Stationary and Emerging Market Fuel Cell System Cost Analysis – Material Handling Equipment FC097

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Battelle

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Washington D.C.

Overview – Program Details

Timeline

Start		End
Nov 2011	FY12 90% Completed	July 2016

Budget (DOE Project Funding)

$541K FY12 Funding

Total $2 M

FY13 Funding $250K

Collaborators

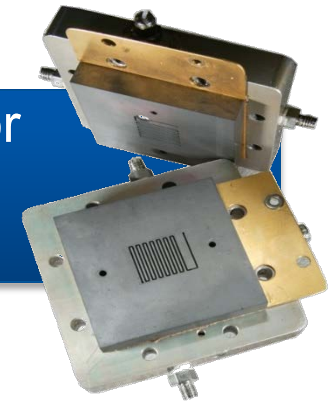
have provided design inputs, cost inputs, design review, and manufacturing cost review

- Hydrogenics
- NexTech
- Ballard
- Crown
- Delphi
- Nuvera
- Bulk Molding Compounds
- American Durafilm
- Metro Mold and Design
- 3M
- SonoTek

Barriers Addressed

Cost reduction of fuel cell components and materials	Manufacturing capability	Customer acceptance

Relevance – Program Objective



5-year program to assist DOE in developing 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 equipment
- Fuel Cell Types - 80°C PEM, 180°C PEM, SOFC technologies
- Annual Production Volumes - 100, 1K, 10K, and 50K (only for primary power 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 (Cost Assessment 100% Complete)
- 1 and 5 kW SOFC for Auxiliary Power Unit (APU) applications (Cost Assessment ~90% Complete)

Relevance – Technical Barriers Addressed

Technical Barriers	Project Goals
Cost reduction of fuel cell components and materials	1. Identify major contributors to fuel cell system cost 2. Quantify potential cost reduction based upon technological improvements
Manufacturing capability	3. Identify major contributors to fuel cell system manufacturing cost 4. Identify areas for manufacturing R&D to improve quality and/or throughput 5. Provide basis for consideration of transition from other industries
Customer acceptance	6. Develop accurate cost projections that can be used to evaluate total cost of ownership and facilitate early market adoption

Approach – Manufacturing Cost Analysis Methodology

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Market Assessment

- 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

System Design

- Conduct literature search
- Develop system design
- Gather industry input
- Size components
- Gather stakeholder input
- Refine design
- Develop BOM
- Define manufacturing processes
- Estimate equipment requirements

