Fuel Cell Transportation Cost Analysis, Preliminary Results

STRATEGIC ANALYSIS INC

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Project ID #FC018

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Overview

Timeline

- Auto/Stationary FC Cost Analysis
  - Project start date: 7/8/10
  - Project end date: 9/7/12
  - Percent completion: 80%
- Transportation FC Cost Analysis
  - Project start date: 11/30/12
  - Project end date: *9/13/16* *(all 5 Budget Periods)*
  - Percent complete: 3% (of total budget)

Budget

- Auto/Stationary FC Cost Analysis
  - Total Project Funding: $746k
- Transportation FC Cost Analysis
  - Total project funding: $1M over 5 years
    - FY12: $166K/$68k for SA/Labs

Barriers

- System Cost:
  - Realistic, process-based system costs
  - Need for realistic values for current and future cost targets
- Demonstrates impact of technical targets & barriers on system cost:
  - Balance of plant components
  - Materials of construction
  - System size and capacity (weight and volume)

Partners

- Argonne National Laboratory
- National Renewable Energy Laboratory

Relevance: Objectives

- **Project Goals:**
  - Process-based cost analysis of stationary, light duty automotive, and bus fuel cell power systems.
  - To be used to used to inform and guide industry R&D and DOE targets.
- **Sensitivity studies**
  - Used to determine system cost effects of reaching specific technical component targets.
- **Five-year project, annually renewed (Transportation Cost Analysis)**
  - Analyze systems of interest identified by ANL.
  - Allows researchers cost impact updates throughout year and feedback on technical advances or proposed strategies.
- **Identify most fruitful research paths to cost reduction**
  - System technology and design parameters
  - System size and capacity
  - Balance of plant components
  - Materials of construction

Relevance: Systems of Interest

- **Stationary**
  - System sizes: 1 kW, 5 kW, 25 kW, 100 kW
  - Annual manufacturing rates: 100, 1k, 10k, 50k
  - Fuel Cell Technologies: Low Temp PEM, High Temp PEM, Solid Oxide
- **Light duty automotive**
  - 80 kW system size
  - Annual manufacturing rates: 1k, 10k, 30k, 80k, 130k, 500k
- **Buses**
  - 150 kW system size
  - Annual manufacturing rates: 1k, 10k, 30k, 80k, 130k, 500k
- **Analyses will be updated annually to reflect altered performance/assumptions/design.**

Approach: SA's DFMA® - Style Costing Methodology

What is DFMA?

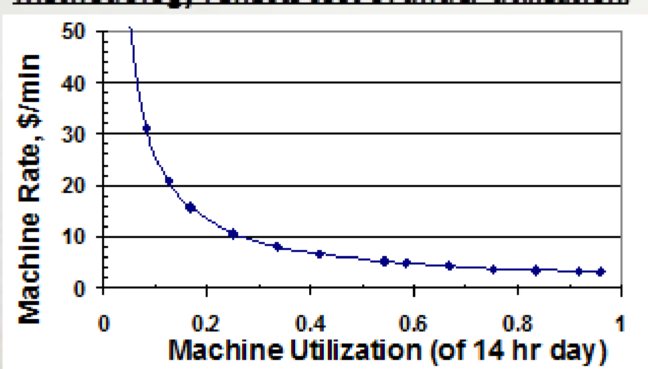
- DFMA® (Design for Manufacturing & Assembly) is a registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Co. design/costing method for the past 20+ years
- SA practices are a blend of:
  - "Textbook" DFMA®, industry standards and practices, DFMA® software, innovation, and practicality

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

Manufacturing Cost Factors:

1. Material Costs
2. Manufacturing Method
3. Machine Rate
4. Tooling Amortization

Methodology reflects cost of under-utilization:



Methodology Reflects Cost of Under-utilization:

Capital Cost
Installation
} **Initial Expenses** → **Used to calculate annual capital recovery factor based on:**
- Equipment Life
- Interest Rate
- Corporate Tax Rate

Maintenance/Spare Parts Utilities
Miscellaneous
} **Operating Expenses**

(Annual Capital Repayment + Annual Operating Payments) / Annual Minutes of Equipment Operation = Machine Rate ($/min)

