Manufacturing Cost Analysis Of Fuel Cell Systems

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Directed Technologies Inc. (DTI)

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FC018

2011 DOE H_2 Program AMR Presentation

DIRECTED TECHNOLOGIES INC

Overview

Timeline

- Builds on DOE contract from 2006-2010 to conduct annual updates
- Current contract
  - Start Date: February 2010
  - End Date: May 2012
- 40% Complete

Funding

- Total project funding
  - DOE share: $ 746K
  - Contractor share: $ 0
- Funding received in FY10: $ 230K
- Funding for FY11: $ 330K
- Total Project Funding:
  - $315k Vehicular
  - $431k Stationary

Barriers

- Fuel Cell Barrier: B "Cost"
- Manufacturing R&D Barriers:

  Fuel Cells A "Lack of High-Volume Membrane Electrode Assembly (MEA) Processes"

  Fuel Cells B "Lack of High-Speed Bipolar Plate Manufacturing Processes"

  Fuel Cells F "Low Levels of Quality Control and Inflexible Processes"

DOE Cost Targets

Characteristic	Units	2010	2015
Stack Cost	$\$/kW_{e\ (net)}$	$25	$15
System Cost	$\$/kW_{e\ (net)}$	$45	$30

Partners/Collaborations

- Argonne National Laboratory
- NREL
- Nuvera
- Extensive other interaction with industry/researchers to solicit design & manufacturing metrics as input to cost analysis.
- Ballard
- Ford

Project Objectives

To assist DOE in developing fuel cell systems by assessing the cost status, identifying key cost drivers, and exploring pathways to cost reduction of automotive and stationary fuel cell systems.

1. **Identify the lowest cost system design and manufacturing methods for the current state-of-the-art technology, at varying power levels:**

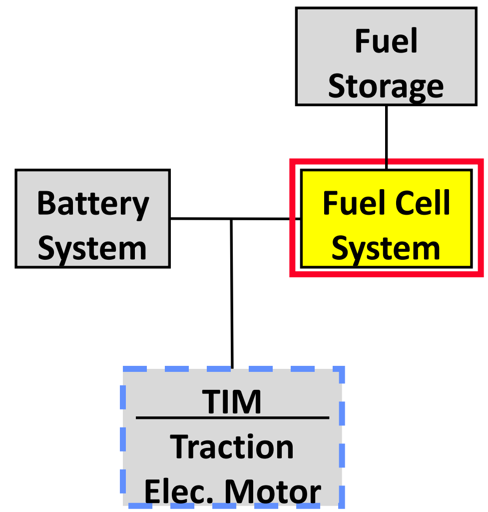
	Vehicular	Stationary
LT PEMFC	80 kW_{net}	1,5,25,100 kW_{net}
HT PEMFC		
SOFC		

2. **Determine costs for these systems at varying production rates:**

Vehicular	Stationary
1k, 30k, 80k, 130k, 500k systems/year	100, 1k, 10k, 50k systems/year

3. **Analyze, quantify & document impact of system performance on cost**
   - *Use cost results to guide future component development*

Vehicle System



Project covers complete FC system (specifically excluding battery, traction motor/inverter, and storage)

Project Task & Status

Cost assessments

	Task 4.1:	**Automotive Fuel Cell Technologies**
[100%]	Task 4.1.1:	Cost of Automotive Fuel Cell Systems
[100%]	Task 4.1.2:	Identification of Capital Equipment and R&D Needs
[100%]	Task 4.1.3:	Optimizing the Oper. Pressure vs. Catalyst Cost Balance
[100%]	Task 4.1.4:	Quality Control
[100%]	Task 4.1.5:	Lifecycle Cost Analysis
[40%]	Task 4.1.6:	Cost of Automotive 2011 Fuel Cell Systems

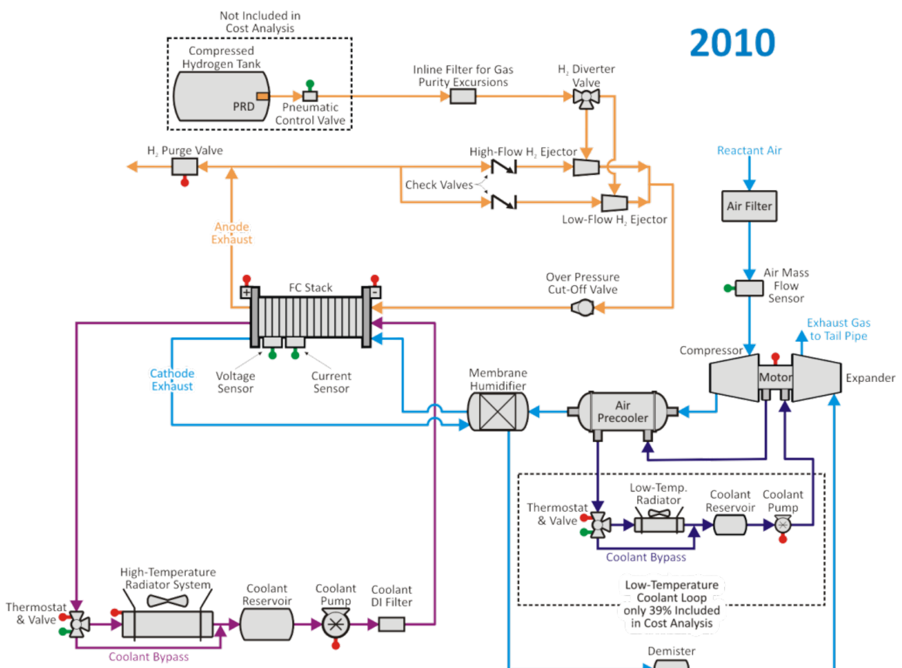
Addressed Today (Tasks 4.1.1–4.1.5)

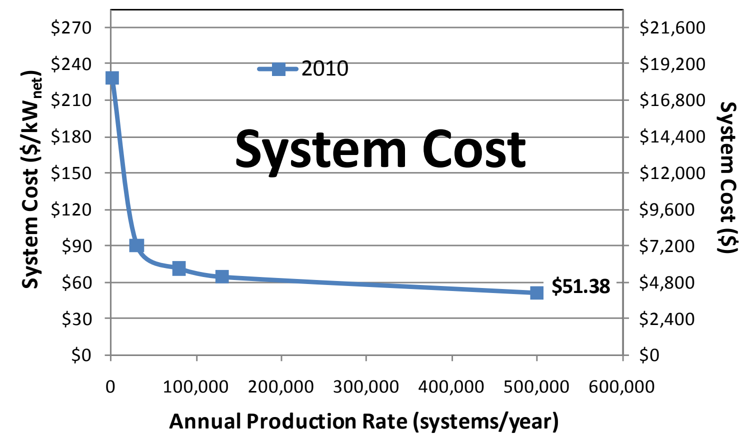
	Task 4.2:	**Stationary Fuel Cell System Technologies**
[40%]	Task 4.2.1:	Stationary LT PEM Stack
[25%]	Task 4.2.2:	Stationary LT PEM BOP
[5%]	Task 4.2.3:	Stationary SOFC Stack
[5%]	Task 4.2.4:	Stationary SOFC BOP
[10%]	Task 4.2.5:	Stationary HT PEM Stack
[10%]	Task 4.2.6:	Stationary HT PEM BOP

Summary of Last Year's AMR Results (2010)

- **DFMA® (Design for Manufacturing and Assembly) is a registered trademark of Boothroyd Dewhurst, Inc.**
- **DTI practices are a blend of:**
  - "Textbook" DFMA®, industry standards & practices, DFMA® software, innovation and practicality
- **Analysis includes effects of bulk purchasing, manufacturing methods, tooling amortization**

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





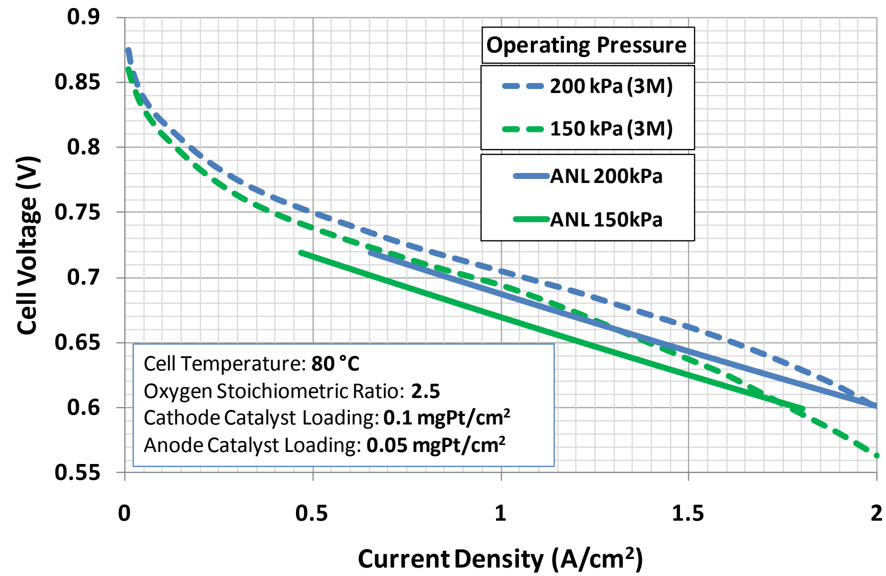
- Power Density = **833 mW/cm²**
- Catalyst Loading = **0.15 mgPt/cm²**

			2010
DOE Target:	Stack Cost	$\$/kW_{e\,(net)}$	**$25**
Study Estimate:	Stack Cost	$\$/kW_{e\,(net)}$	**$25**
DOE Target:	System Cost	$\$/kW_{e\,(net)}$	**$45**
Study Estimate:	System Cost	$\$/kW_{e\,(net)}$	**$51**

Operating Pressure vs. Catalyst Cost Optimization

- 2009 and 2010 polarization based on 3M NSTF performance with design point guided by Fuel Cell Tech Team
  - 833 mW/cm^2
  - 0.15 mg Pt/cm^2
  - 2.5 Air Stoichiometry
  - 80°C