Cost Modeling

- 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

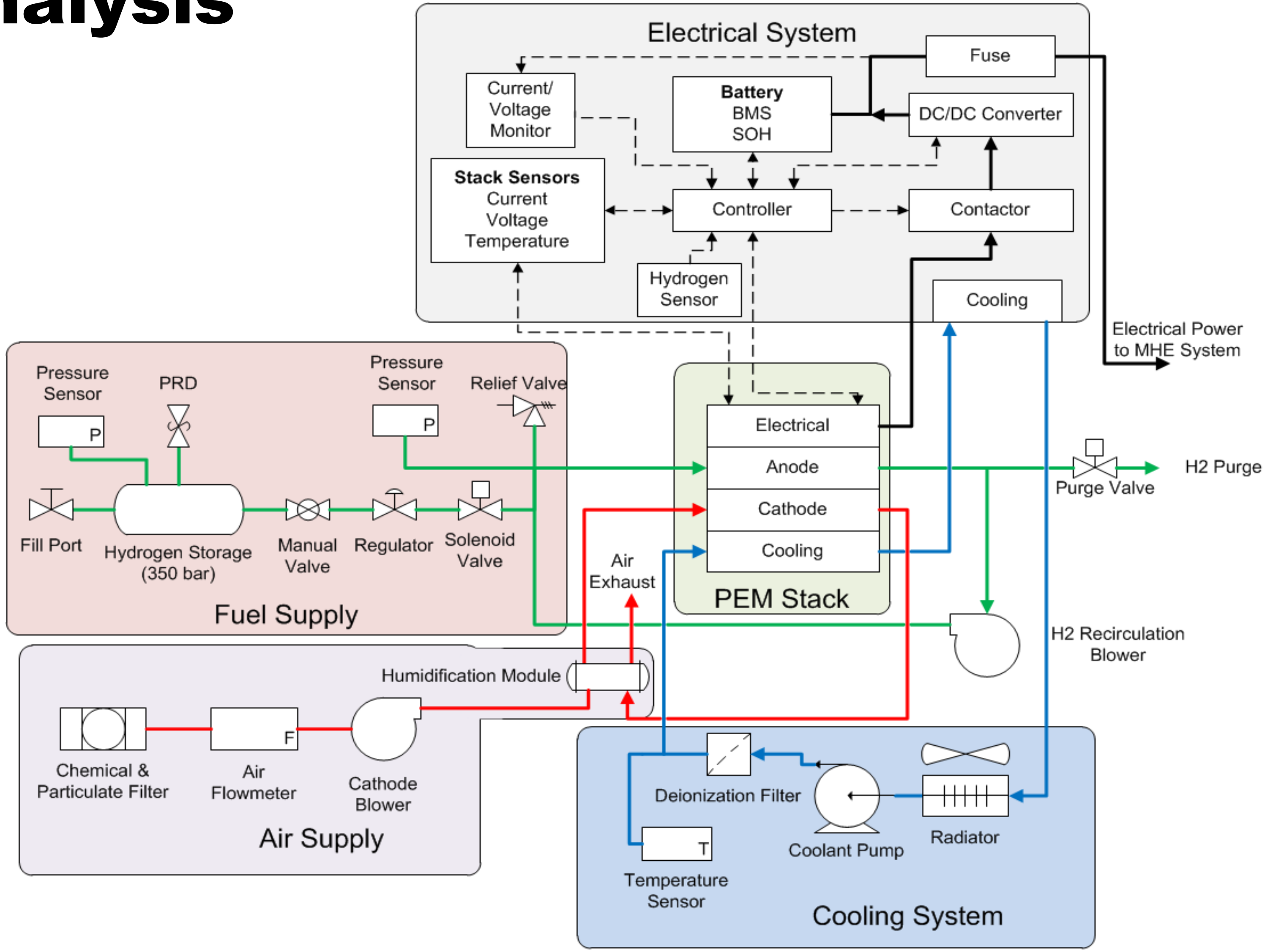
Sensitivity & Life Cycle Cost Analysis

- Sensitivity analysis of individual cost contributors
- Life cycle cost analysis to estimate total cost of ownership

Progress & Accomplishments – FY 12

- Completed the manufacturing cost analysis for PEM fuel cells for material handling applications
  - Presented these results at the Fuel Cell Seminar
- For SOFC systems for truck APU applications
  - Completed the system design
  - Performed DFMA® analysis of the stack and finalized stack costs
  - Balance of Plant cost analysis underway

Progress & Accomplishments – PEMFC System Design Basis for MHE Cost Analysis



Progress & Accomplishments – Additional Design Details

Component	Specification
Fuel (Anode)	• 99.95% H_2, fueled at a centralized plant location • Fuel stored onboard at 350 bar • No humidification • Regulated to 2 psig pressure at the stack • Recirculation with periodic purges
Air (Cathode)	• Filtered for particulates and chemicals (passive) • Humidification • Flow is 2.5X stoichiometric
Cooling	• Liquid cooled (low conductivity glycol/de-ionized water mixture in a closed-loop)
Electric	• 48 VDC regulated output • Buck DC/DC converter • Hybridized system with Li-ion technology to supply short bursts of peak power • Peak power requirements nominally 300% of net fuel cell power, last for 3–5 sec
General	• 10,000 hr lifetime • Includes ballast to maintain comparable system weight with competitor products