Approach: 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

Cost Excluded from SA Analysis + Cost Included in SA Analysis = OEM Price

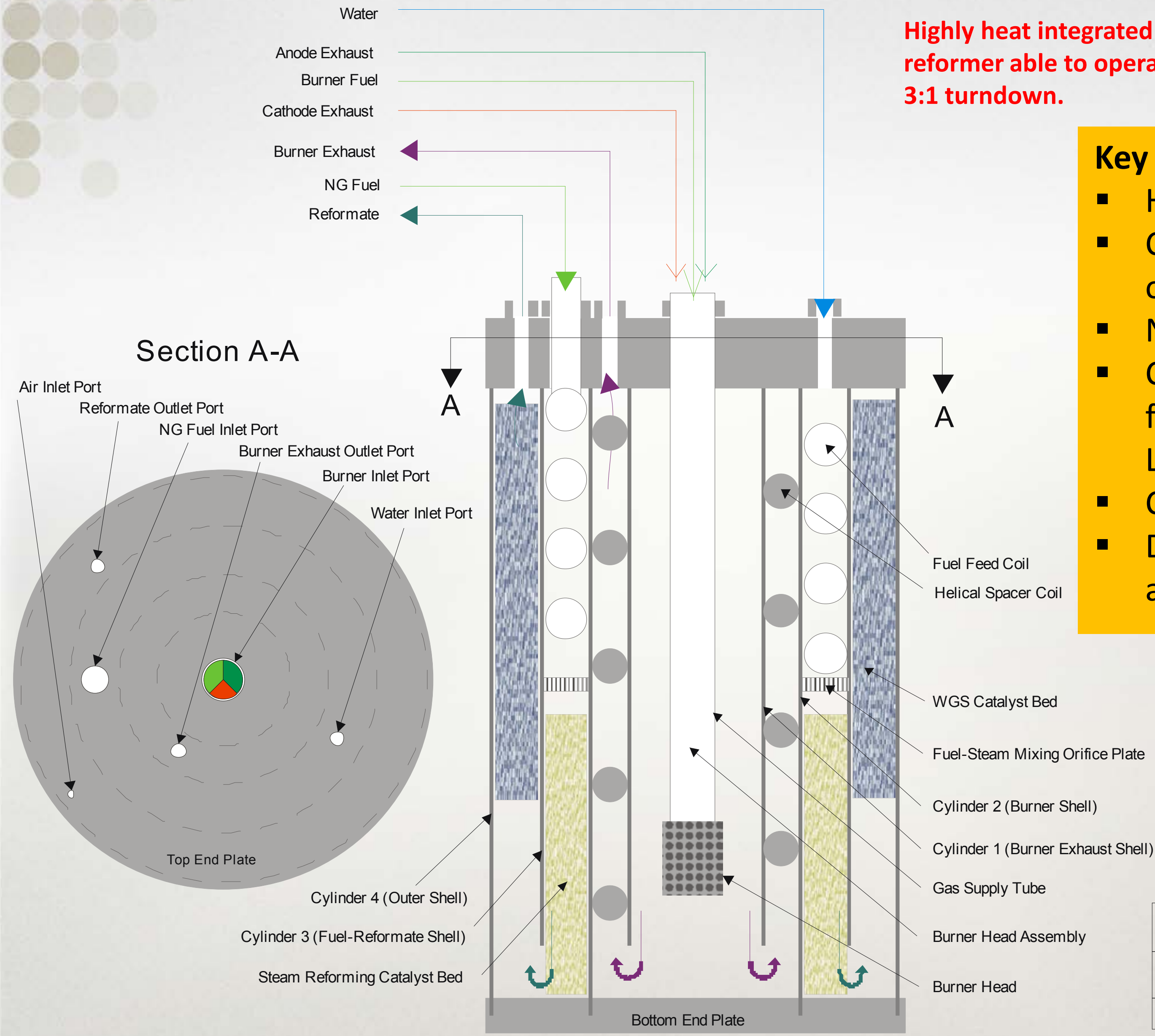
Approach: Basic Cost Modeling Work Flow

1. Obtain or create system design for technology of interest
    - ANL or Industry partner provides key parameters, system diagram
2. Develop physical embodiment of system design
    - Materials, scaling, dimensions, design embodiment
    - ANL/Industry partner may provide design details
3. Investigate & conceptually model the manufacturing process train for system production
    - Manufacturing methods based on SA experience, industry input, analogy to similar products
4. Vary key parameters to obtain sensitivity data for modeled technology
5. Share results with ANL, NREL, DOE, and Industry to obtain feedback/improvements
6. Modify cost analysis as needed

Accomplishments: Stationary FC Systems

- **Design includes SMR reformer for natural gas reforming and fuel cell unit based on one of three technologies:**
  - Low Temperature PEM, preliminary analysis complete
  - High Temperature PEM, preliminary analysis complete
  - Solid Oxide, preliminary analysis underway
- **Integrated reformer design based on Ballard prototype**
- **Systems for all three FC technologies analyzed at different system sizes and manufacturing rates**
  - System size 1kW, 5kW, 25kW, and 100kW
  - 100kW system represents four parallel 25 kW systems
  - Manufacturing rates of 100, 1k, 10k, and 50k systems/year
- **Final analysis will incorporate analysis refinements developed for Solid Oxide into High and Low Temp PEM analyses.**

Stationary System Reactor Design



Highly heat integrated thermal reformer able to operate with 3:1 turndown.