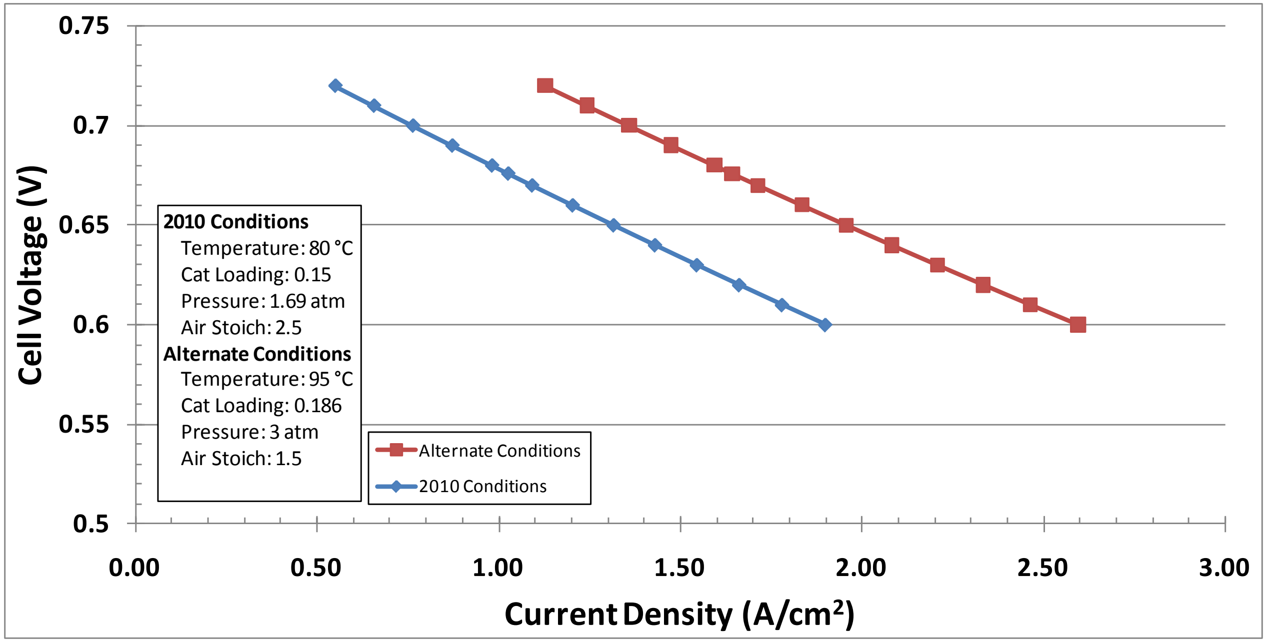
- New Polarization Curves Used
  - ANL (Rajesh Ahuwalia) prepared first principles model of latest 3M performance
  - Used in ANL automotive modeling
  - Adds stack voltage losses
  - Created simplified model for DTI allowing us to vary
    - Pressure
    - Cathode Loading
    - Temperature
    - Air Stoichiometry



ANL polarization model enables DTI to conduct multi-variable optimization over pressure, catalyst loading, temperature, and air stoichiometry

ANL Simplified Polarization Curve Fit Used in Analysis

Based on:
- 2009/2010 3M data
- NSTF Catalysts
- Pure H_2 anode gas
- 0.05 mgPt/cm² anode loading



$$VI = C_0 + a_1 l_{Pt} + a_2 l_{Pt}^2 + b_1 p + b_2 p^2 + c_1 T + c_2 T^2 + d_1 SR + d_2 SR^2 + e_1 V + e_2 V^2 \quad (\pm 0.08\ W/cm^2)$$

Constants	C_o	a_1	a_2	b_1	b_2	c_1	c_2	d_1	d_2	e_1	e_2
Values	-3.0046	0.7011	-0.1674	0.3609	-0.0273	0.0148	-1.5332E-05	0.2374	-0.0455	3.5212	-3.0046

Variables	Units
VI = Cell Voltage x Current Density	W/cm²
L_{pt} = Cathode Catalyst Loading	mgPt/cm²
T = Cell Temperature	K
SR = Oxygen Stoichiometric Ratio	
V = Cell Voltage	V

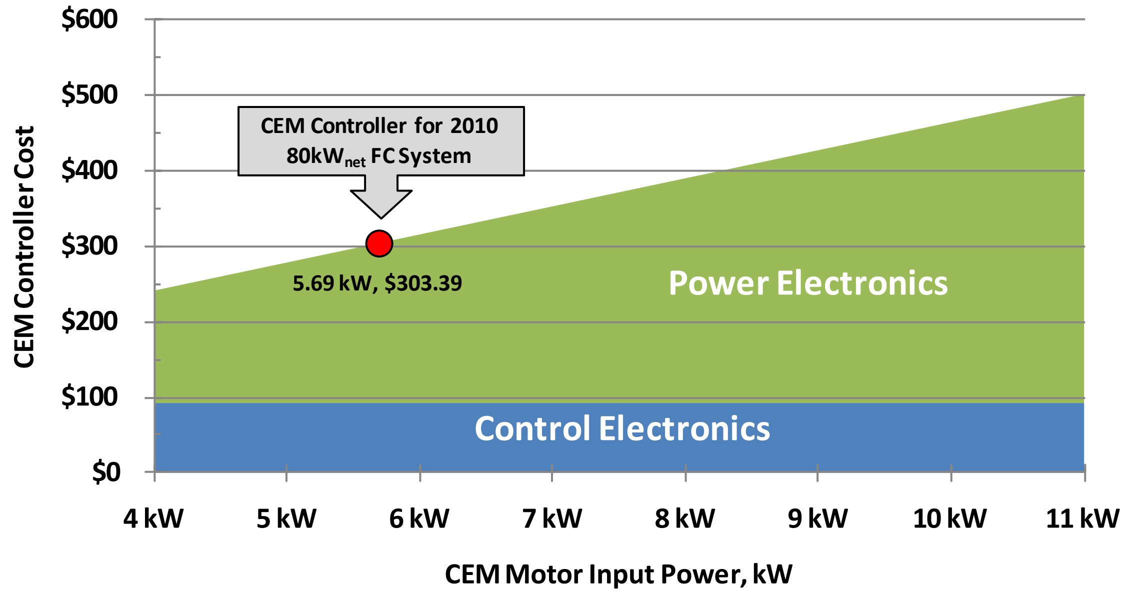
Parameter	Ranges of Validity	
	Minimum	Maximum
Cell Voltage	0.6 V	0.72 V
Oxygen Stoichiometric Ratio	1.5	2.5
Pressure	1.25 atm	3.0 atm
Temperature	75°C	95°C
Cathode Catalyst Loading	0.10 mgPt/cm²	0.20 mgPt/cm²
Total Catalyst Loading	*0.15 mgPt/cm²*	*0.25 mgPt/cm²*

CEM Controller Scaling

- CEM= Compressor-Expander-Motor
- Most system components in model already scaled with power/flow rates, etc.
- Controller for the CEM unit did not previously scale
- Conferred with Honeywell to establish scaling relationship

Need CEM scaling to allow automated cost optimization

	Nominal 80kW$_{net}$ Fuel Cell System	Nominal 160 kW$_{net}$ Fuel Cell System
Input Motor Power	5.69 kW	11.38 kW
Control Electronics	**$91.02** *(30% of controller cost)*	**$91.02** *(17.6% of controller cost)*
Power Electronics	**$212.38** *(70% of controller cost)*	**$424.76** *(82.4% of controller cost)*
Total CEM Controller	**$303.39**	**$515.77**



Operating Pressure vs. Catalyst Cost Optimization

		Base Case (2010 Status)	Base Case w/ Updates	Base Case w/ Updates & ANL Curve	Optimized Case
Annual Production Rate	systems/year	500,000	500,000	500,000	500,000
Stack Efficiency @ Rated Power	%	55%	55%	55%	55%
Cell Voltage @ Rated Power	V/cell	0.676	0.676	0.676	0.676
Oxygen Stoichiometric Ratio		2.5	2.5	2.5	1.5
Peak Stack Operating Pressure	atm	1.69	1.69	1.69	3
Peak Stack Operating Temperature	°C	90	90	90	95
Total Platinum-Group Catalyst Loading	mgPt/cm²	0.15	0.15	0.15	0.186
MEA Areal Power Density @ Rated Power	mW/cm²	833	833	732	1,110
Power Density Equation Selected		Standard	Standard	ANL Curve Fit	ANL Curve Fit
System Cost	$\$/kW_{net}$	**$51.38**	**$51.92**	**$54.72**	**$47.81**

- Quality control additions
- Update sheet metal prices
- Improved pressure drop calculations
- Other misc. changes

- Imposition of ANL curve fits of 3M performance (Additional cost change due to bipolar plate losses)

- Optimization by varying mass, temperature, air stoichiometry, and cathode loading

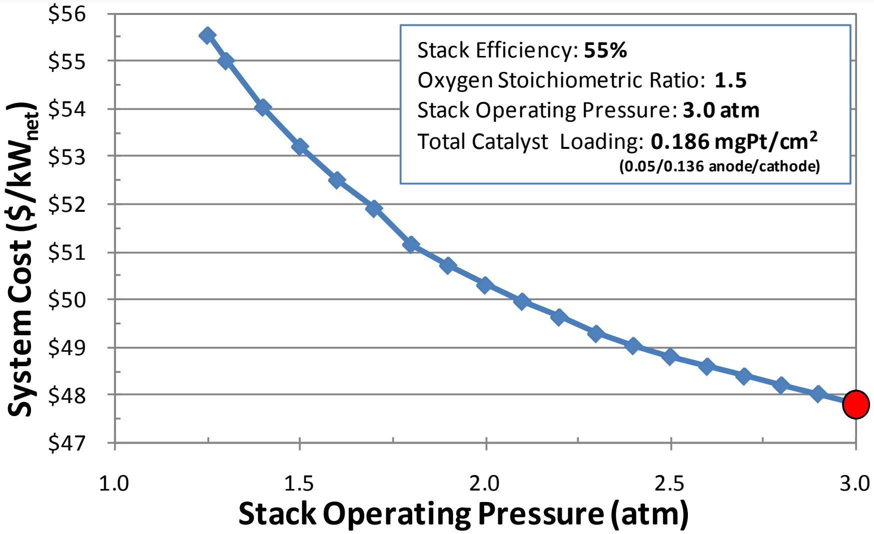
For 0.676 V/cell, Optimizes at:

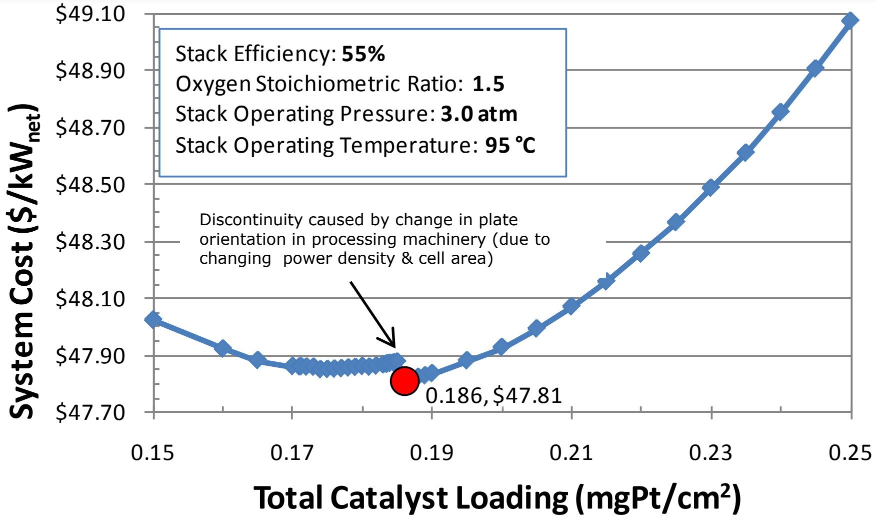
- Peak Pressure
- Peak Temperature
- Minimum Air Stoichiometry
- Intermediate Catalyst Loading

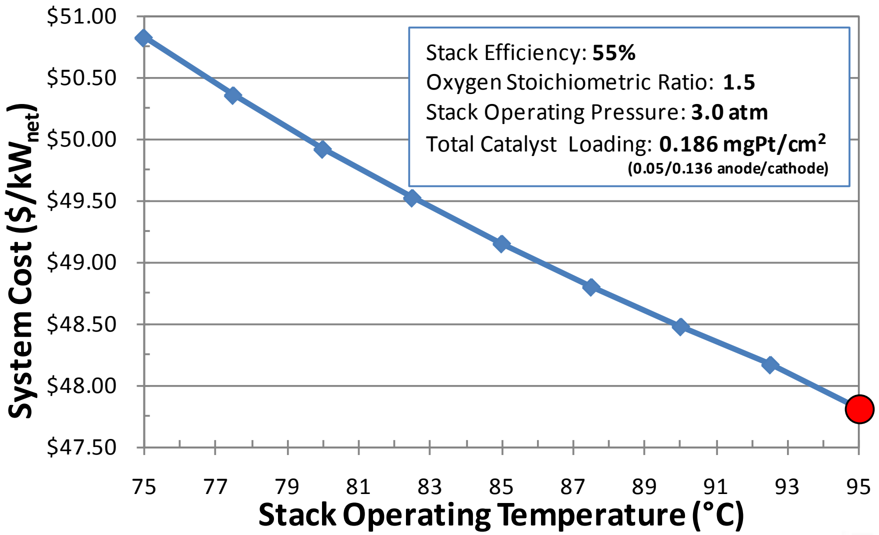
Optimization lead to dramatic increase in power density 732mW/cm² to 1,110mW/cm²

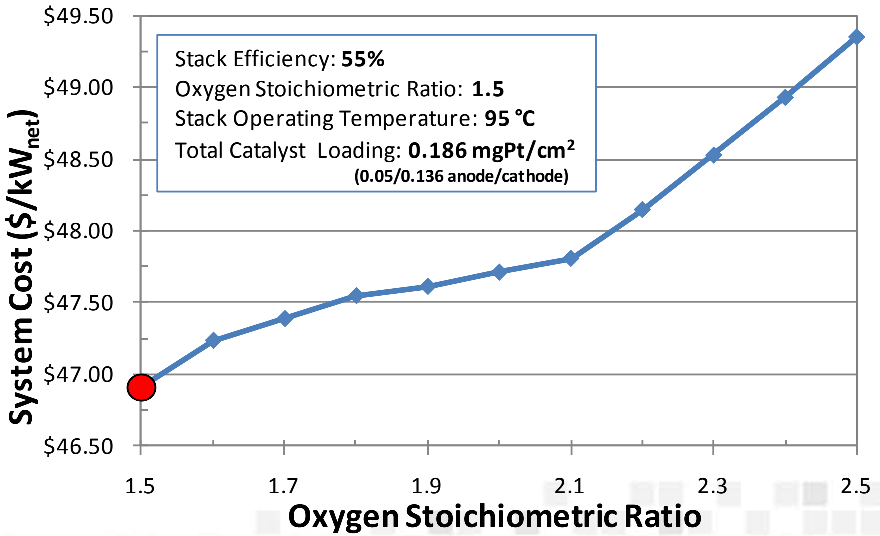
Parameter	Ranges of Validity: Minimum	Ranges of Validity: Maximum
Cell Voltage	0.6 V	0.72 V
Oxygen Stoichiometric Ratio	1.5	2.5
Pressure	1.25 atm	3.0 atm
Temperature	75°C	95°C
Cathode Catalyst Loading	0.10 mgPt/cm²	0.20 mgPt/cm²
Total Catalyst Loading	*0.15 mgPt/cm²*	*0.25 mgPt/cm²*

Single-Variable Sensitivity Analysis (at 0.676 V/cell)



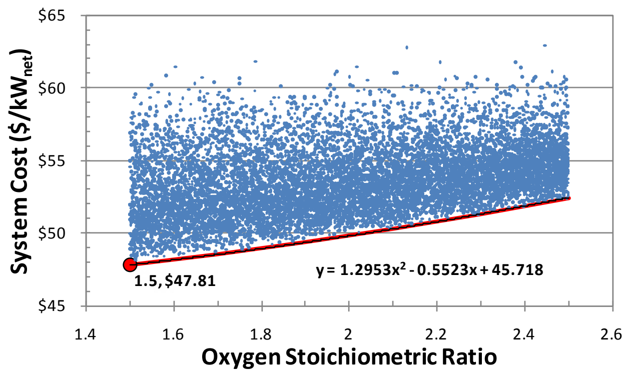


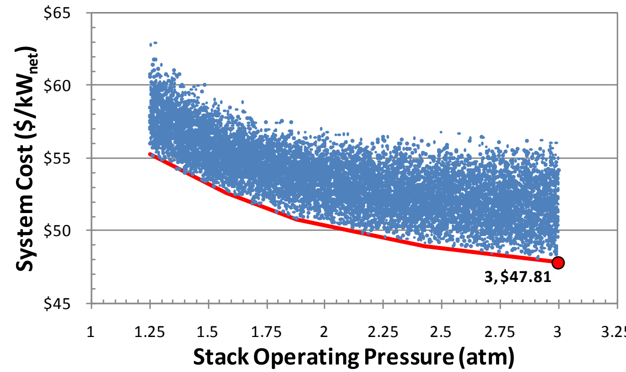




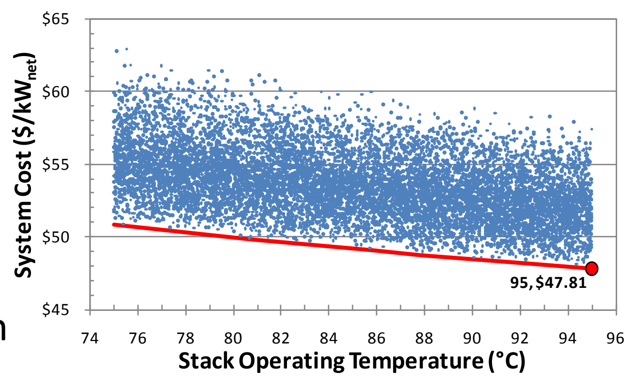
Monte Carlo Analysis confirms Single-Variable Analysis Trends

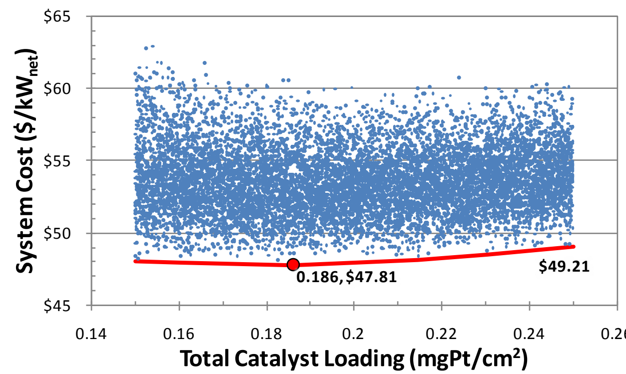
- Pressure and O_2 stoichiometric ratio are most sensitive parameters.
- Catalyst loading has surprisingly low correlation with system cost (within optimization range).
- Stack temperature has modest correlation with system cost.
- Minimum system cost occurs at limits of 3 of 4 variables.
  - Suggests that variable limits should be expanded and/or scrutinized.
  - Generally consistent with linear optimization: polarization curve is linear in region examined





Same data set for all 4, just plotted differently.