Progress & Accomplishments – MHE PEMFC System Specification

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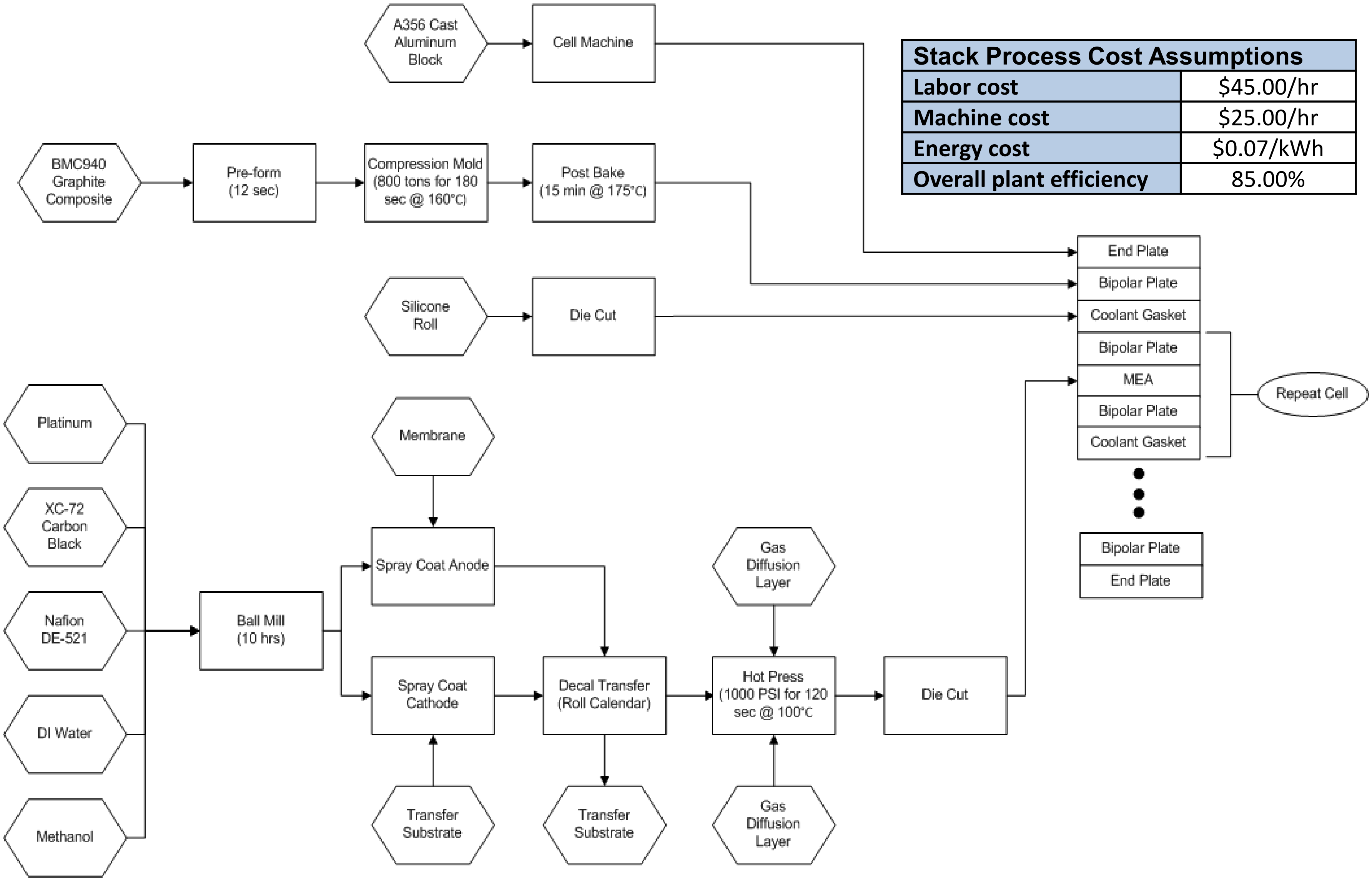
Parameter	10 kW System	25 kW System
Power Density (W/cm^2)	0.65	
Current Density (A/cm^2)	1.0	
Cell Voltage (VDC)	0.65	
Active Area Per Cell (cm^2)	200	400
Net Power (kW)	10	25
Gross Power (kW)	11	27.5
Number of Cells (#)	85	106
Full Load Stack Voltage (VDC)	55	69
Membrane Base Material	PFSA, 0.2mm thick, 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	