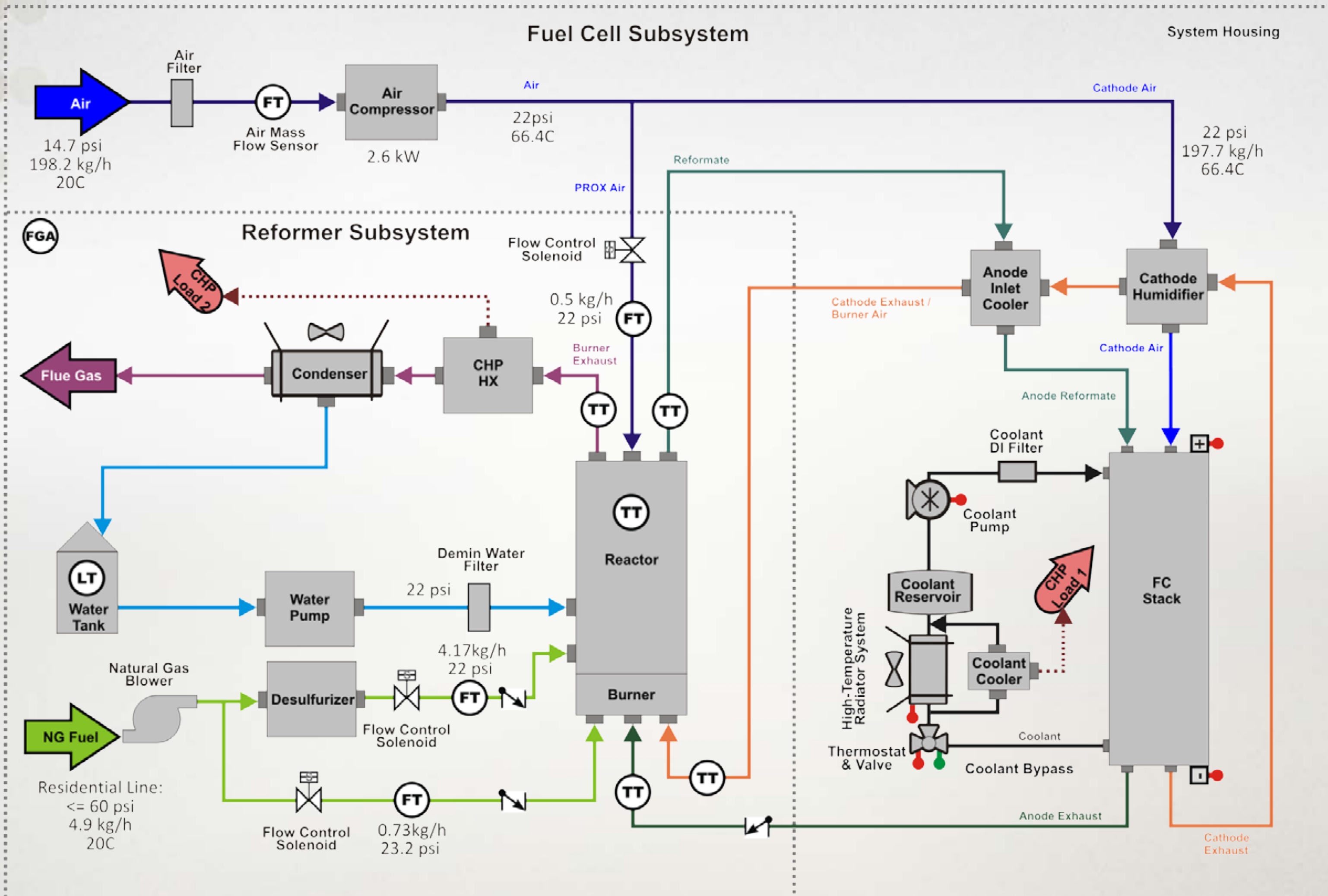
Key Features:

- High thermal integration
- Concentric design modeled on Tokyo Gas[1,2] concept
- Natural Gas Steam Reforming
- Combines HX and functions for SMR, WGS, & PROX (for Low-Temp PEM).
- Catalyst on metal monoliths
- Designed for rapid assembly and low cost

1 US Patent 7,037,472 B2
2 US Patent 7,182,921 B2

Title: Reactor Assembly
Revision Date: 15 November 2011
Drawn by:

Stationary System Design, Low Temperature PEM



LT Stationary PEM

Power Management & Electronics (not shown):

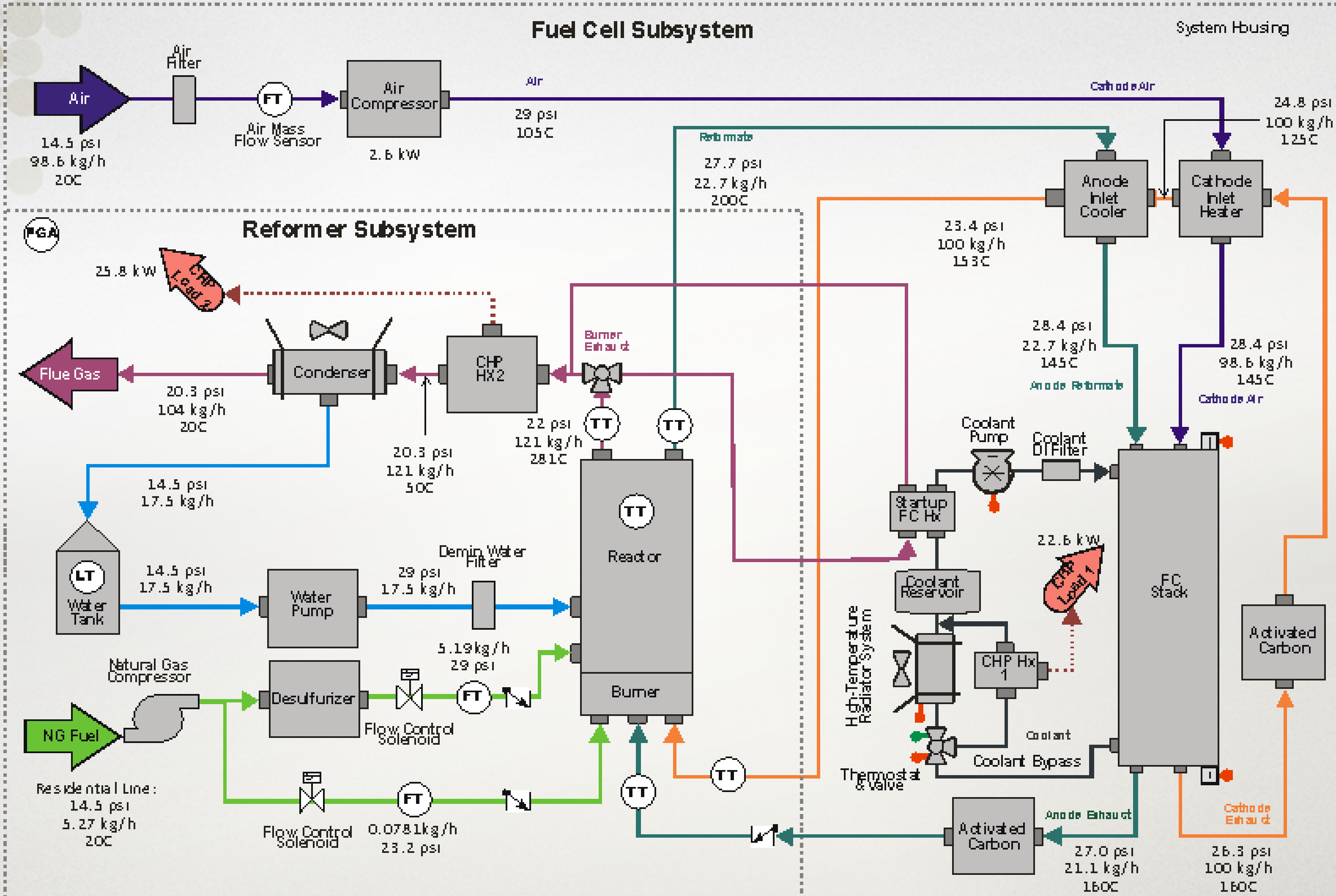
Reformer System Controller	DC/DC Converter
Fuel Cell System Controller	DC/DC Regulator
Compressor Motor Controller	AC/DC Inverter
Wiring, Cabinet	Batteries