- For a $2/$kW_{net}$ total cost increase, one could simultaneously relax each of the parameters:
  - Increase the oxygen stoichiometric ratio to 1.7
  - Drop the stack operating pressure to 2.7 atm
  - Drop the stack operating temperature to 90°C
  - Increase the catalyst loading to 0.2 $mgPt/cm^2$

Technical Accomplishments

Quality Control

Quality Control Devices for Stack				
Part Tested	**Diagnostic System**	**Fault/Parameters Tested**	**Basis**	**Location of QC component**
Membrane	XRF (point measurement only)	Thickness, pinholes, shorting, leaks, delamination	BASF XRF	At end of membrane line just before re-roll
NSTF Catalyst	IR Camera (cooled)	Catalyst Loading, particle size, defects, general Pt uniformity	NREL IR Camera	Inspection of NSTF on Kapton
NSTF Catalyst	IR Camera (cooled)	Catalyst Loading, particle size, defects, general Pt uniformity	NREL IR Camera	Inspection of NSTF on membrane
MEA	XRF (point measurement only)	Thickness, cracks, delamination	BASF XRF	Inspection of GSL/NSTF/Membrane
Gasketed MEA	Optical Thickness and Surface Topology System	Thickness and completeness of gasket and complete MEA	Based on Ballard Online Thickness and surface topology tool	Inspection after MEA insertion molding
Bipolar Plate	Non-Contact Laser Triangulation Probe	Flow field depth, plate size, thickness, defects	NIST future triangulation sensor testbed	After stamping press
GDL (Microporous Layer)	Mass Flow Meter	Proper layer coverage	Ballard Mass Flow Meter	part of microporous layer addition
GDL (Microporous Layer)	Viscometer	Proper layer coverage	Ballard Viscometer	part of microporous layer addition
GDL (Final Product)	Online Vision System	Cracks, improper layer coverage, defects	Ballard Online Vision System	final step before GDL hot pressing
End Plate	Mass Scale	Completeness of injection molding	Basic Industrial Mass Scale	
End Plate	Conveyor Mass Scale	Completeness of injection molding	Based on ThermoFischer Scientific CheckWare	End of endplate fabrication
End Plate	Human Visual Inspection	Completeness of injection molding, surface texture/color		End of process train
Laser Welding for Bipolar Plates	Optical Seam Inspection System	Completeness of laser weld	Precitec Group Laser Welding Inspection Machines	During laser welding operation

Total Cost Increase from QC Equipment

	Technology Level	2011				
	Systems/year	**1,000**	**30,000**	**80,000**	**130,000**	**500,000**
QC Cost ($/kW$_{net}$)	Membrane QC	$5.14	$0.17	$0.06	$0.04	$0.01
	NSTF Catalyst Deposition QC	$1.24	$0.04	$0.03	$0.04	$0.03
	MEA QC	$4.76	$0.16	$0.06	$0.04	$0.02
	Bipolar Plates QC	$0.35	$0.03	$0.03	$0.03	$0.03
	MEA Frame Gasket QC	$1.17	$0.19	$0.18	$0.18	$0.18
	GDL QC	$0.61	$0.02	$0.02	$0.02	$0.02
	End Plate QC	$0.21	$0.01	$0.00	$0.00	$0.00
	Laser Welding BPP QC	$0.35	$0.03	$0.03	$0.03	$0.03
	Total ($/kW$_{net}$)	**$13.81**	**$0.66**	**$0.43**	**$0.38**	**$0.32**

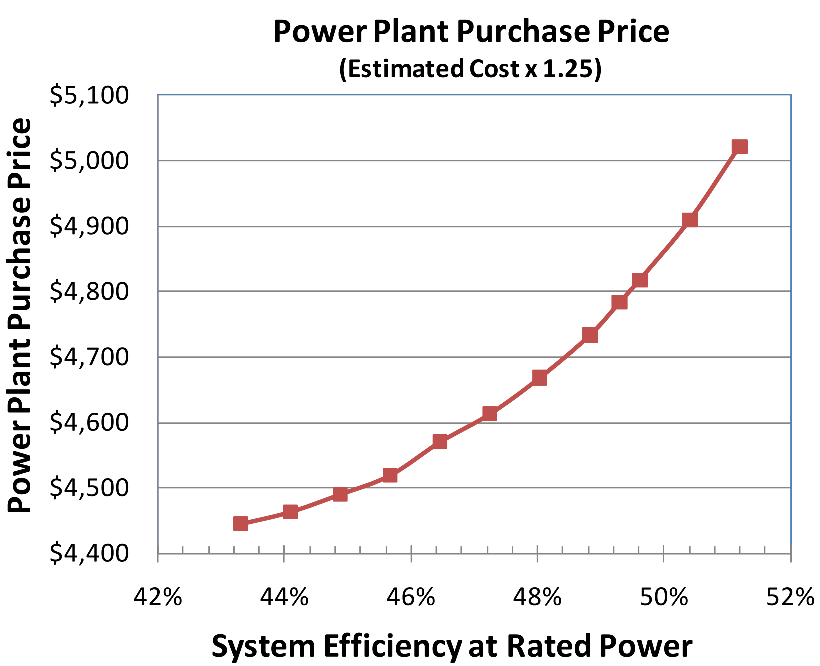
- Previous analysis revisited to ensure adequate QC
- New QC system added for stack

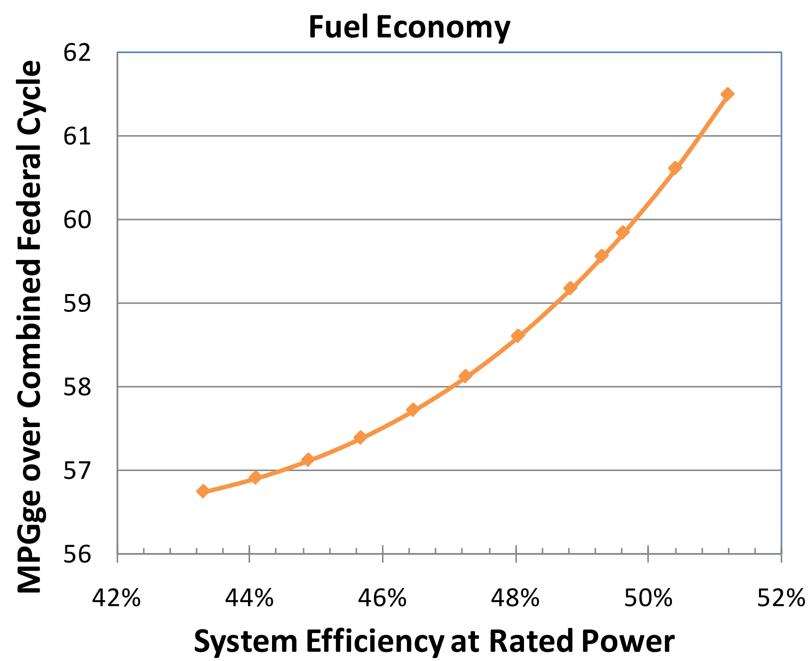
Cost impact at high manufacturing volumes is modest

Lifecycle Cost Analysis (LCA): tradeoff between capital cost & fuel cost

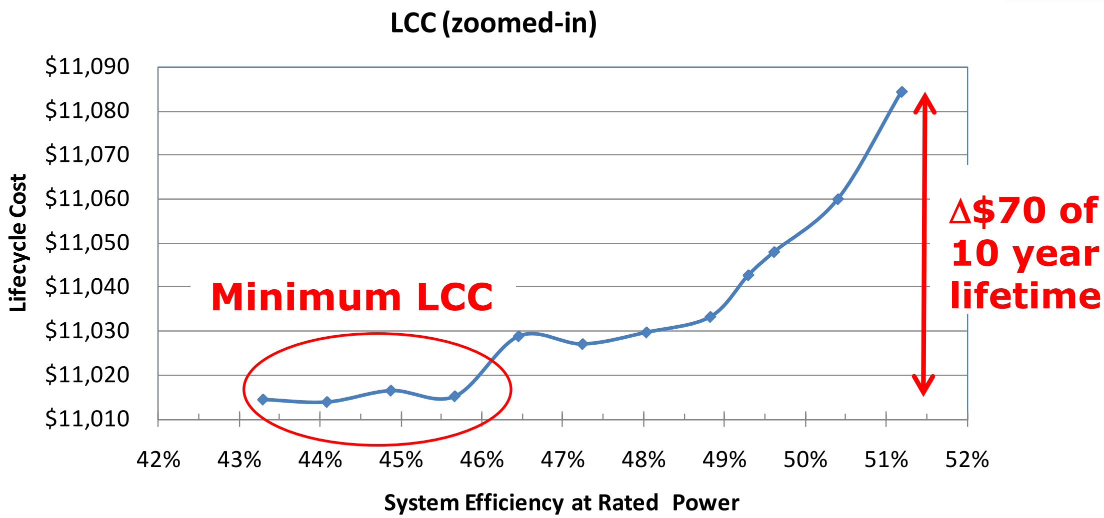
- Simplified analysis to determine optimum balance between stack initial capital cost and fuel costs
  - Net present value approach
- Stack cost is a function of stack size/cell voltage
  - Multi-variable optimization conducted for each system to determine optimum operating conditions
- Fuel economy determined by ANL via GCTools model
  - Midsize sedan
  - Combined Federal Drive Cycle
  - Fixed vehicle mass

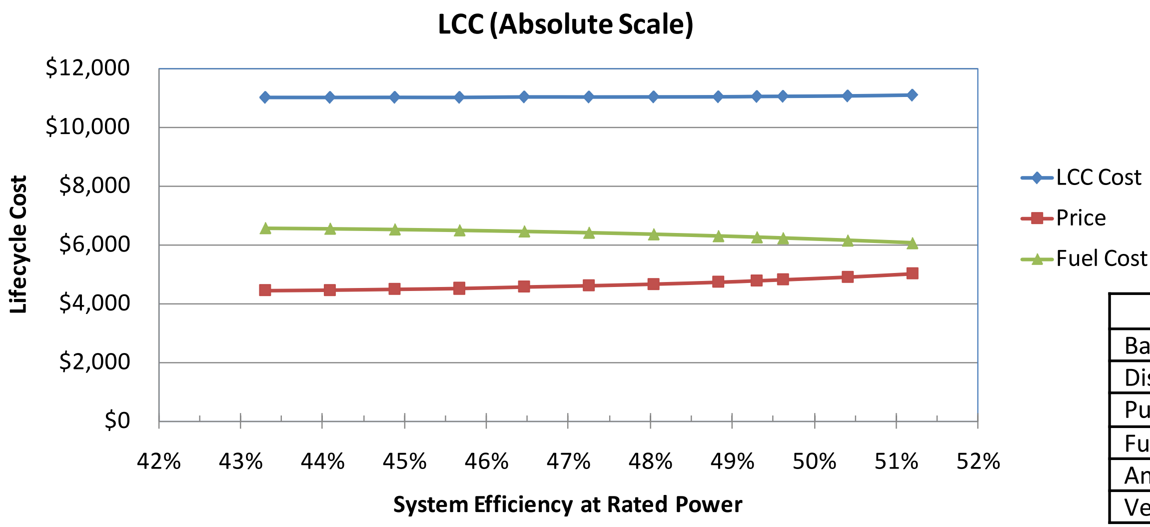
Baseline Assumptions	
Base year	2010
Discount Rate	10%
Purchase Markup	25%
Fuel Cost	$5/kgH$_2$
Annual Miles Driven	12,000 miles
Vehicle Lifetime	10 years