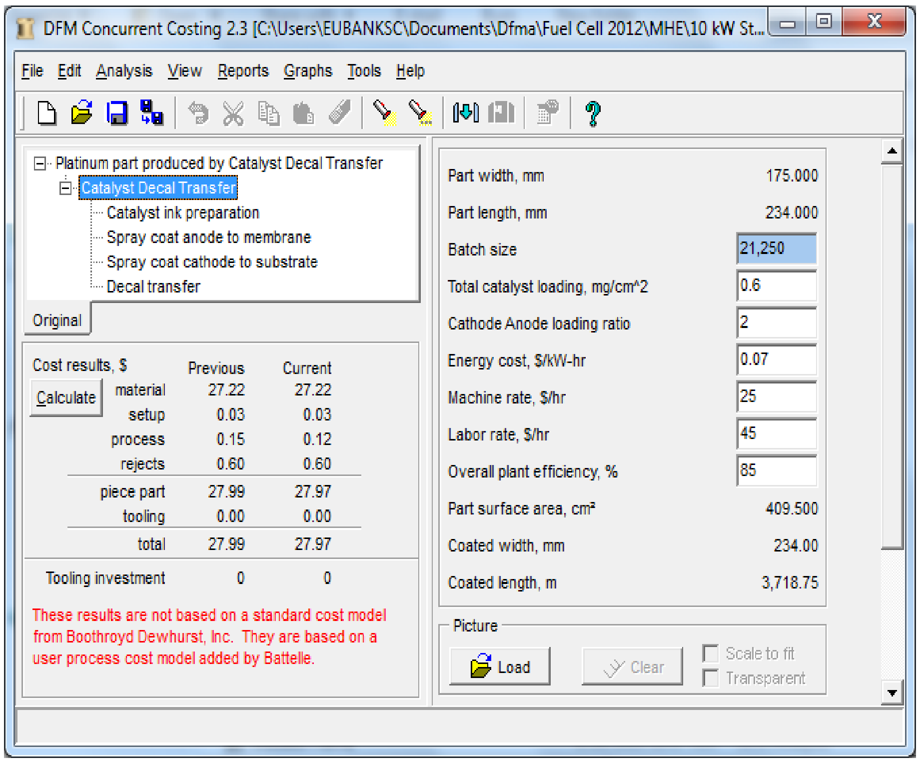
Progress & Accomplishments – PEMFC Stack Manufacturing Process Overview

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



Progress & Accomplishments – 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

Progress & Accomplishments – Manufacturing Processes Evaluated

Process	Method Evaluated	Alternatives Not Evaluated
Catalyst Deposition	Spray coating	• Slot die coating • Tape casting • Nanostructure Thin Film
	Single layer with decal transfer	• Dual head slot die
Bipolar Plate	Compression molding	• Die stamping & coating
MEA Forming	Ruler blade die cutting	• Laser cutting
Gasket Forming	Ruler blade die cutting	• Laser cutting • Injection molding

Progress & Accomplishments – Major Stack Material and Process Assumptions

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%

Progress & Accomplishments – Capital Cost Assumptions

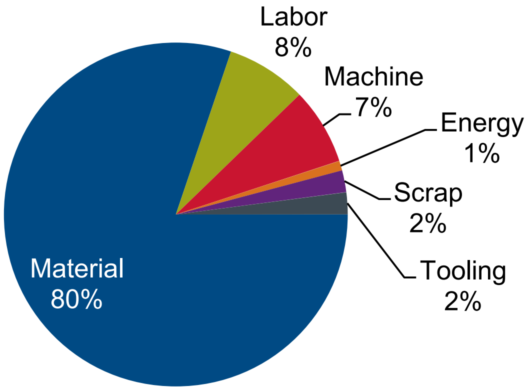
Capital Cost	Unit Cost (2012$)	Units	Total Cost (2012$)	Assumption/Reference
Factory Total Construction Cost	250	$/sq ft	855,750 to 5,545,000	• Includes Electrical Costs ($50/sq ft) • Total plant area based on line footprint plus 1.5x line space for working space, offices, shipping, etc. • Varies with 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% Capital Cost		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

Progress & Accomplishments – 10 kW MHE PEMFC Stack Manufacturing Cost

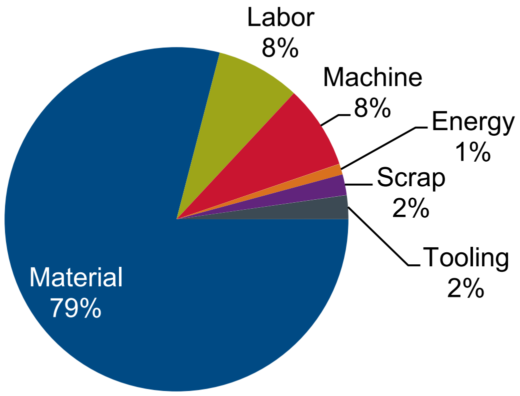
Stack Component	100 Units ($)	1000 Units ($)	10,000 Units ($)
Bipolar plates	726	725	724
MEA	3,333	2,964	2,415
Cooling gasket	139	139	139
Tie rods and hardware	40	40	40
End plates	54	54	54
Stack assembly	65	52	50