Title: System Diagram - 25kW

Revision Date: 31 May 2011

Drawn by: Julie Perez

Stationary System Design, High Temperature PEM



Power Management & Electronics (not shown):

Reformer System Controller	DC/DC Converter
Fuel Cell System Controller	DC/DC Regulator
Compressor Motor Controller	AC/DC Inverter
Wiring, Cabinet	Batteries

Title: System Diagram - 25kW

Revision Date: 15 November 2011

Drawn by:

HT Stationary PEM

Accomplishments:
Low Temp PEM Stationary FC Systems

- System preliminary total system cost results are shown below

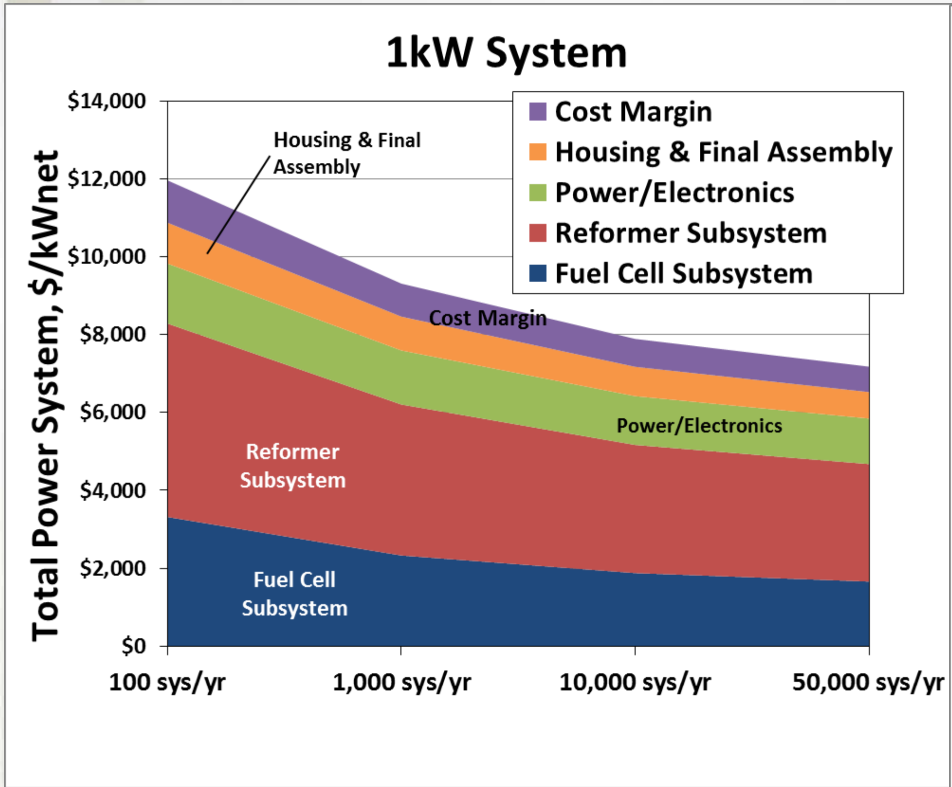
	Total System Cost, $			
	1 kW sys	5 kW sys	25 kW sys	100 kW sys
100 sys/yr	$11,963	$19,586	$43,083	$108,131
1,000 sys/yr	$9,311	$15,554	$35,066	$90,665
10,000 sys/yr	$7,891	$13,165	$28,702	$71,748
50,000 sys/yr	$7,179	$11,748	$25,223	$63,503

