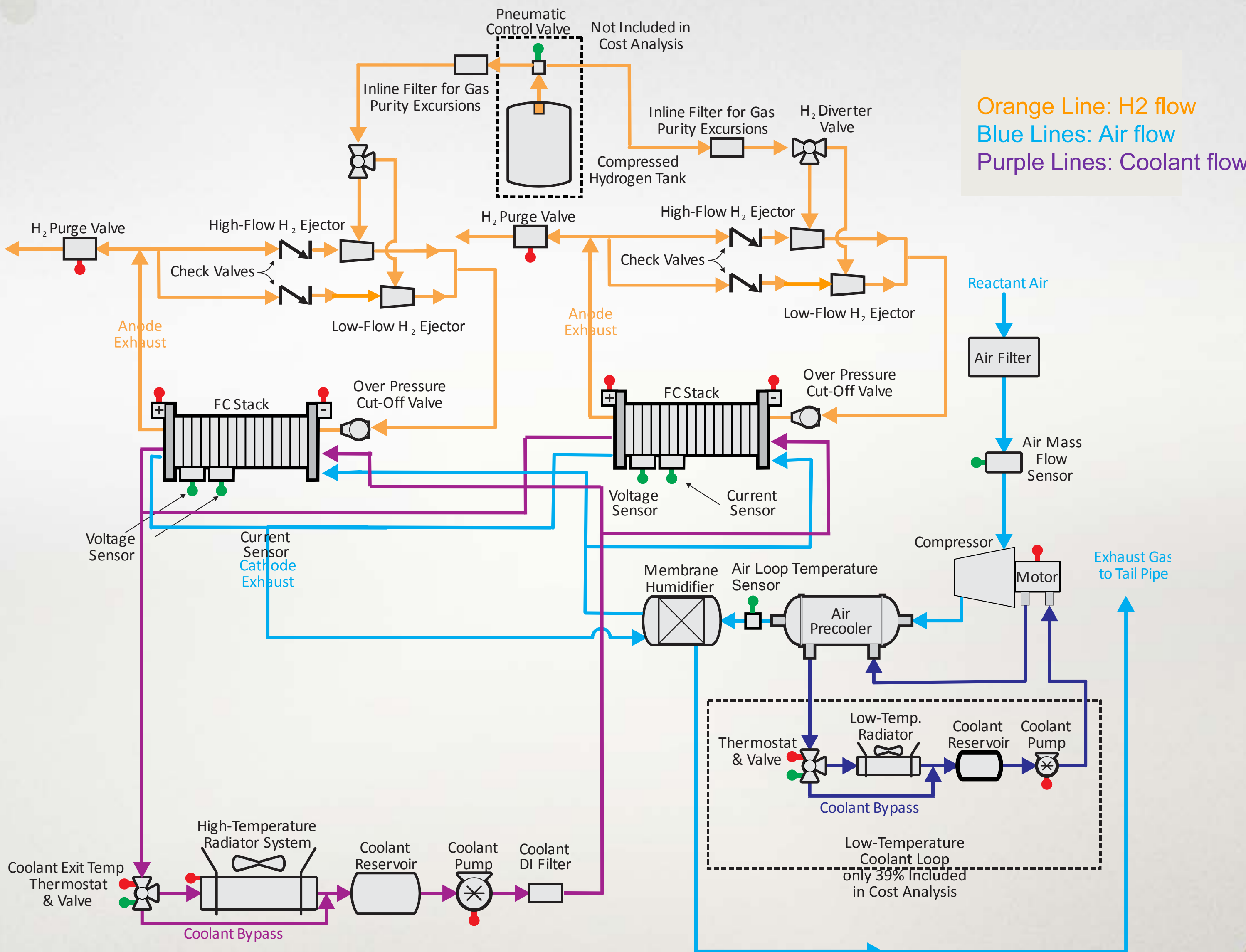


2012 80 $kW_{electric}$ Automotive System Diagram



Orange Line: H2 flow
Blue Lines: Air flow
Purple Lines: Coolant flow

2012 160kWe Fuel Cell Bus System Diagram



System design is similar to automotive configuration. Key differences include: two stacks (not one), lower pressure, no expander, and longer target lifetime.