Lifecycle Cost Analysis Results (Baseline Assumptions)



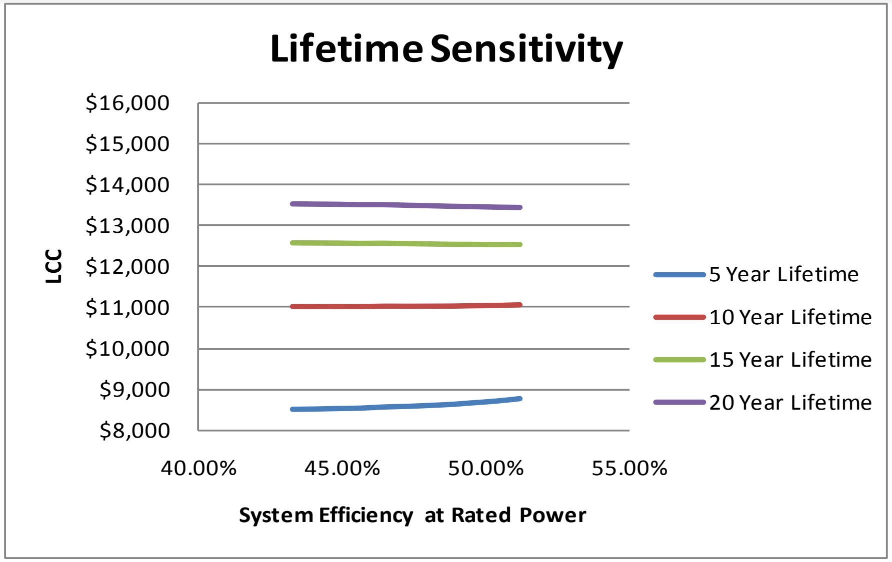


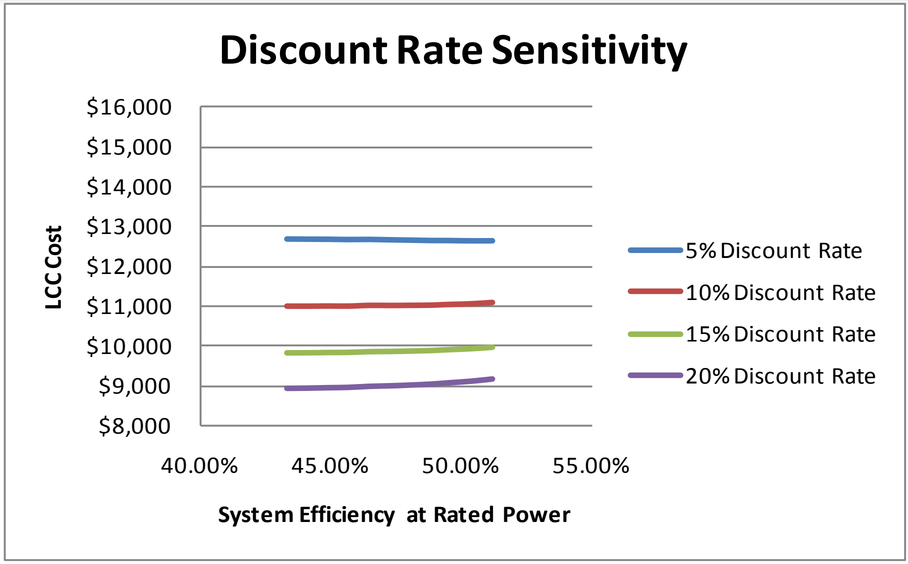
Minimum cost occurs at lower efficiency system.
But lifecycle cost benefit is quite low…. for baseline assumptions.

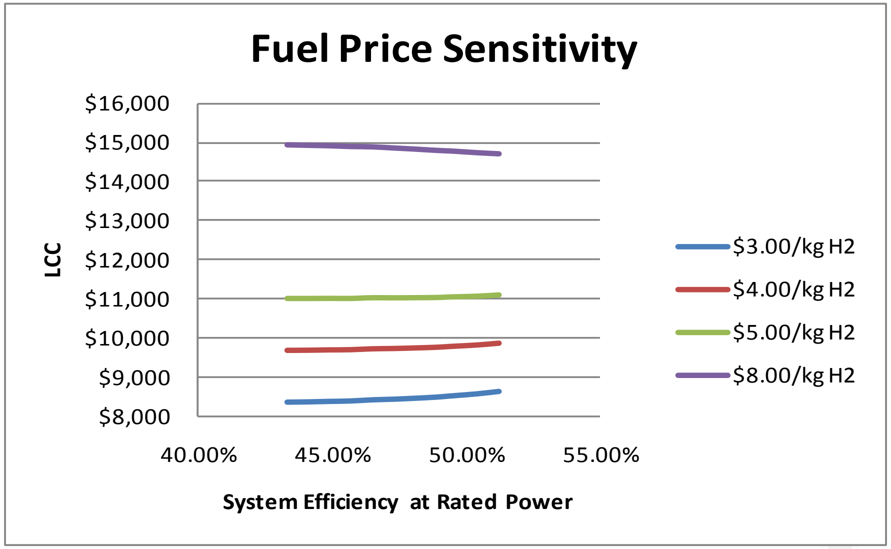
Baseline Assumptions	
Base year	2010
Discount Rate	10%
Purchase Markup	25%
Fuel Cost	$5/kgH_2$
Annual Miles Driven	12,000 miles
Vehicle Lifetime	10 years

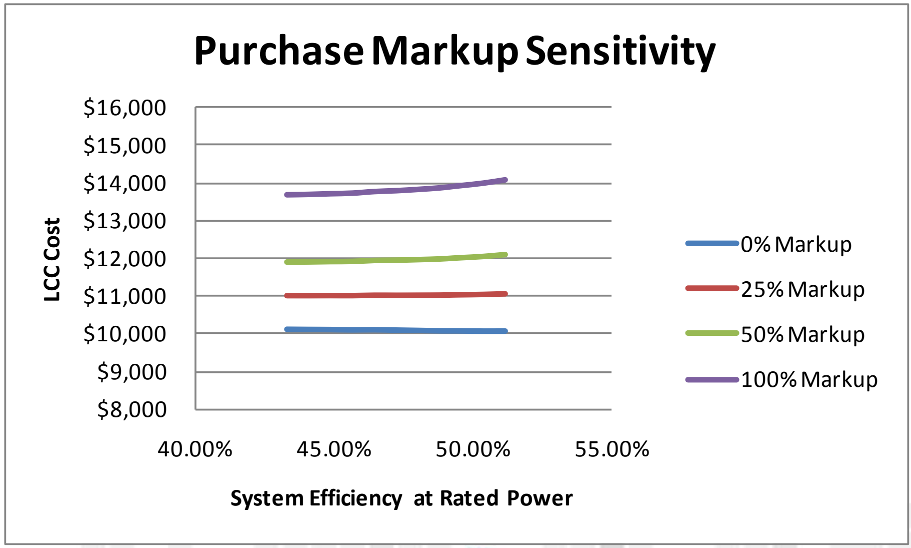
Technical Accomplishments

LCA Sensitivity Analysis









LCC Sensitivity Analysis generally confirms baseline trends.

Identification of Capital Equipment and R&D Needs

- **Assessed R&D needs from a system cost perspective**
- **Quantified risk on basis of two scaled factors:**
  - **Cost Risk – Risk that a cost assumption (capital cost, material cost, etc.) would lead to appreciable system cost impact**
  - **Process Risk – Risk that a processing assumption (manufacturing method, speed, QC method) would lead to appreciable system cost impact.**

	Description of System at Specified Score	Score
Cost Assumption Risk Scale	Firm cost basis for a common machine/material or cost uncertainty that has minimal effect on total system cost	1
	Rough estimate of common machine/material based on consultation. Potential variation from cost due to further analysis will have low total system cost impact	2
	Rough estimate that has uncertainty that could lead to a large change in total system cost	3
Process Risk Scale	Common process done at large scale, high confidence in output quality, no/very-little R&D or non-standard product customization required	1
	Common process done at large scale but needs R&D for specific application, high/moderate confidence in output quality, little R&D risk	2
	Needs R&D for large-scale production and specific application, may have been demonstrated at low production rate but not high rates, moderate/high risk in output quality at rates required, moderate R&D risk	3

Identification of Capital Equipment and R&D Needs

Fuel Cell Stack Components

Stack Component Manufacturing			
Step/Component	Process Risk	Cost Assumption Risk	Total Score
Bipolar Plate Stamping	1	1	2
Bipolar Plate Coating	1.67	2	3.67
Membrane Production	2.5	3	5.5
NSTF Coating	3	3	6
Microporous GDL	2	2	4
M & E Hot Pressing	2	2	4
M & E Cutting & Slitting	1	1	2
MEA Frame/Gaskets	2	2	4
Coolant Gaskets (Laser Welding)	2	1	3
End Gaskets (Screen Printing)	2	1	3
End Plates	1	1	2
Current Collectors	1	1	2
Compression Bands	1	2	3
Stack Assembly	1	2	3
Stack Conditioning	2	2	4

Stack Manufacturing Machinery Capital Costs			
Step	Cost $/Process Train	No. of Process Trains	Capital Cost
Bipolar Plate Stamping	$393,057	41	$16,115,331
Bipolar Plate Coating	$68,529,662	~20*	$68,529,662
Membrane Production	$30,000,000	1	$30,000,000
NSTF Coating	$1,284,255	12	$15,411,056
Microporous GDL Creation	$1,271,840	17	$21,621,283
M & E Hot Pressing	$187,542	37	$6,939,065
M & E Cutting & Slitting	$130,958	2	$261,917
MEA Frame/Gaskets	$598,772	154	$92,210,849
Coolant Gaskets (Laser Welding)	$789,955	32	$25,278,555
End Gaskets (Screen Printing)	$630,187	1	$630,187
End Plates	$333,760	3	$1,001,280
Current Collectors	$67,089	1	$67,089
Compression Bands	$521,983	2	$1,043,965
Stack Assembly	$799,418	51	$40,770,338
Stack Conditioning	$147,516	145	$21,389,879
Stack Total			**$341,270,457**

* Bipolar plate coating is based on a vendor-proprietary manufacturing method that consists of multiple sub-process trains. The process train quantity listed is an average of the constituent sub-trains.