Note: All costs include manufacturing scrap

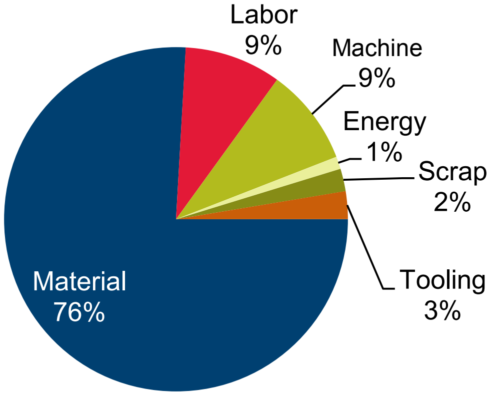
10 kW Stack Costs
100 units/year



10 kW Stack Costs
1000 units/year

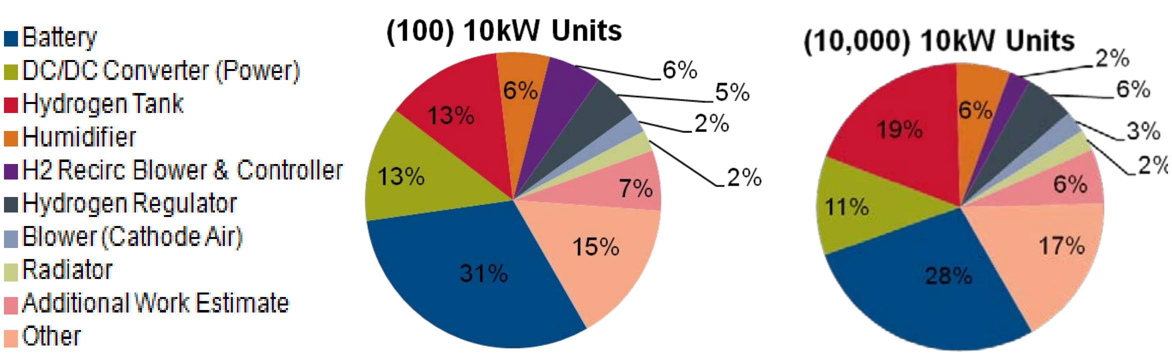


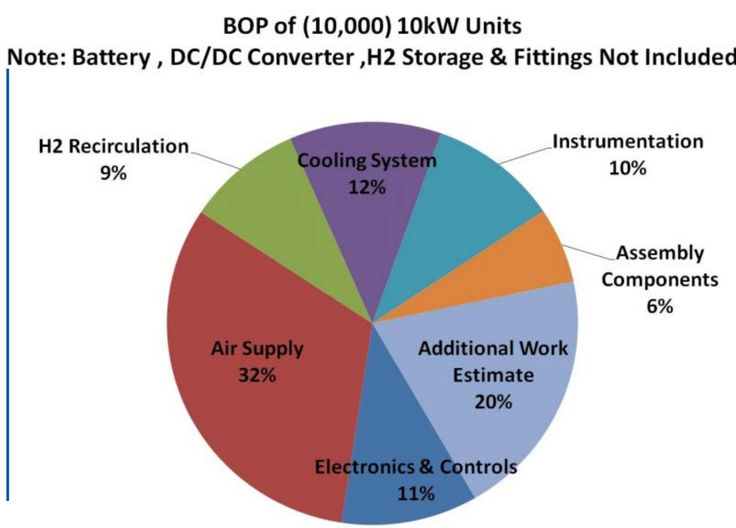
10 kW Stack Costs
10,000 units/year



Progress & Accomplishments – 10 kW MHE PEMFC BoP Manufacturing Cost

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





Progress & Accomplishments – 10 kW MHE PEMFC System Cost Summary

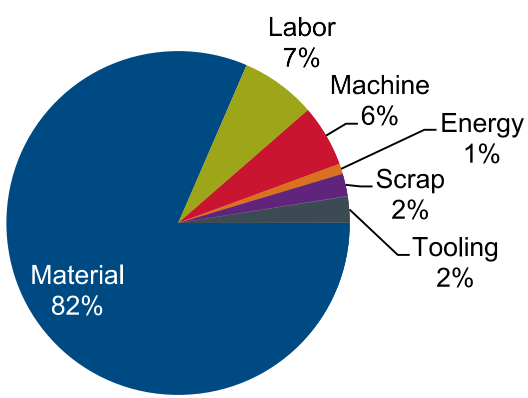
Description	100 Units	1,000 Units	10,000 Units
Total stack manufacturing cost, with scrap	$4,357	$3,974	$3,422
Stack manufacturing capital cost	$2,825	$283	$74
Balance of plant	$27,272	$21,079	$17,856
System assembly, test, and conditioning	$279	$267	$266
Total system cost, pre-markup	**$34,733**	**$25,603**	**$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