2012 Transportation Fuel Cell System Details

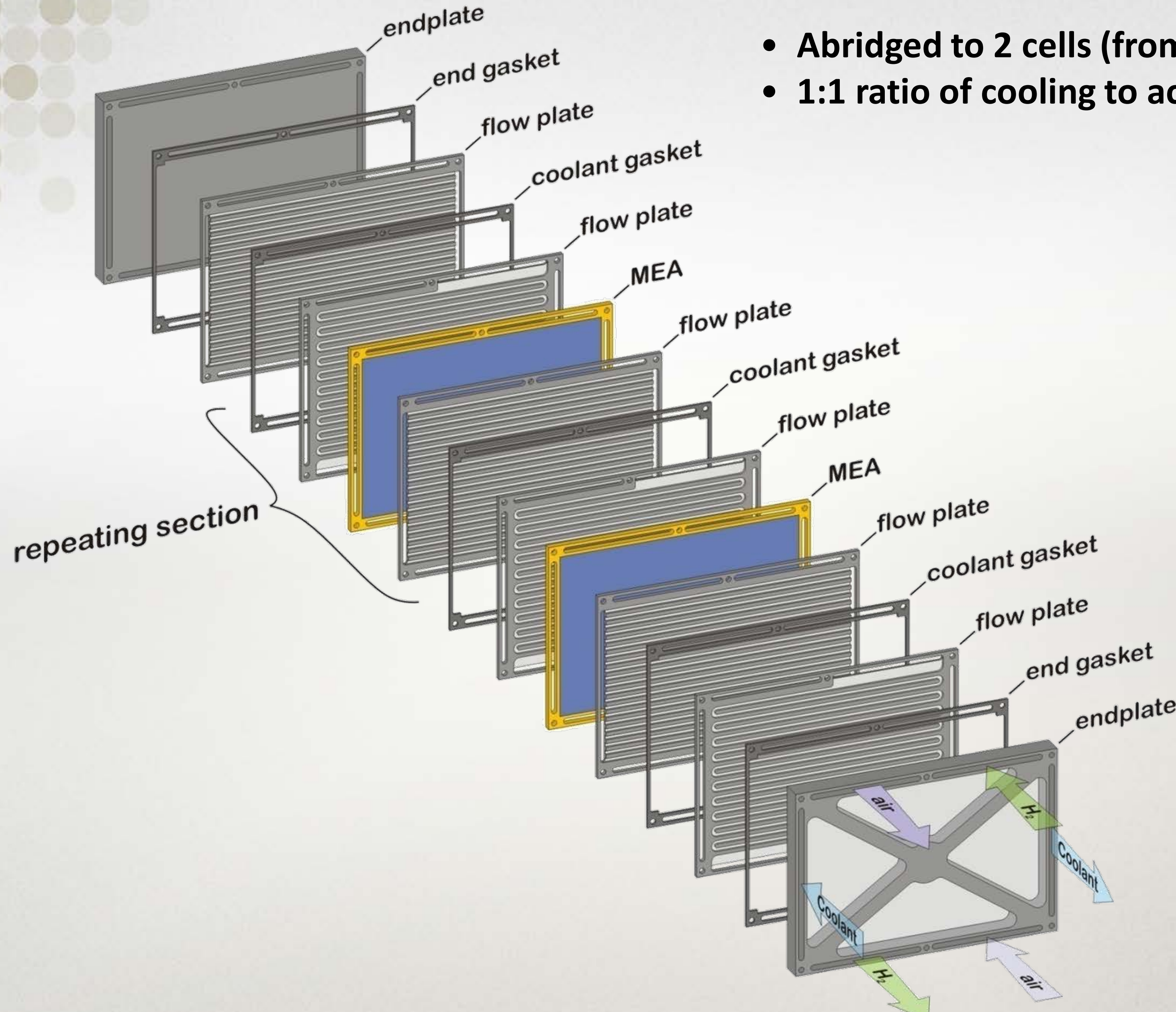
	2012 Auto Technology System	2012 Bus Technology System
Power Density (mW/cm^2)	**984**	**716**
Total Pt loading (mgPt/cm^2)	**0.196**	**0.4**
Net Power (kW$_{net}$)	**80**	**160**
Gross Power (kW$_{gross}$)	88.24	177.10
Operating Pressure (atm)	**2.50**	**1.80**
Peak Stack Temp. (°C)	87	74
Active Cells	369	739
Membrane Material	Nafion on 25-micron ePTFE	Nafion on 25-micron ePTFE
Radiator/ Cooling System	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler
Bipolar Plates	Stamped SS 316L with TreadSton Litecell™ Coating	Stamped SS 316L with TreadStone Litecell™ Coating
Air Compression	**Centrifugal Compressor, Radial-Inflow Expander**	**Centrifugal Compressor, Without Expander**
Gas Diffusion Layer (GDL)	Carbon Paper Macroporous Layer with Microporous Layer (Ballard Cost)	Carbon Paper Macroporous Layer with Microporous Layer (Ballard Cost)
Catalyst Application	3M Nanostructured Thin Film (NSTF™)	3M Nanostructured Thin Film (NSTF™)
Air Humidification	Tubular Membrane Humidifier	Tubular Membrane Humidifier
Hydrogen Humidification	None	None
Exhaust Water Recovery	None	None
Membrane Electrode Assembly (MEA) Containment and Gasketing	Screen Printed Seal on MEA Subgaskets, GDL crimpted to Catalyst Coated Membrane (CCM)	Screen Printed Seal on MEA Subgaskets, GDL crimpted to Catalyst Coated Membrane (CCM)
Coolant & End Gaskets	Laser Welded (Cooling gasket), Screen-Printed Adhesive Resin (End gasket)	Laser Welded (Cooling), Screen-Printed Adhesive Resin (End)
Freeze Protection	Drain Water at Shutdown	Drain Water at Shutdown
Hydrogen Sensors	2 for FC System 1 for Passenger Cabin (not in cost estimate) 1 for Fuel System (not in cost estimate)	2 for FC System 1 for Passenger Cabin (not in cost estimate) 1 for Fuel System (not in cost estimate)
End Plates/ Compression System	Composite Molded End Plates with Compression Bands	Composite Molded End Plates with Compression Bands
Stack Conditioning (hrs)	5	5

Bus compared to auto:

- Lower power density
- Higher cat. loading
- Higher net power
- Lower pressure
- No expander