- **Most Processed are “standard” extrapolations of existing techniques.**
- **Catalyst application has highest process risk because it has potential to impact power density.**
  - **Has been demonstrated on low-production but not at high production.**
- **Membrane production has similar potential impact on power density**
  - **Should be straight forward engineering scale-up of known processed, but without analogy at high production, cost risk remains.**

Identification of Capital Equipment and R&D Needs

Balance of Plant (BOP) Components

BOP Component Manufacturing			
Step/Component	**Process Risk**	**Cost Assumption Risk**	**Total Score**
Membrane Air Humidifier	2	3	5
Belly Pan	1	1	2
Ejectors	2	1	3
Stack Housing	1	1	2
Air Precooler	1	1	2
Demister	1	1	2
CEM	2	2	4

Balance of Plant Manufacturing Machinery Capital Costs			
Step	**Cost $/Process Train**	**No. of Process Trains**	**Capital Cost**
Membrane Air Humidifier	4,073,562	2	$8,147,123
Belly Pan	50,000	1	$50,000
Ejectors	***[Not Calculated]***	***N/A***	***[Not Calculated]***
Stack Insulation Housing	1,748,320	1	$1,748,320
Air Precooler	***[Not Calculated]***	***N/A***	***[Not Calculated]***
Demister	309,696	1	$309,696
CEM	***[Not Calculated]***	***N/A***	***[Not Calculated]***
(Partial) BOP Total	Does not include processes with un-calculated capital costs →		**$10,255,139**

Of BOP components, the air humidifier stands out for several reasons:

- **No direct mass produced analogies**
- **Required membrane areas may be large**
- **Alternate materials affect cost**
- **Tubular vs. plate-frame affects cost**
- **No issue is a show-stopper: but combination leads to cost risk**

CEM rates a moderate cost uncertainty

- **detailed cost analysis conducted**
- **but cost is high ($732) leading to potential for appreciable cost impact**

Technical Accomplishments

Simplified System Cost Model

- Based on 2010 DFMA model (not based on 2011 interim optimization)

- System details for 2010 can be found in DTI's report *Mass Production Cost Estimation for direct H2 PEM Fuel Cell Systems for automotive Applications: 2010 Update*

C_{system} = Total System Cost = $C_{stack} + C_{thermal} + C_{water} + C_{fuel} + C_{air} + C_{BOP}$

C_{stack} = Total fuel cell stack cost

150V $C_{stack} = 3.6945E\text{-}05(A \times L \times PC) + (0.0101199 \times A) + 240.905$

200V $C_{stack} = 3.6945E\text{-}05(A \times L \times PC) + (0.0100287 \times A) + 276.345$

250V $C_{stack} = 3.6945E\text{-}05(A \times L \times PC) + (0.0101193 \times A) + 295.23$

300V $C_{stack} = 3.6945E\text{-}05(A \times L \times PC) + (0.010004 \times A) + 336.16$

Where: *A = Total active area of the stack (cm2)*
V = Stack voltage (V)
L = Pt Loading (mg/cm2)
PC = Platinum cost ($/troy ounce)

$C_{thermal}$ = Thermal Management System cost

$= (111.35 \times Q_{HT} / \Delta T_{HT} + 151.15) + (111.35 \times Q_{LT} / \Delta T_{LT} + 62.91) + (-3.2064E\text{-}07 \times P_{HT}^3 + 4.4031E\text{-}04 \times P_{HT}^2 - 0.13364 \times P_{HT} + 46.69) + (-3.2064E\text{-}07 \times P_{LT}^3 + 4.4031E\text{-}04 \times P_{LT}^2 - 0.13364 \times P_{LT} + 46.69)$

Where: Q = Radiator Duty ($kW_{thermal}$)
ΔT = Difference between stack operating temperature and ambient temperature (°C)
P = Power of Radiator (W)

C_{water} = Water Management System cost

$= (-8.9241E\text{-}22 \times A5 + 1.7526E\text{-}16 \times A^4 - 1.2851E\text{-}11 \times A^3 + 4.2888E\text{-}07 \times A^2 - 0.00494 \times A - 73.839) + (58.08 \times (Q/\Delta T)/0.092065) + 6.12$

Where: A = Humidifier Membrane Area (cm2)
Q = Heat Duty for Precooler
ΔT = Delta Temp. (compr. exit air minus ambient air)(°C)

C_{fuel} = Fuel Management System cost

$= (3801.97 \times P3 - 2967.73 \times P^2 + 1573.1 \times P - 87.807) + 152.96$

Where: P = blower power (kW)

C_{air} = *Air Management System*

= (50.6304 x P) + (0.18798 x MF) + 477.29

Where: *P* = Air Peak Pressure (atm)
MF = Air Mass Flow (kg/hr)

C_{BOP} = Balance of Plant cost

Where: C_{BOP} = *$464.29*

Validity Range for Thermal Management System

Parameter	Minimum Value	Maximum Value	Units
ΔT	40	70	**°C**
Q	100	325	**kW_{gross}**
Motor Power	100	600	**W**

Validity Range for Stack Cost

Parameter	Minimum Value	Maximum Value	Units
System Power	60	120	**kW_{net}**
Platinum Loading	0.1	0.8	**mg/cm^2**
Total Active Area	70,000	165,000	**cm^2**
Platinum Cost	800	2,000	**$/troy ounce**

Validity Range for Air Management System

Parameter	Minimum Value	Maximum Value	Units
Pressure	1.5	2.5	**Atm**
Air Mass Flow	300	650	**kg/hr**

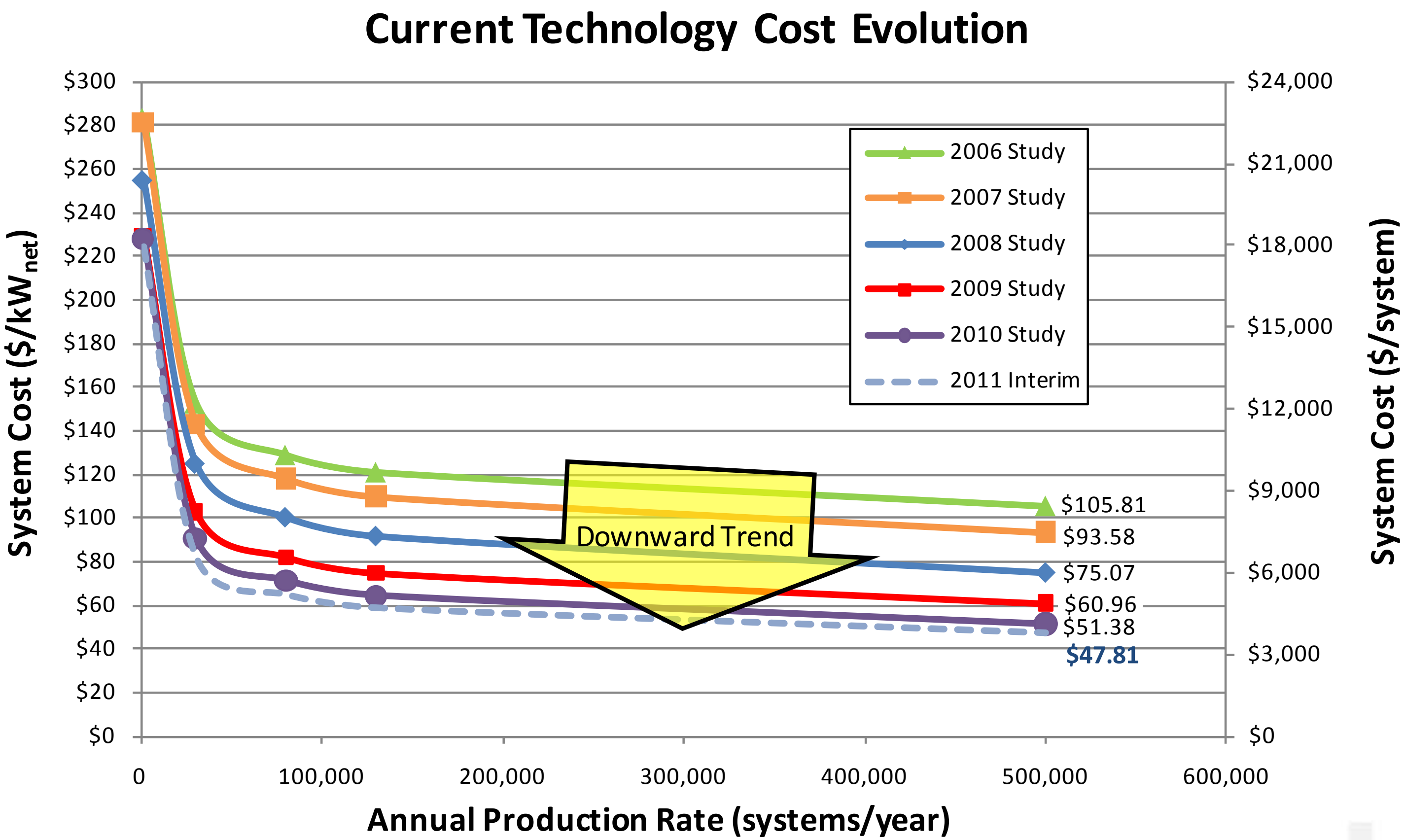
Validity Range for Water Management System

Parameter	Minimum Value	Maximum Value	Units
ΔT	40	80	**°C**
Q	1	10	**kW**
Membrane Area	20,000	60,000	**cm^2**

Cost Trends

Since 2006:

The current technology cost projection has dropped by 55% (at 500,000 sys/year) due to a combination of technology improvement and analysis refinement



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DFMA Cost Analysis of Stationary Fuel Cell Analysis

All systems to be Combined Heat & Power (CHP) operated on Natural Gas

1) Low temperature PEM Fuel Cell Systems

- Steam Reformer- Water Gas Shift-PROX
- Reformate fed to the stack
- Low pressure (~1atm)
- Fuel Cell stack similar to automotive stacks (Nafion on ePTFE, SS bipolar plates, liquid cooling, but with adjusted power density, catalyst loading, etc.)
- Integrated & modular reactor (combines fuel preheater, reformer, boiler, WGS, PROX)