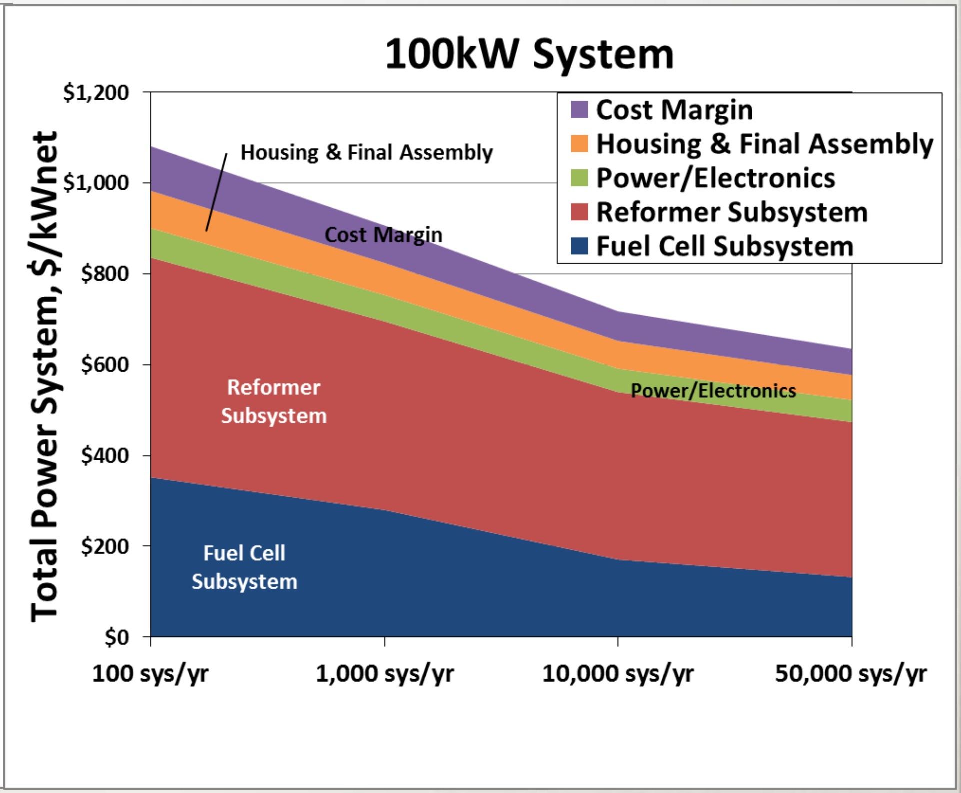
	Total System Cost per kWnet			
	1 kW sys	5 kW sys	25 kW sys	100 kW sys
100 sys/yr	$11,963	$3,917	$1,723	$1,081
1,000 sys/yr	$9,311	$3,111	$1,403	$907
10,000 sys/yr	$7,891	$2,633	$1,148	$717
50,000 sys/yr	$7,179	$2,350	$1,009	$635

- Each System is broken down into 5 sections
  - Fuel cell subsystem
    - Stack
    - Fuel Cell System Balance of Plant (BOP)
  - Reformer subsystem
    - Reactor
    - Reformer Balance of Plant
  - Power & Electronics subsystem
  - Housing and Final System Assembly
  - Cost Margin