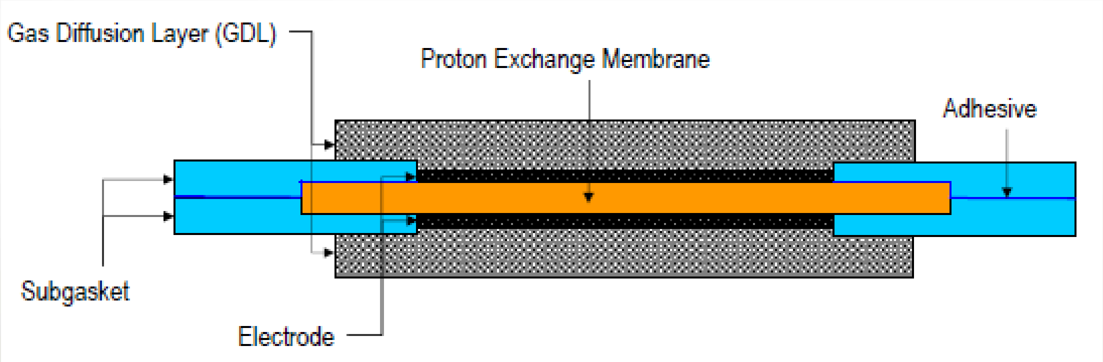
PEM Fuel Cell Stack Concept

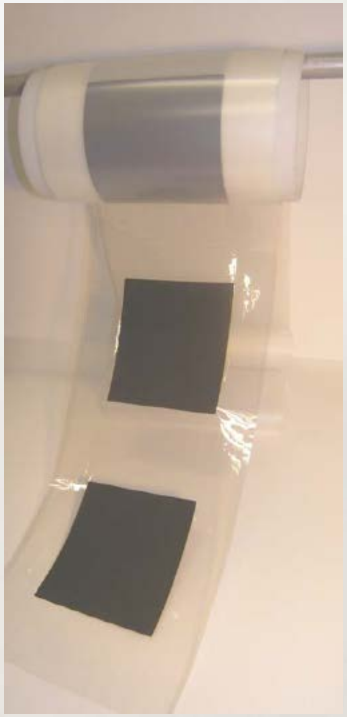
- Abridged to 2 cells (from 369) for clarity
- 1:1 ratio of cooling to active cells



Example of Defining Physical Embodiment

5-Layer Membrane Electrode Assembly (MEA) and its Subgasket Sealing Frame





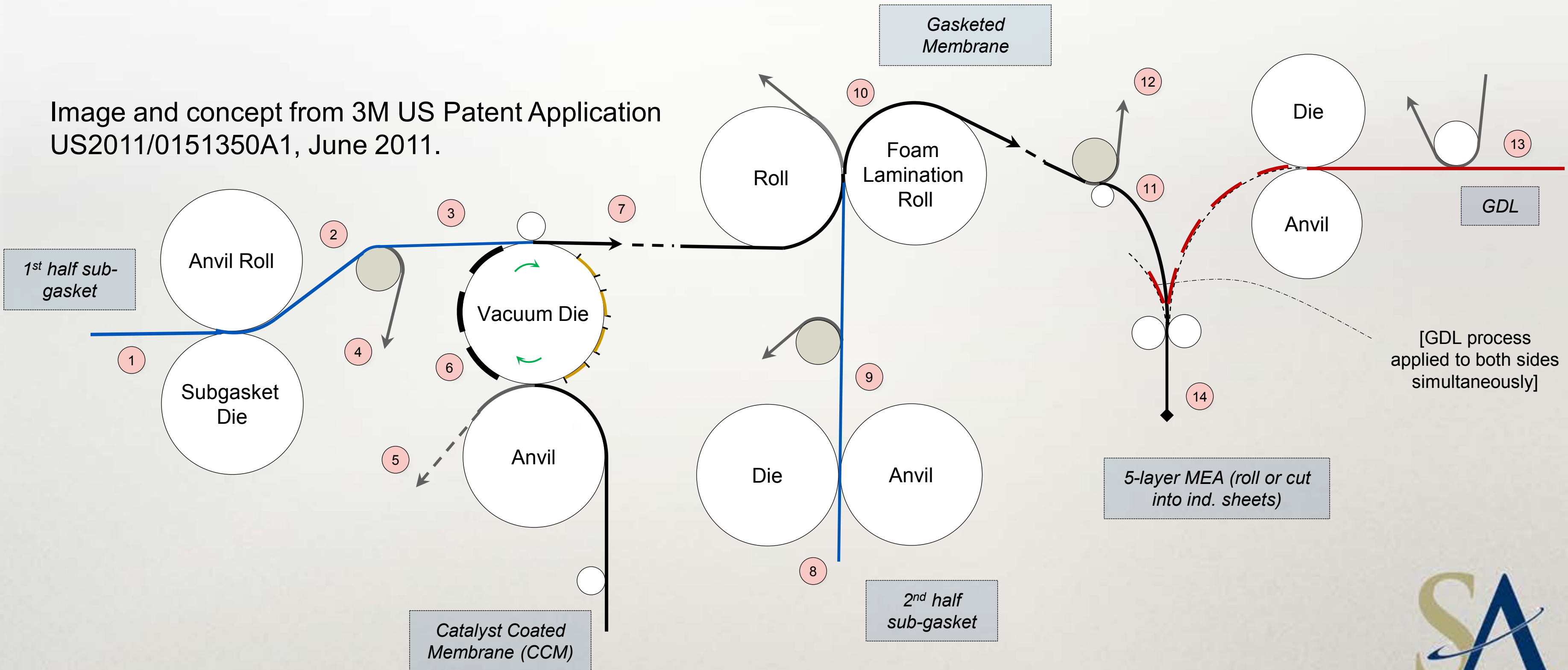
(Figures not to scale: They show much greater border area than is expected in an optimized design.)

Images from: “Membrane-Electrode-Assemblies for PEM Fuel Cells: Material Concepts, Design and Components Integration”, Oliver D. Conradi, 3M, Workshop, Material till Bransleceller, KTH Stockhom, 16 June 2011.

Example of Manufacturing Process Train: Roll-to-roll process for Sub-Gasket Application

- Roll-to-roll process to surround & bond membrane with sub-gasket for structural support and sealing of gases during operation
  1. Catalyst coated membrane (CCM) web formation
  2. Attach membranes to first half of sub-gasket ladder web
  3. Attach second half of sub-gasket ladder web to half sub-gasketed membrane
  4. Attach Gas Diffusion Layers (GDL's) to sub-gasketed membrane (and cut to form individual) 5-layer MEA's

Image and concept from 3M US Patent Application US2011/0151350A1, June 2011.