2) High Temperature PEM Fuel Cell Systems

- Similar to above but using ~160C PBI-based membrane fuel cell stack
- Smaller WGS, eliminates PROX
- Higher quality waste heat for CHP

3) Solid Oxide Fuel Cell Systems

Stationary Systems	Power Level	Annual Prod. Rate	Due Dates
Low Temp. PEMFC	1,5,25,100 kW_{net}	100, 1k, 10k, 50k systems/year	5/8/2011 (prelim. Results)
High Temp. PEMFC			9/8/2011 (prelim. Results)
SOFC			1/8/2012 (prelim. Results)

Automotive Cost Analysis

- Complete 2011 Cost Update
- Document in Report

Collaborations

- **Directed Technologies Inc. (DTI)** – Prime
- **Argonne National Laboratory**: unpaid collaboration
  - Preparation of polarization data used in multi-variable cost optimization
  - GCTool analysis of FC vehicle fuel economy
- **NREL:** unpaid collaboration
  - Consultation on quality control systems
- **Ballard:** unpaid collaboration
  - Consultation on quality control systems
  - Stationary reformer system studies and mechanical design
- **Nuvera:** unpaid collaboration
  - Consultation on stack operating parameters, mechanical construction, and cost modeling of system at low voltage/high-current-density operating point
- **Ford:** unpaid collaboration
  - Extensive consultation on all aspects of the fuel cell power system. Review of report, in-person presentations, and multiple topic specific conference calls.
- **Honeywell:** unpaid collaboration
  - Consultation on CEM controller scaling
  - (Extensive paid interaction on CEM design/costing during previous years)
- Interaction with multiple other industry/researchers to solicit design & manufacturing metrics as input to cost analysis.

Project Summary

Relevance: Chart annual FC system cost progress and identify promising pathways for future cost reduction.

Approach: Conduct DFMA analysis and a series of focused cost studies.

Technical Achievements:

- Documented 2010 vehicular FC analysis in written report
- Prepared interim 2011 vehicular FC system cost estimates projecting a system cost of $47.81/kW (at 500k systems/year)
- Conducted a multi-variable cost optimization
- Conducted lifecycle cost analysis
- Investigated stack quality control systems
- Assessed R&D status of FC manufacturing systems
- Began stationary fuel cell system cost analysis

Collaborations: No formal partners on project but extensive unpaid collaboration with ANL, NREL , Ballard, Ford, Nuvera, Honeywell, many others.

Future Work:

- Complete 2011 automotive FC system cost analysis & documentation
- Complete stationary fuel cell system DFMA analysis (LT PEM, HT PEM, SOFC systems)

End of Presentation

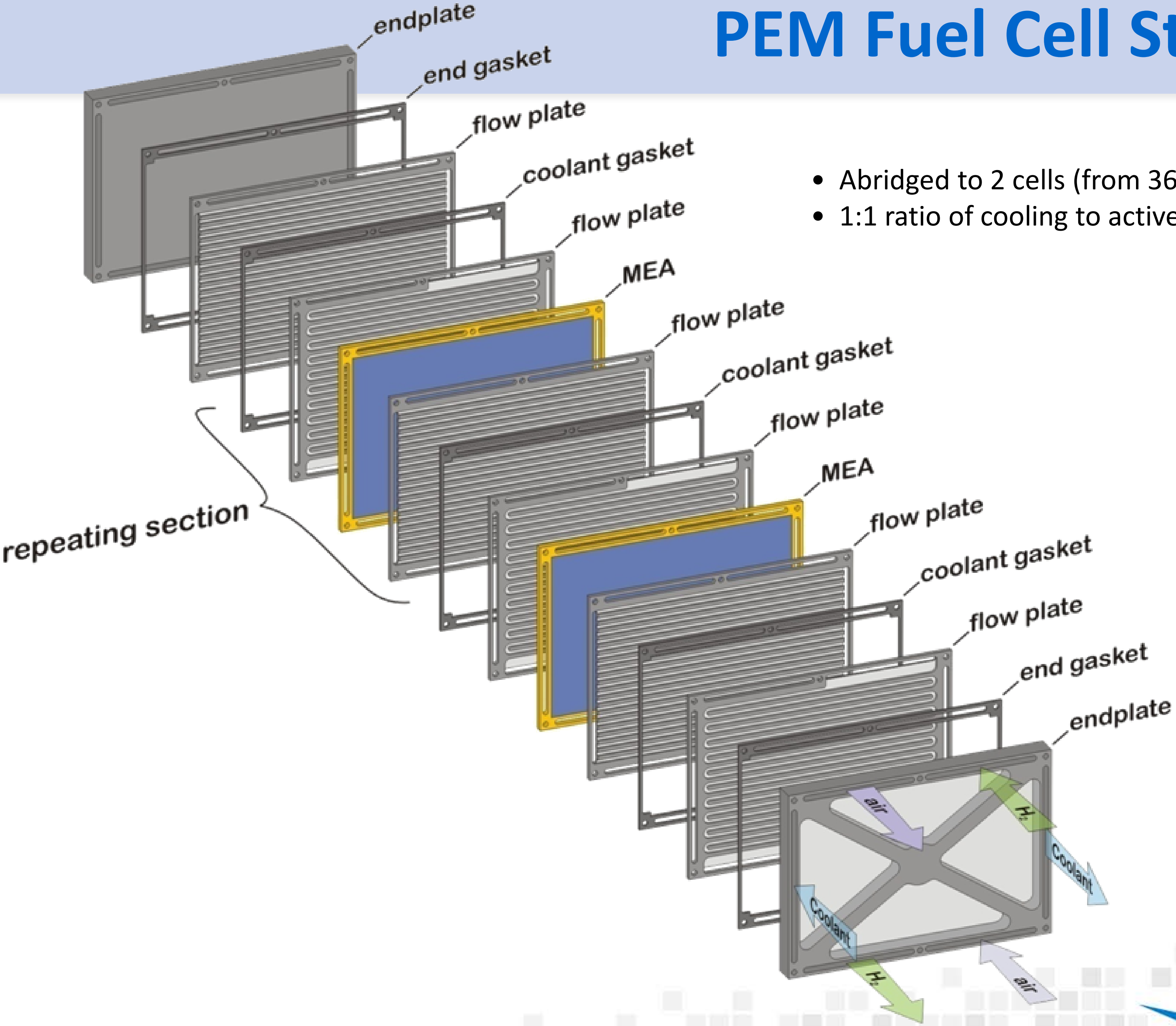
Thank you.

Additional Slides

The following slides are provided for further clarification

PEM Fuel Cell Stack

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



2011 DOE H_2 Program AMR Presentation

DIRECTED TECHNOLOGIES INC

Bill of Materials: Stack (2011 Interim Results)

	2011 - Interim				
Annual Production Rate	**1,000**	**30,000**	**80,000**	**130,000**	**500,000**
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	89.25	89.25	89.25	89.25	89.25
Bipolar Plates (Stamped)	$1,814.05	$381.82	$368.49	$366.97	$364.39
MEAs					
Membranes	$4,862.61	$811.62	$493.60	$381.51	$195.55
Catalyst Ink & Application (NSTF)	$1,339.76	$658.35	$652.44	$645.89	$646.25
GDLs	$1,796.43	$846.44	$522.25	$403.84	$182.14
M & E Hot Pressing	$70.97	$6.53	$5.36	$5.10	$5.09
M & E Cutting & Slitting	$436.32	$15.92	$6.86	$4.77	$2.30
MEA Frame/Gaskets	$773.77	$231.91	$224.09	$221.30	$216.21
Coolant Gaskets (Laser Welding)	$212.22	$28.47	$26.85	$26.48	$25.11
End Gaskets (Screen Printing)	$149.48	$5.08	$1.96	$1.25	$0.53
End Plates	$91.83	$26.43	$22.36	$20.21	$15.36
Current Collectors	$51.67	$7.13	$5.32	$4.77	$4.16
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Housing	$60.86	$6.96	$5.87	$5.30	$4.73
Stack Assembly	$76.12	$40.69	$34.95	$33.62	$32.06
Stack Conditioning	$170.88	$53.87	$47.18	$41.38	$28.06
Total Stack Cost	$11,916.99	$3,129.22	$2,423.61	$2,167.88	$1,726.92
Total Stack Cost ($/kW$_{net}$)	$148.96	$39.12	$30.30	$27.10	$21.59
Total Stack Cost ($/kW$_{gross}$)	$133.52	$35.06	$27.15	$24.29	$19.35

- 6.9 to 1 cost reduction between low and high manufacturing rates

Bill of Materials: Balance of Plant (2011 Interim Results)

	2011 - Interim				
Annual Production Rate	**1,000**	**30,000**	**80,000**	**130,000**	**500,000**
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	89.25	89.25	89.25	89.25	89.25
Air Loop	$1,813.00	$1,086.74	$923.07	$892.49	$858.11
Humidifier and Water Recovery Loop	$903.00	$280.43	$184.92	$152.42	$99.07
High-Temperature Coolant Loop	$547.84	$463.35	$395.88	$374.04	$344.58
Low-Temperature Coolant Loop	$100.21	$87.43	$77.90	$73.44	$67.98
Fuel Loop	$251.94	$198.65	$170.49	$163.40	$152.96
System Controller	$171.07	$136.85	$102.64	$95.80	$82.11
Sensors	$1,706.65	$893.00	$659.96	$543.45	$225.49
Miscellaneous	$331.71	$194.12	$171.44	$164.80	$156.83
Total BOP Cost	$5,825.42	$3,340.58	$2,686.31	$2,459.84	$1,987.12
Total BOP Cost ($/kW$_{net}$)	$72.82	$41.76	$33.58	$30.75	$24.84
Total BOP Cost ($/kW$_{gross}$)	$65.27	$37.43	$30.10	$27.56	$22.26

- 2.9 to 1 cost reduction between low and high manufacturing rates

Bill of Materials: System (2011 Interim Results)

	2011 - Interim				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	89.25	89.25	89.25	89.25	89.25
Fuel Cell Stacks	$11,916.99	$3,129.22	$2,423.61	$2,167.88	$1,726.92
Balance of Plant	$5,825.42	$3,340.58	$2,686.31	$2,459.84	$1,987.12
System Assembly & Testing	$157.17	$112.84	$110.91	$111.05	$110.67
Total System Cost ($)	$17,899.58	$6,582.64	$5,220.82	$4,738.77	$3,824.71
Total System Cost ($/$kW_{net}$)	$223.74	$82.28	$65.26	$59.23	$47.81
Total System Cost ($/$kW_{gross}$)	$200.55	$73.75	$58.50	$53.09	$42.85