Accomplishments:
Low Temp PEM Stationary FC Systems

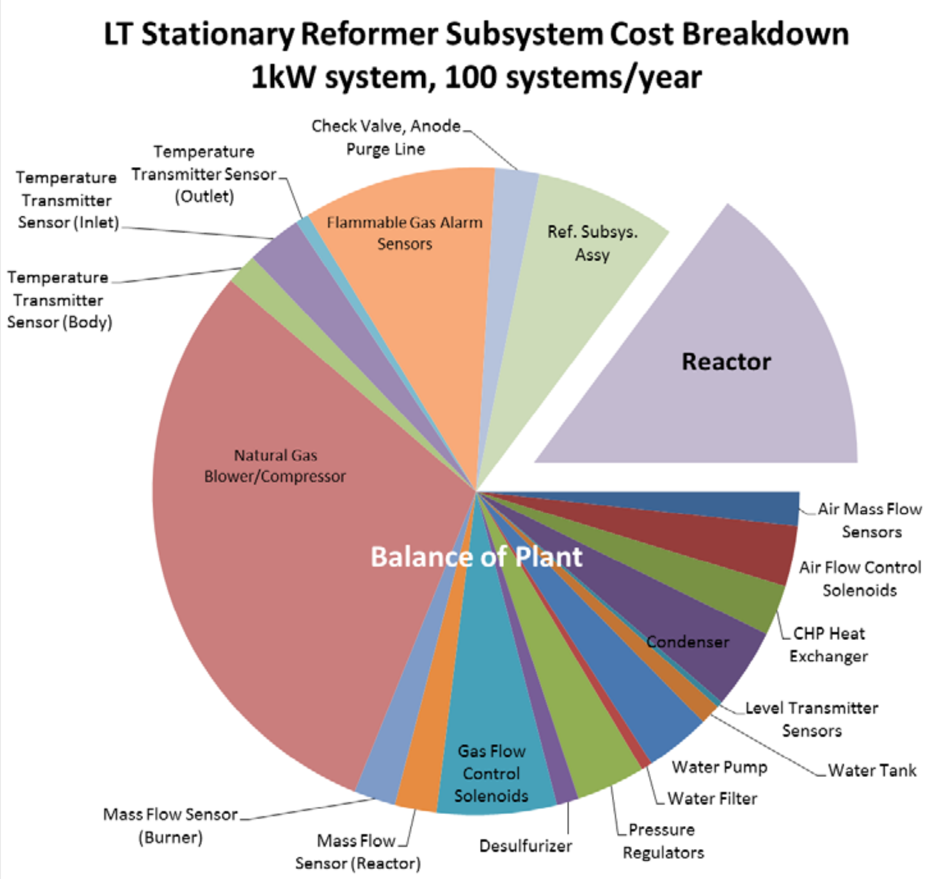
Preliminary total system cost results

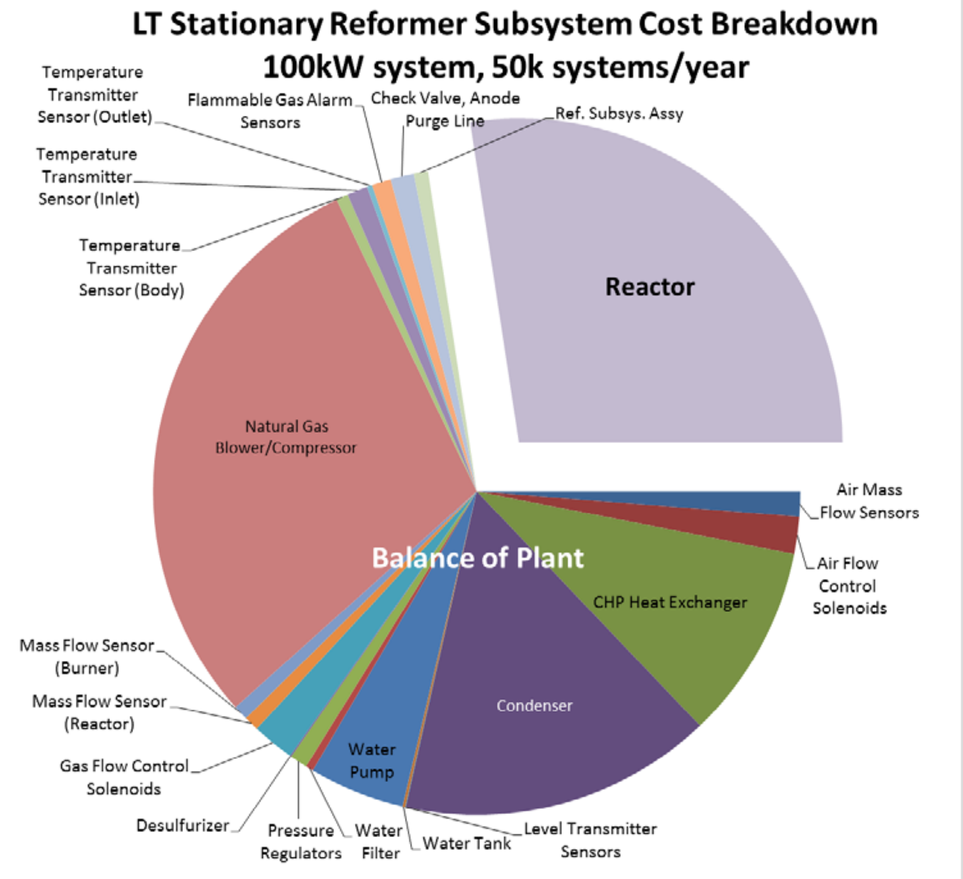




- **Reformer Subsystem is major contributor to system cost.**
- **Reformer BOP is dominant fraction of Ref. Subsystem cost.**

Accomplishments:
Low Temp Stationary Reformer Subsystem Cost Breakdown





- BOP dominates the cost of the reformer subsystem.
- This observation also holds true for the High Temp. PEM system.
- Additional scrutiny of these BOP costs is planned.

Accomplishments:
High Temp PEM Stationary FC Systems

- System preliminary total system cost results

	Total System Cost, $			
	1 kW/sys	5 kW/sys	25 kW/sys	100 kW/sys
100 sys/yr	$11,463	$20,943	$43,105	$129,969
1,000 sys/yr	$8,834	$16,719	$36,968	$106,371
10,000 sys/yr	$7,498	$14,199	$29,194	$83,653
50,000 sys/yr	$6,871	$12,493	$25,586	$74,694

	Total System Cost per kWnet			
	1 kW/sys	5 kW/sys	25 kW/sys	100 kW/sys
100 sys/yr	$11,463	$4,189	$1,724	$1,300
1,000 sys/yr	$8,834	$3,344	$1,479	$1,064
10,000 sys/yr	$7,498	$2,840	$1,168	$837
50,000 sys/yr	$6,871	$2,499	$1,023	$747

- Each System is broken down into 5 sections
  - Fuel cell subsystem
    - Stack
    - Fuel Cell System Balance of Plant (BOP)
  - Reformer subsystem
    - Reactor
    - Reformer Balance of Plant
  - Power & Electronics subsystem
  - Housing and Final System Assembly
  - Cost Margin