Reconsideration of MEA Gasket Results in Lower Cost

	2011 Approach	2012 Approach		
Case	Frame Gasket	Sub-Gasket Roll-to-Roll Addition	Screen Printed Seals	Total Sub-gasket Approach
Materials	\$1.78/kW	\$0.47/kW	\$0.03/kW	\$0.52/kW
Manufacturing	\$1.56/kW	\$0.30/kW	\$0.24/kW	\$0.56/kW
Tooling	\$0.04/kW	\$0.05/kW	\$0.0/kW	\$0.04/kW
Total	\$3.39/kW	\$0.825/kW	\$0.27/kW	\$1.09/kW

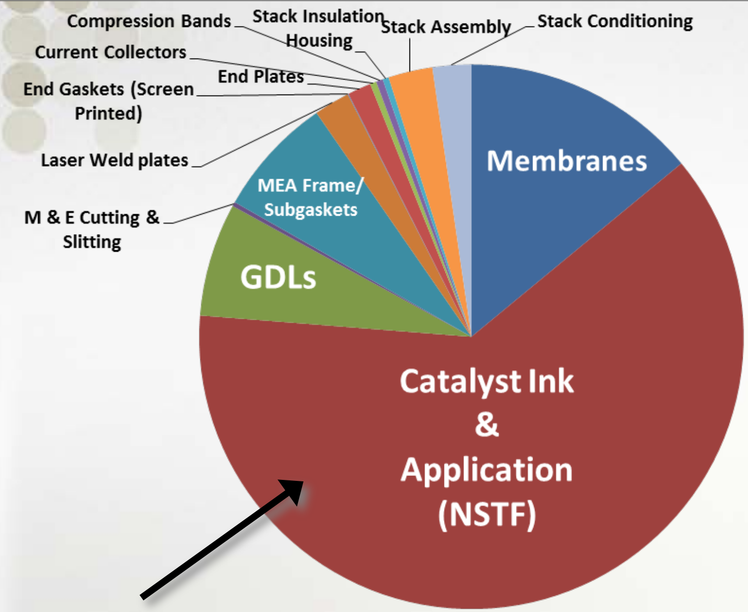
(All costs at 500k systems/year)

Savings over MEA Frame Gasket Approach: ~\$2.30/kW

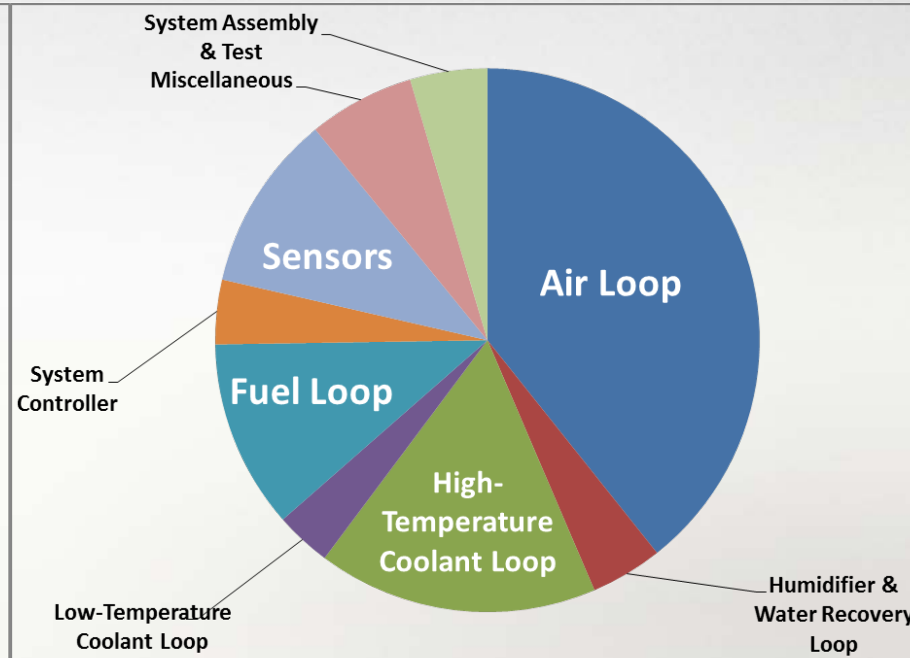
Note: We have used a cost of \$1.67/m^2 for 100 micron PET film. Since two layers are needed, this equates to \$4.18/$m^2_{\text{active area}}$.
If Dupont Teonex® (Polyethylene naphthalate, PEN) film is used at \$7.46/m^2, the total Sub-gasket approach cost increases to \$2.82/kW.

2012 Auto Fuel Cell System: Stack and System Cost Results

At 500,000 systems/year



Dominated by Platinum catalyst material cost (at $1150/troy oz)