- 4.7 to 1 cost reduction between low and high manufacturing rates

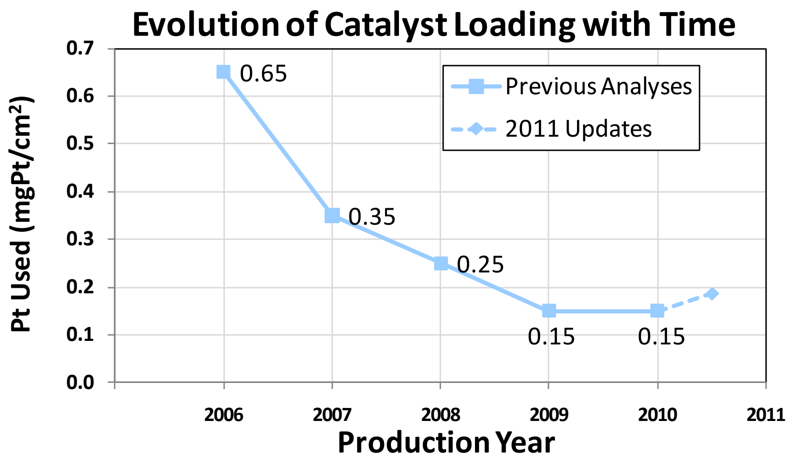
General Cost Analysis Rules

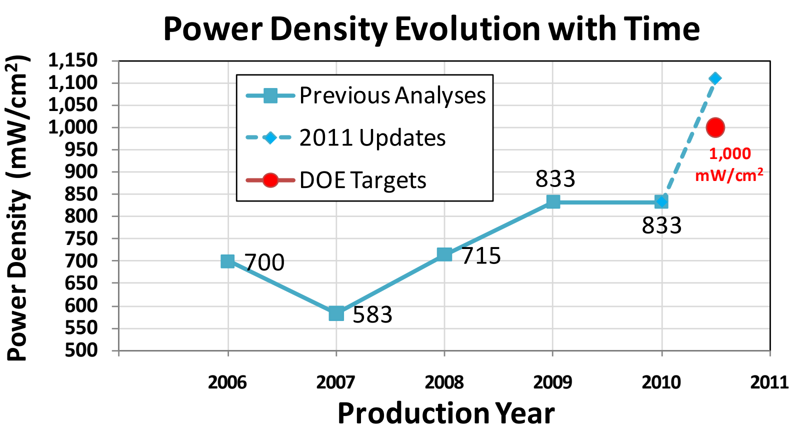
- U.S. labor rates: $45/hr (fully loaded)
- $1,100/troy oz. Pt cost used for consistency

<u>Some costs *NOT* included:</u>

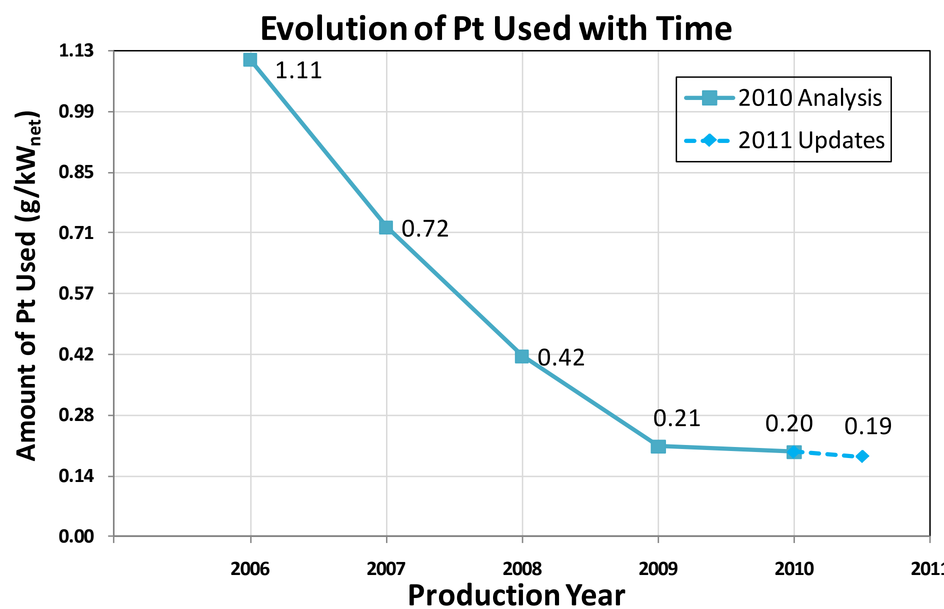
- 10% capital cost contingency
- Warranty
- Building costs (equipment cost included but not building in which equipment is housed)
- Sales Tax
- Non-Recurring engineering costs
- Markup for fuel cell manufacturer/assembler
  - Only purchased components (membrane, GDL) include a manufacturer markup
  - Otherwise there is no markup to the fuel cell manufacturer/assembler for any components

Power Density & Platinum Loading





- Areal catalyst loadings have been decreasing
- Catalyst loading reductions appear to be slowing down
- Focus has switched to durability/robustness



Possible significant future improvements:

- Power density increases
- Switch to non-Pt catalyst

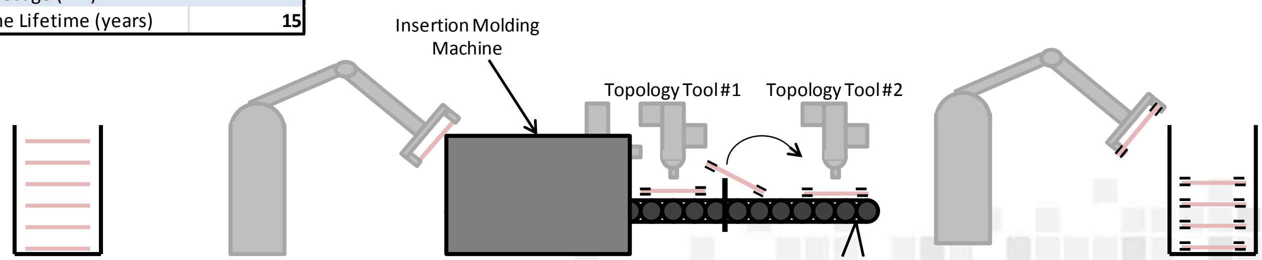
Quality Control

	Total Cost Increase from QC Equipment					
	Technology Level	2011				
	Systems/year	1,000	30,000	80,000	130,000	500,000
QC Cost ($/kW$_{net}$)	Membrane QC	$5.14	$0.17	$0.06	$0.04	$0.01
	NSTF Catalyst Deposition QC	$1.24	$0.04	$0.03	$0.04	$0.03
	MEA QC	$4.76	$0.16	$0.06	$0.04	$0.02
	Bipolar Plates QC	$0.35	$0.03	$0.03	$0.03	$0.03
	MEA Frame Gasket QC	$1.17	$0.19	$0.18	$0.18	$0.18
	GDL QC	$0.61	$0.02	$0.02	$0.02	$0.02
	End Plate QC	$0.21	$0.01	$0.00	$0.00	$0.00
	Laser Welding BPP QC	$0.35	$0.03	$0.03	$0.03	$0.03
	Total ($/kW$_{net}$)	**$13.81**	**$0.66**	**$0.43**	**$0.38**	**$0.32**

Example: MEA Frame/Gasket

MEA Frame Gasket					
Technology Level	2010				
Systems/year	1,000	30,000	80,000	130,000	500,000
Cost Without QC ($/kW$_{net}$)	*$5.87*	*$3.99*	*$3.90*	*$3.85*	*$3.77*
Cost With QC ($/kW$_{net}$)	*$7.04*	*$4.19*	*$4.08*	*$4.03*	*$3.95*
Δ Cost ($/kW$_{net}$)	**$1.17**	**$0.19**	**$0.18**	**$0.18**	**$0.18**

MEA Frame Gasket QC Key Parameters	
Capital Cost	$100,000
Cameras	$35,000
Accessories	$17,500
Plate Flipper	$5,000
Power Usage (kW)	1
Machine Lifetime (years)	15



Quality Control Devices for Stack				
Part Tested	Diagnostic System	Fault/Parameters Tested	Basis	Location of QC component
Membrane	XRF (point measurement only)	Thickness, pinholes, shorting, leaks, delamination	BASF XRF	At end of membrane line just before re-roll
NSTF Catalyst	IR Camera (cooled)	Catalyst Loading, particle size, defects, general Pt uniformity	NREL IR Camera	Inspection of NSTF on Kapton
NSTF Catalyst	IR Camera (cooled)	Catalyst Loading, particle size, defects, general Pt uniformity	NREL IR Camera	Inspection of NSTF on membrane
MEA	XRF (point measurement only)	Thickness, cracks, delamination	BASF XRF	Inspection of GSL/NSTF/Membrane
Gasketed MEA	Optical Thickness and Surface Topology System	Thickness and completeness of gasket and complete MEA	Based on Ballard Online Thickness and surface topology tool	Inspection after MEA insertion molding
Bipolar Plate	Non-Contact Laser Triangulation Probe	Flow field depth, plate size, thickness, defects	NIST future triangulation sensor testbed	After stamping press
GDL (Microporous Layer)	Mass Flow Meter	Proper layer coverage	Ballard Mass Flow Meter	part of microporous layer addition
GDL (Microporous Layer)	Viscometer	Proper layer coverage	Ballard Viscometer	part of microporous layer addition
GDL (Final Product)	Online Vision System	Cracks, improper layer coverage, defects	Ballard Online Vision System	final step before GDL hot pressing
End Plate	Mass Scale	Completeness of injection molding	Basic Industrial Mass Scale	
End Plate	Conveyor Mass Scale	Completeness of injection molding	Based on ThermoFischer Scientific CheckWare	End of endplate fabrication
End Plate	Human Visual Inspection	Completeness of injection molding, surface texture/color		End of process train
Laser Welding for Bipolar Plates	Optical Seam Inspection System	Completeness of laser weld	Precitec Group Laser Welding Inspection Machines	During laser welding operation