Progress & Accomplishments – 25 kW MHE PEMFC Stack Manufacturing Cost

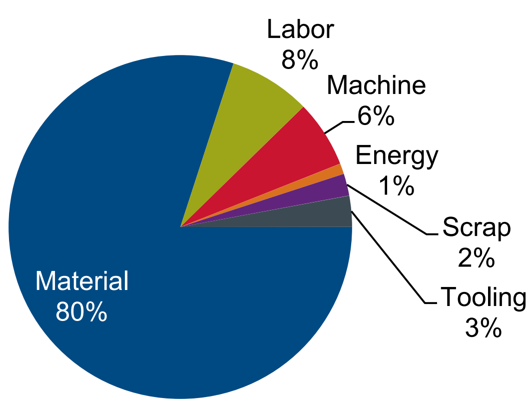
Stack Component	100 Units ($)	1,000 Units ($)	10,000 Units ($)
Bipolar plates	1,461	1,475	1,457
MEA	6,887	6,138	4,941
Cooling gasket	280	280	280
Tie rods and hardware	40	40	40
End plates	80	80	80
Stack assembly	68	54	53

Note: All costs include manufacturing scrap

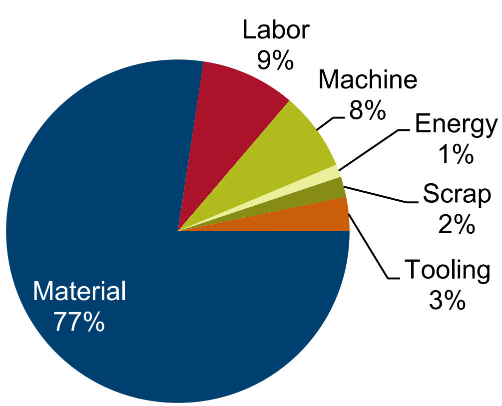
25 kW Stack Costs
100 units/year



25 kW Stack Costs
1000 units/year

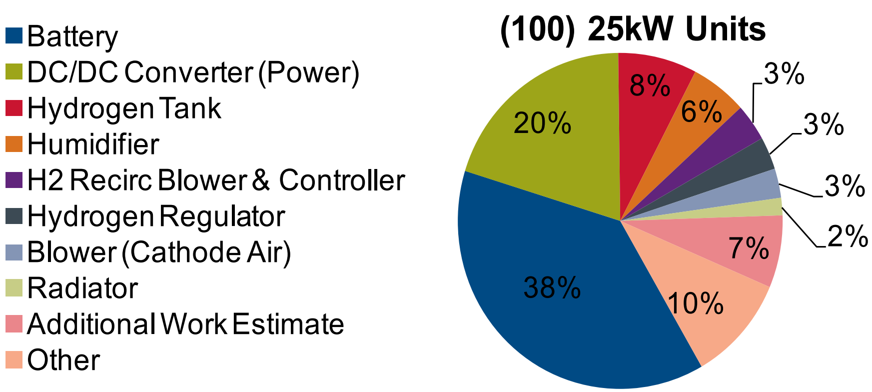