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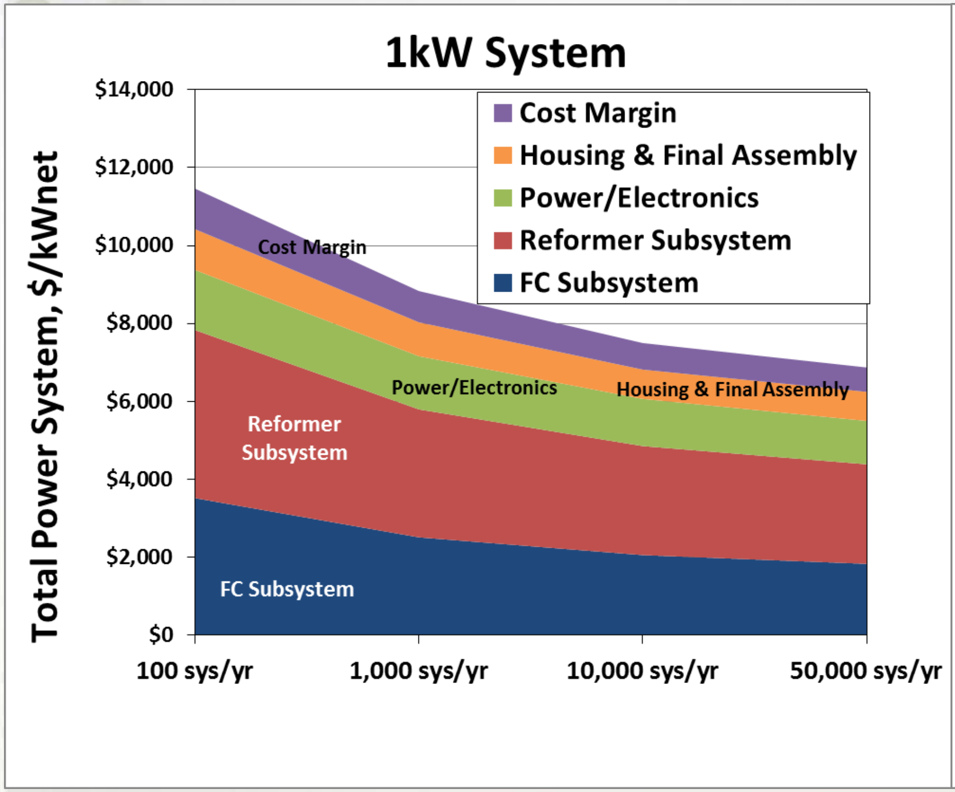
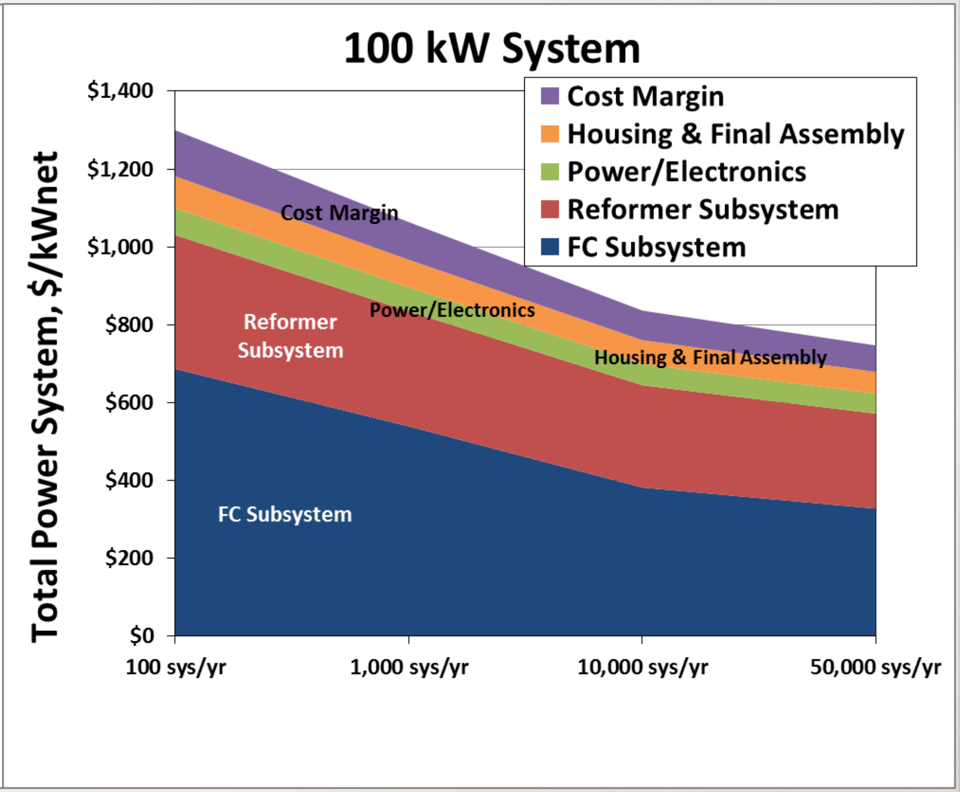
Accomplishments: High Temp PEM Stationary FC Systems