Stack Cost

$1,613

$20 / kW$_e$

Balance of Plant Cost

$2,143

$27 / kW$_e$

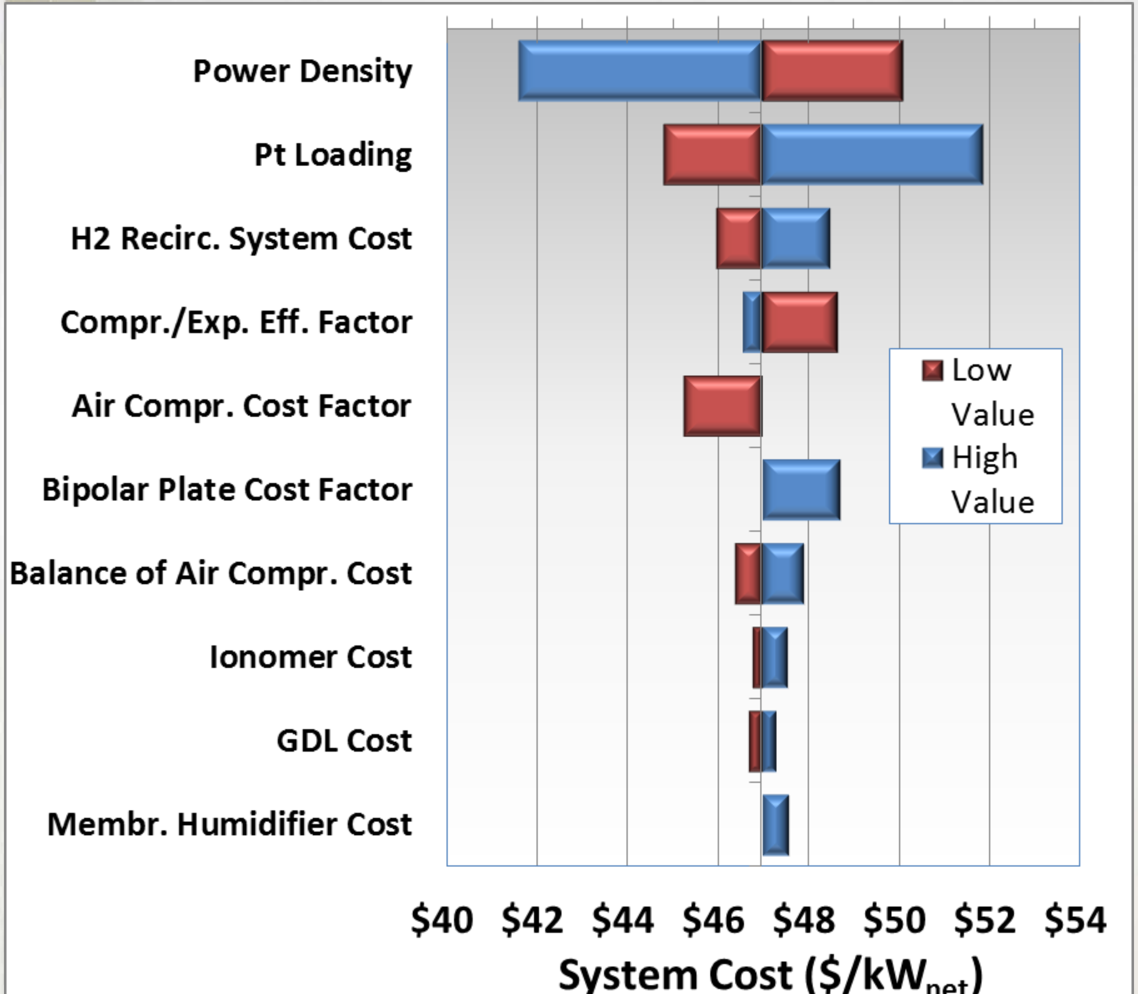
System Cost

$3,756

$47 / kW$_e$

NSTF= 3M's nanostructured thin-film catalyst technology

2012 Auto Fuel Cell System: Power Density & Catalyst Loading Remain Dominant Cost Parameters

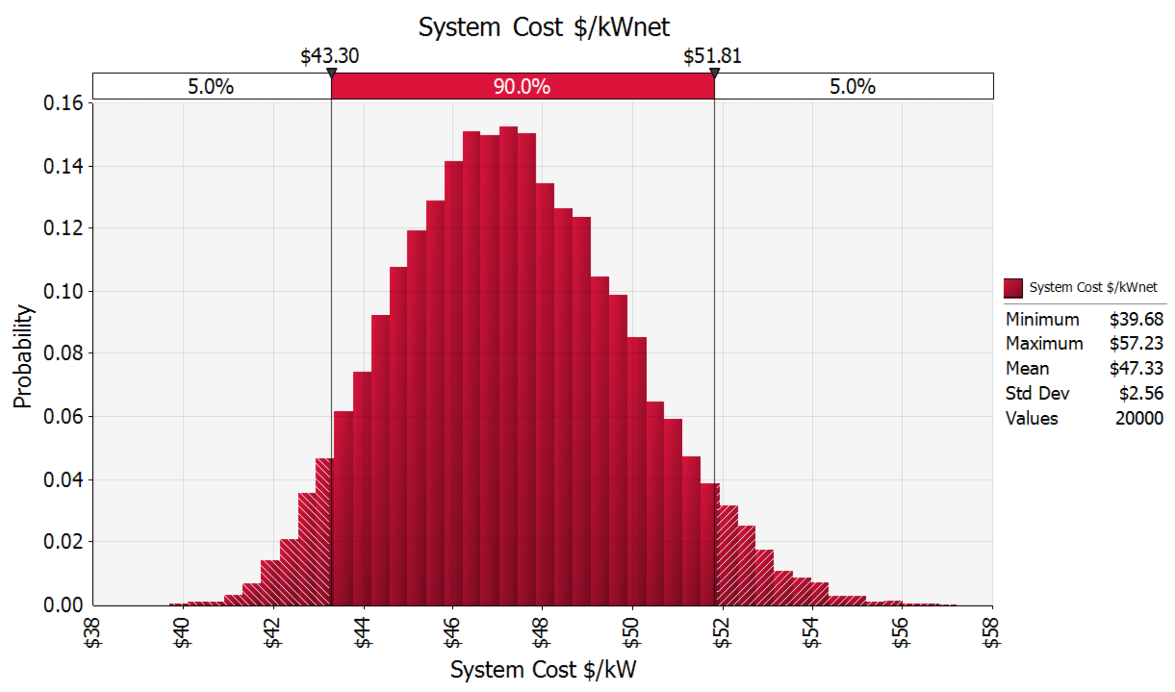


System Cost ($/kWnet), 500,000 sys/year

Parameter	Units	Low Value	Base Value	High Value
Power Density	mW/cm^2	833	**984**	1464
Pt Loading	mgPt/cm^2	0.15	**0.196**	0.3
H2 Recirc. System Cost	$/system	$160.25	**$240.38**	$360.57
Compr./Exp. Eff. Factor		0.90	**1**	1.03
Air Compr. Cost Factor		0.8	**1**	1
Bipolar Plate Cost Factor		1	**1.0**	1.5
Balance of Air Compr. Cost	$/system	$97.53	**$146.30**	$219.45
Ionomer Cost	$/kg	$45.65	**$75.06**	$148.55
GDL Cost	$/m^2	$3.23	**$4.45**	$5.80
Membr. Humidifier Cost	$/system	$52.94	**$52.94**	$100
2012 Auto System Cost			**$46.95**	