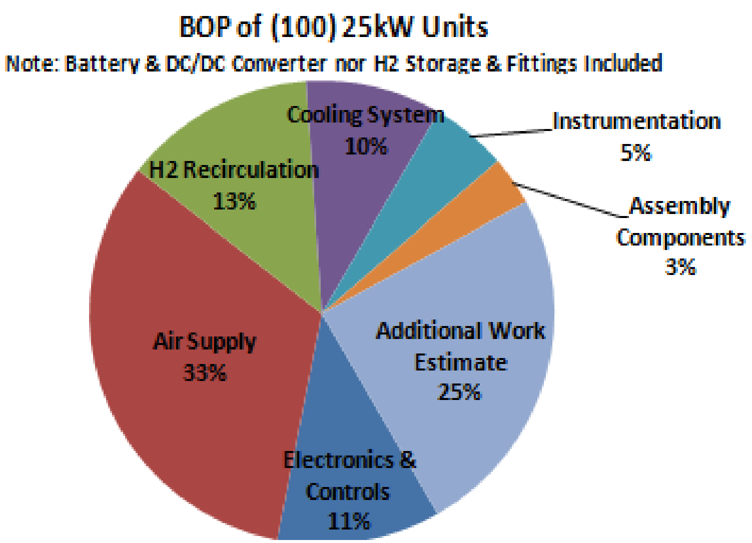
25 kW Stack Costs
10,000 units/year



Progress & Accomplishments – 25 kW MHE PEMFC BoP Manufacturing Cost

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

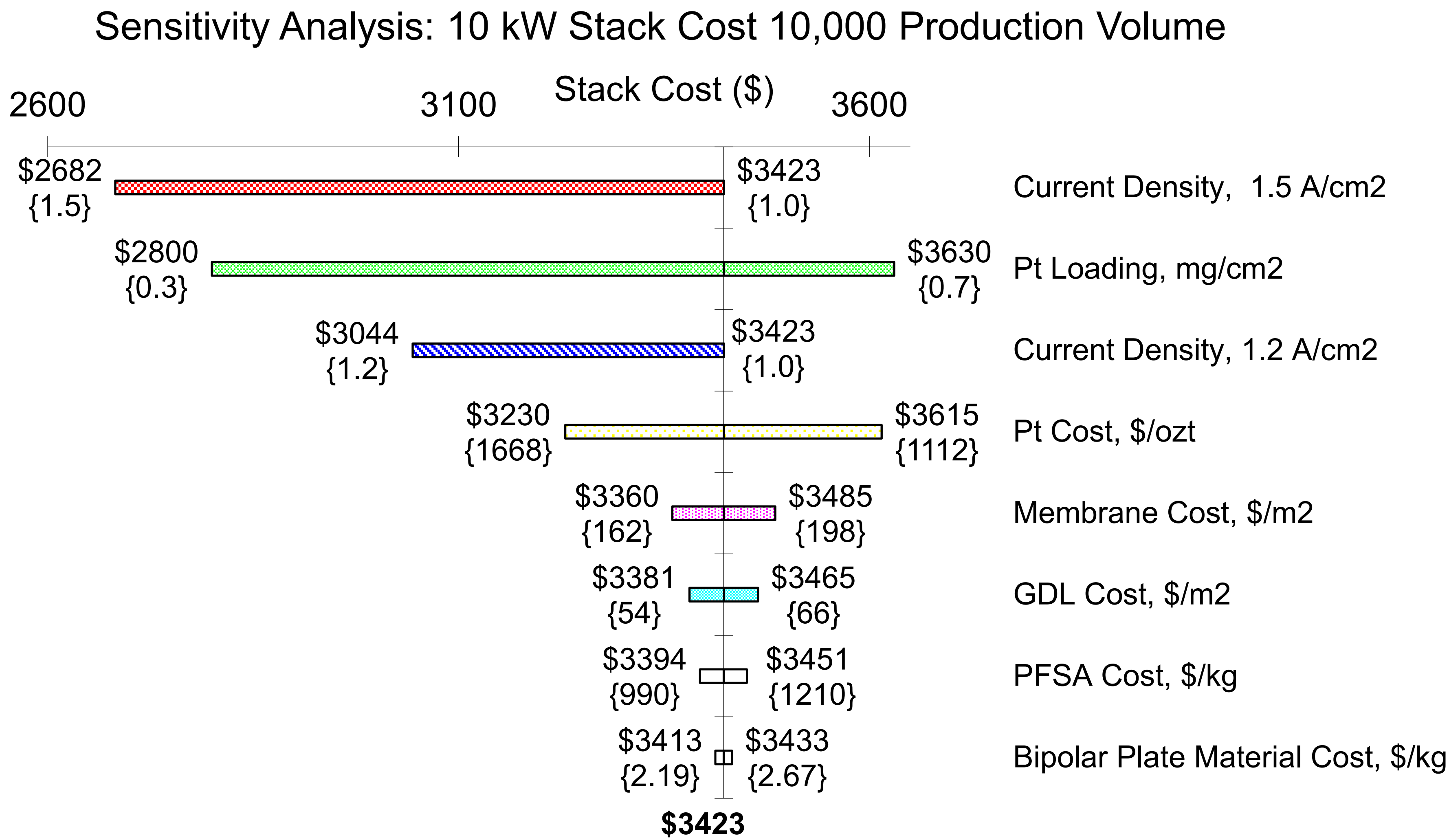




Progress & Accomplishments – 25 kW MHE PEMFC System Cost Summary

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
Balance of plant	$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**

Progress & Accomplishments – 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.

Progress & Accomplishments - 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

Progress & Accomplishments – MHE PEMFC System BoP Cost Drivers

1. Energy Storage
2. H_2 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**

Progress & Accomplishments – Life Cycle Cost Analysis Assumptions

	Fuel Cell	Battery
Cost of Forklift Only ($)	25,000	25,000
Cost of Power System ($)	35,000	5000 (each forklift has 2 batteries)
Hours of Operation per Year (hours)	3,000	3000
Total Number of Shifts	2	2
Hours per Shift	4.4	4.4
Average Operating Time w/o Refueling/Recharging (hours)	7.5	4
Time for Refueling (min)	3.3	-
Time for Changing out Batteries (min)	-	30
Costs of Battery Charging Infrastructure ($ per Truck)	-	2500
Number of Times Fuel Cell Refueled/Battery Changed During Day	2	2
Cost of Refueling/Recharging ($)	612[a]	5,100
Electricity/Hydrogen Fuel Costs ($)	4,800[b]	980[c]
Fuel Cell/Battery Replacement Costs Every 3 Years ($)	15,600[d]	5,000 (X 2 as each forklift has 2 batteries)

a. Assumes operator cost of $15/hr. Refuel the fuel cell twice. Replace the battery twice
b. Assumes that truck uses 0.2 kg/operational hour. Operates for 3000 hours. Cost of hydrogen is $8 per kg.
c. Assumes electricity use is ~3kWh, batteries are charged for 8 hours. Two batteries are replaced every day, 340 days a year.
d. Replacing only fuel cell stack and battery pack. Based on cost of manufacturing 10 kW fuel cell stack.

Progress & Accomplishments – Life Cycle Cost Analysis Results

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Net Present Value Analysis of Fuel Cell and Battery Powered Forklifts for 2 Shift Operations for Approximately 9 hours Per Day

	Fuel Cell Powered Fork Lift	Battery Powered Forklift
NPV of Capital Costs ($)	95,407	60,251
NPV of O&M Costs ($)	52,610	59,104
NPV of Total Costs of the System ($)	148,017	119,355

Net Present Value Analysis of Fuel Cell and Battery Powered Forklifts for 3 Shift Operations for Approximately 16 hours Per Day

	Fuel Cell Powered Fork Lift	Battery Powered Forklift
NPV of Capital Costs ($)	95,407	94,555
NPV of O&M Costs ($)	95,518	124,535
NPV of Total Costs of the System ($)	190,925	219,091

Progress & Accomplishments – Results Summary

- For MHE applications, BoP component costs driving total system cost
- Production volume has negligible effect on stack cost
  - Precious metal, graphite composite and commodity cost constant across all volumes
  - Material processing requirements limit throughput
- For fuel cells to penetrate MHE applications further cost reduction is required as demonstrated by LCA analysis

Proposed Future Work

FY13	FY14, FY15, FY16
• Complete assessment 1 and 3 kW of SOFC systems for APU applications • Complete updating assessment of backup power systems	• Complete additional new analyses – CHP systems, Primary power systems • Revisit and update previous analyses based upon technological advancements

Summary

- **Relevance:** Help answer questions on opportunities for cost reduction to penetrate non-automotive applications
- **Approach:** Perform cost modeling including DFMA® analysis of a generic fuel cell system design developed for the application
- **Technical Accomplishments and Progress:** Completed cost analysis of PEMFC for MHE applications. Cost analysis of SOFC for APU applications underway
- **Technology Transfer/Collaborations:** Working with a number of industry collaborators (e.g., Ballard, Hydrogenics, Nuvera) for design inputs, cost inputs, design review and results review
- **Proposed Future Research:** Complete cost analysis of SOFC (1 and 5 kW) for APU applications and update cost analysis of backup power systems