- **Upper & lower limits vetted with Fuel Cell Tech Team.**

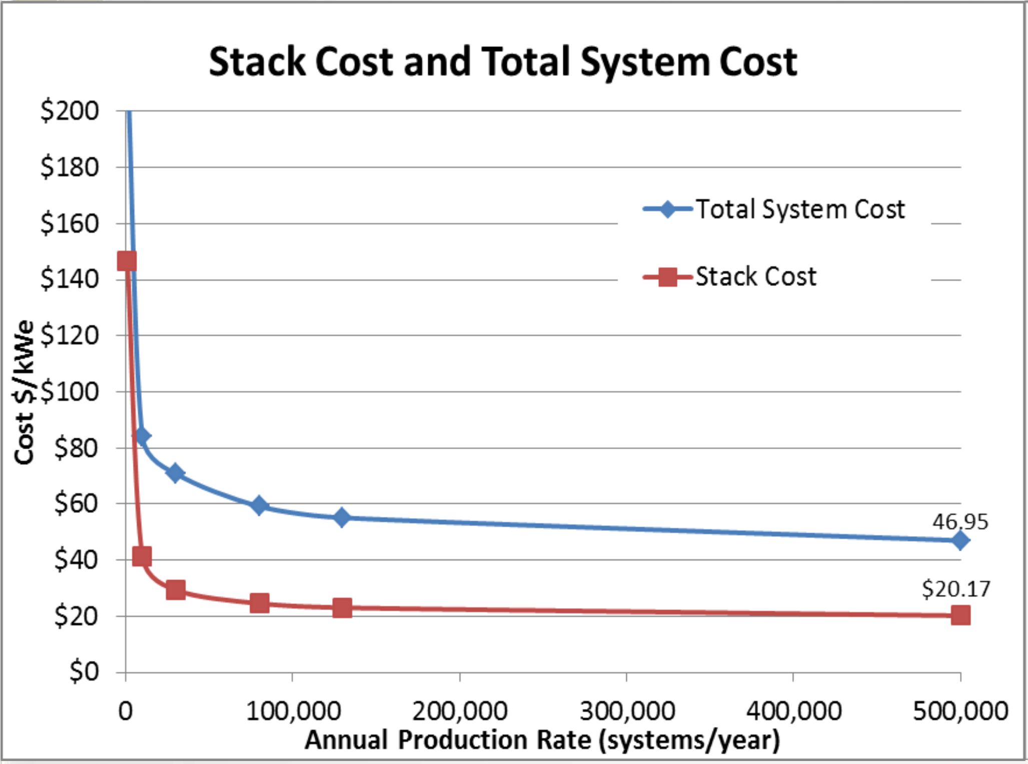
2012 Auto Fuel Cell System: 90% Confidence System Cost is between $43 & $52/kWe

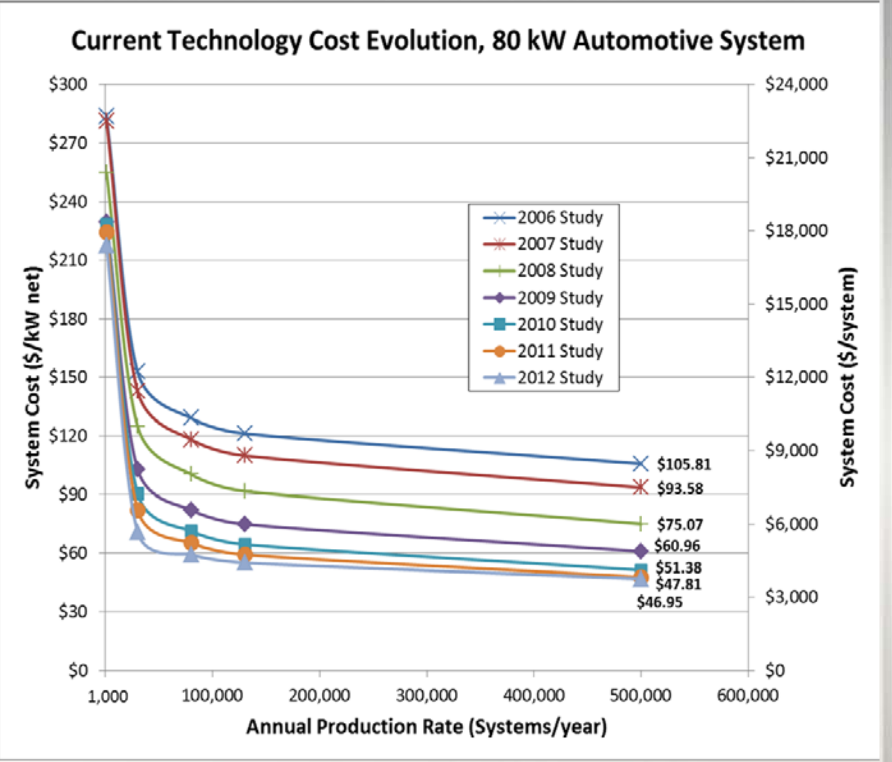


Based on Monte Carlo analysis for 500k systems/year

2012 Technology Monte Carlo Analysis, 500k sys/year				
Parameter	**Unit**	**Minimum Value**	**Likeliest Value**	**Maximum Value**
Power Density	mW/cm2	833	**984**	1464
Pt Loading	mgPt/cm2	0.15	**0.196**	0.3
Ionomer Cost	$/kg	$45.65	**$75.06**	$148.55
GDL Cost	$/m2	$3.23	**$4.45**	$5.80
Bipolar Plate & Coating Cost Factor		1	**1**	1.5
Membrane Humidifier Cost	$/system	$61.00	**$61.00**	$100.00
Product of Compr/Expander/Motor&MotorController Efficiencies		0.415	**0.51**	0.54
Air Compressor Cost Factor		0.8	**1**	1
Balance of Air Compressor Cost	$/system	$97.53	**$146.30**	$219.45
Hydrogen Recirculation System Cost	$/system	$160.25	**$240.38**	$360.57

2012 Automotive System Cost Continues Downward Trend



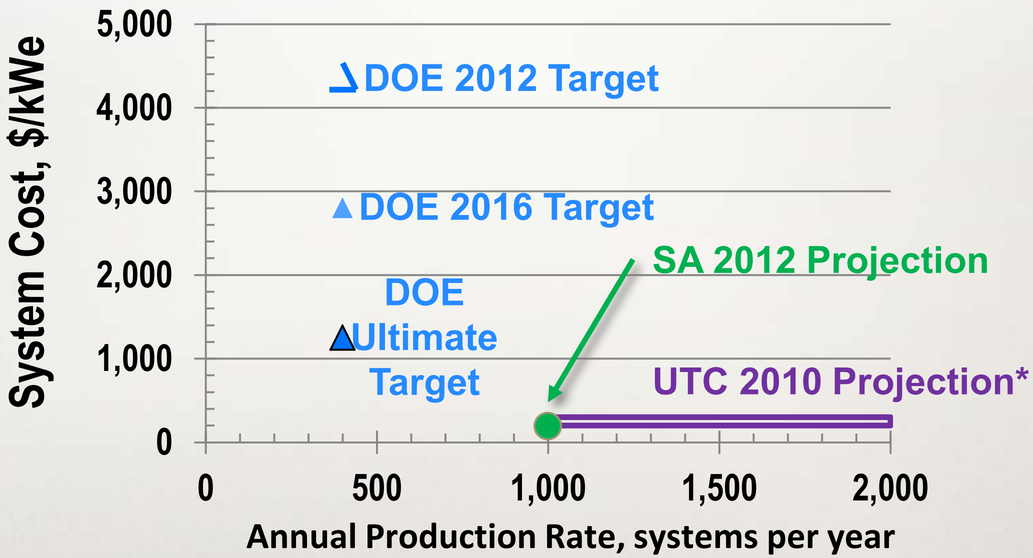


- Stack and System cost curves exhibit similar shape as seen in previous year's analysis.
- "Knee in curve" occurs at ~50k systems/year.
- Downward cost trend observed for subsequent analysis years

Other DFMA Applications: 40’ Transit Bus Fuel Cell Power System

2012 Bus Total System Cost Results: ~$200/kW at 1,000 systems per year

	2012 Bus System
Annual Production Rate	1,000
System Net Electric Power (Output)	160
System Gross Electric Power (Output)	177.10
Fuel Cell Stacks	$21,651.24
Balance of Plant	$8,707.03
System Assembly & Testing	$152.34
Total System Cost ($)	$30,510.60
Total System Cost ($/kW$_{net}$)	$190.69
Total System Cost ($/kW$_{gross}$)	$172.28



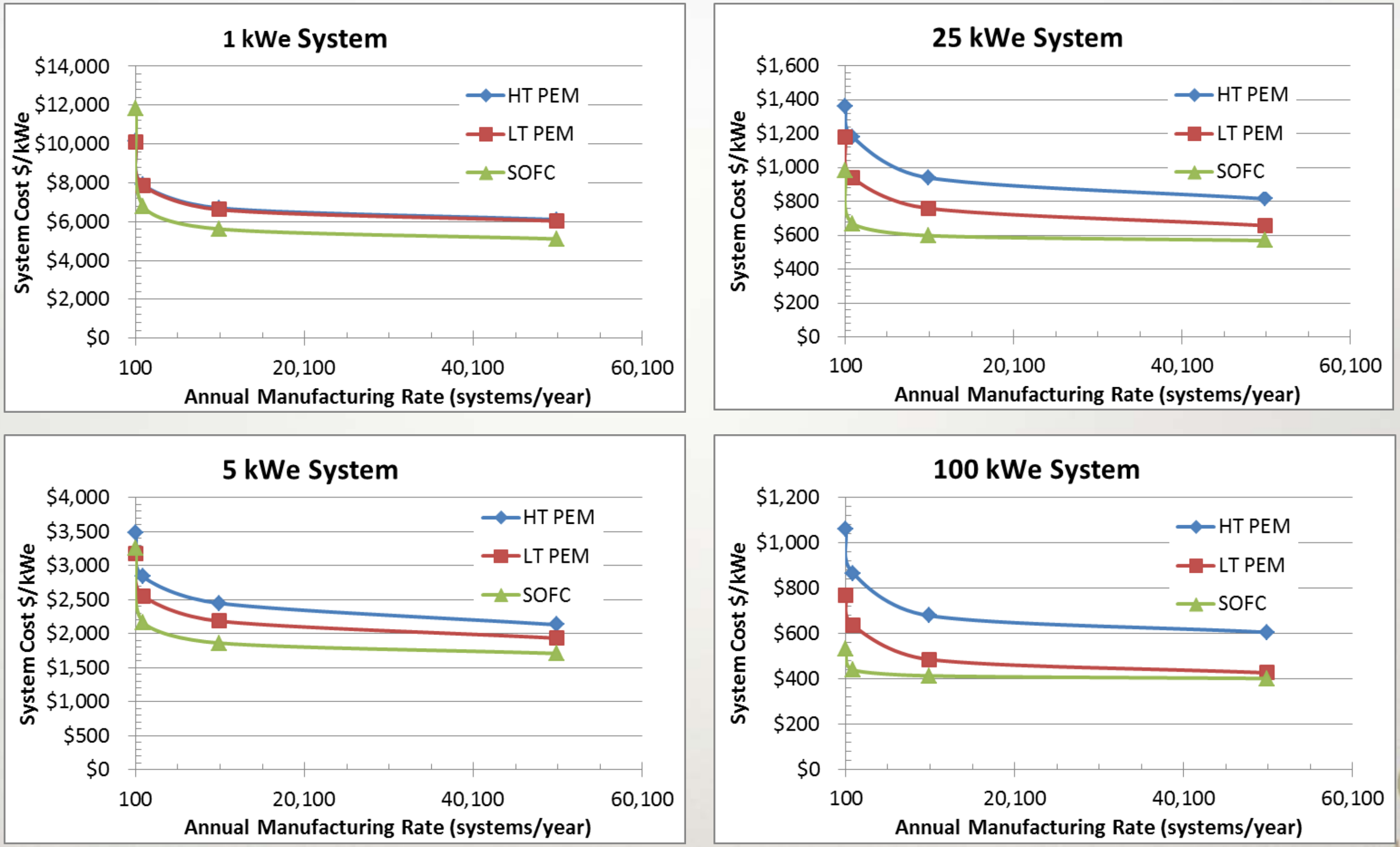
DOE Targets include Fuel Cell plus Batteries whereas SA Target are Fuel Cell only.

* 2010 DOE AMR Joint DOE/DOT Bus Workshop, “Progress and Challenges for PEM Transit Fleet Applications”, Tom Madden, UTC, 7 June 2010: 2010 UTC Preliminary Bus Fleet Cost Target: $200-300/kW in 1,000’s per year.

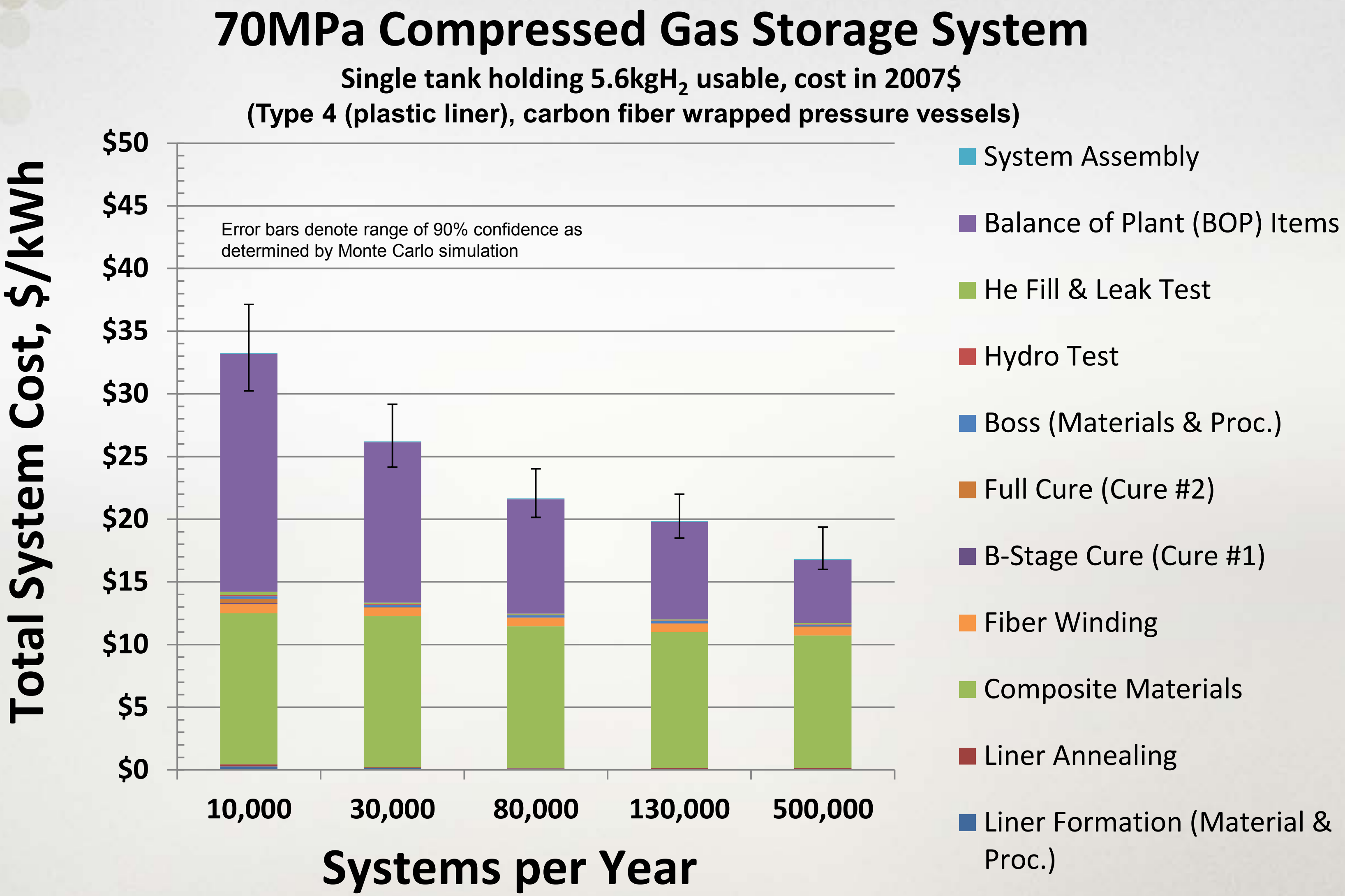
Other DFMA Applications: Stationary Fuel Cell Power Systems

Three Fuel Cell Technologies Examined:

- Low Temperature PEM (80°C Nafion® membrane)
- High Temperature PEM (160°C Polybenzimidazole (PBI) membrane)
- Solid Oxide (planar cells, 750°C operation)



Other DFMA Applications: High Pressure H_2 Storage Vessels



Material cost, driven by carbon fiber cost, and BOP costs dominate at all annual production rates.

Summary

- Process based cost analysis useful for:
  - Cost estimation at multiple manufacturing rates
  - Determination of key cost drivers
  - Iteration on cost comparisons to determine lowest cost design or process
  - May be applied at approximate or very high level of detail
- 2012 estimates for 80kW Automotive FC Systems
  - \$43-\$52/kW (\$47/$kW_{e\text{-}net}$) @ 500k systems/year
- 2012 estimates for 160kW Bus FC Systems
  - \$180-\$233/kW (\$191/$kW_{e\text{-}net}$) @ 1,000 systems/year
- Standard outputs
  - System schematic
  - Component design
  - Cost variation with manufacturing rate
  - Tornado sensitivity chart
  - Monte Carlo analysis showing 90% confidence cost range

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Questions?

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