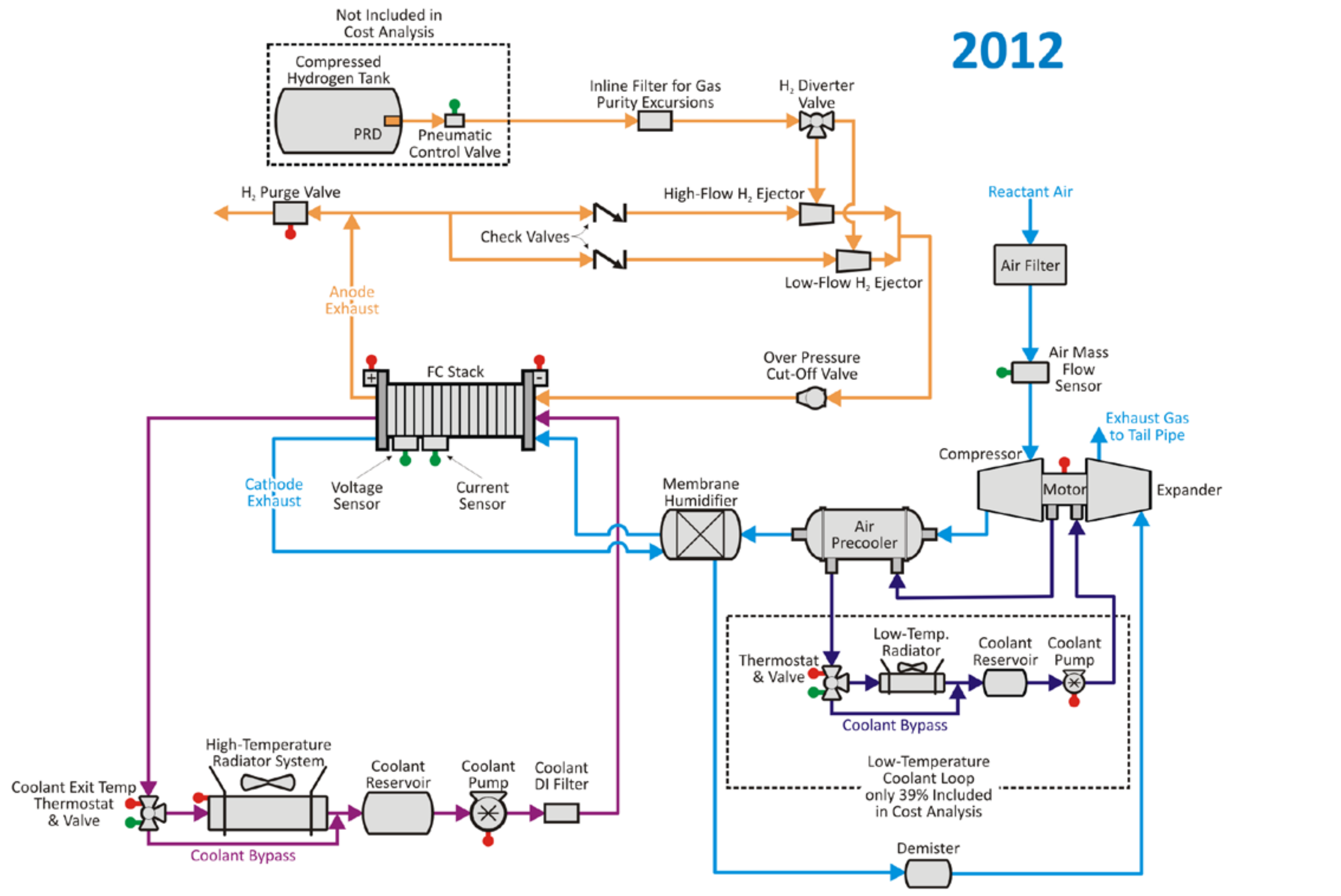
Preliminary total system cost results





- **High Temp. PEM Stationary system follows same trend as Low Temp. PEM Sys.**
  - **Reformer Subsystem is major cost contributor.**
  - **Reformer BOP, rather than reactor itself, is cost driver.**

Accomplishments:
2012 80kW Automotive Update System Diagram



No substantive configuration changes between 2011 & 2012.

Accomplishments: 2012 Automotive Update System Details

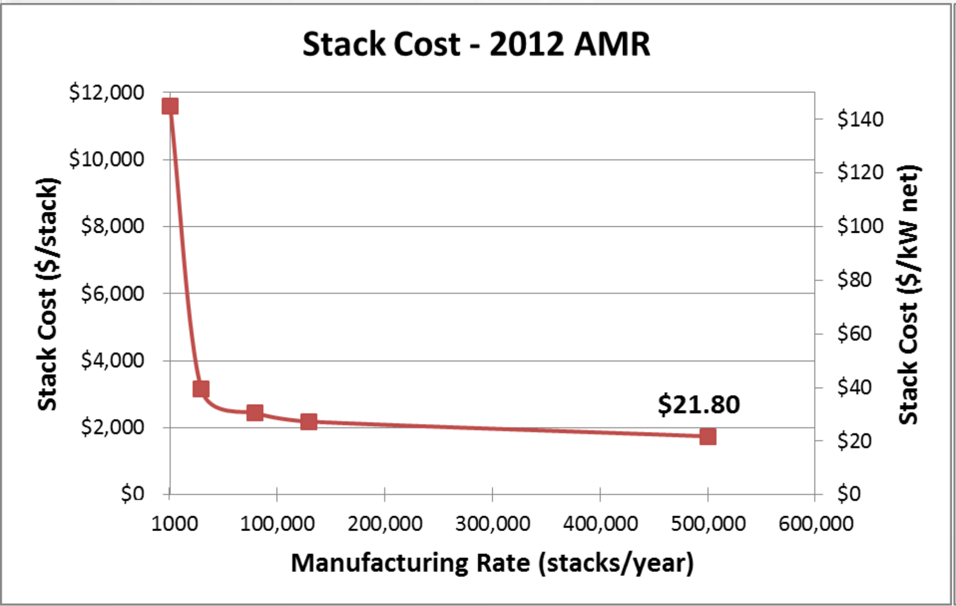
	2011 AMR System	2012 AMR System
Power Density (mW/cm^2)	1,110	1,110
Total Pt loading ($mgPt/cm^2$)	0.186	0.186
Gross Power (kW_{gross})	89.25	89.25
Operating Pressure (atm)	3.0	3.0
Peak Stack Temp. (°C)	95	95
Active Cells	369	369
Membrane Material	Nafion® on 25-micron ePTFE	Nafion® on 25-micron ePTFE
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 TreadStone Coating	Stamped SS 316L with TreadStone Coating
Air Compression	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, Radial-Inflow Expander
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Microporous Layer	Carbon Paper Macroporous Layer with Microporous Layer
Catalyst Application	Nanostructured Thin Film (NSTF)	Nanostructured Thin Film (NSTF)
Air Humidification	Tubular Membrane Humidifier	Tubular Membrane Humidifier
Hydrogen Humidification	None	None
Exhaust Water Recovery	None	None
MEA Containment	Injection-Molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E	Injection-Molded LIM Hydrocarbon MEA Frame/Gasket
Coolant & End Gaskets	Laser Welding/ Screen-Printed Adhesive Resin	Laser Welding/ Screen-Printed Adhesive Resin
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

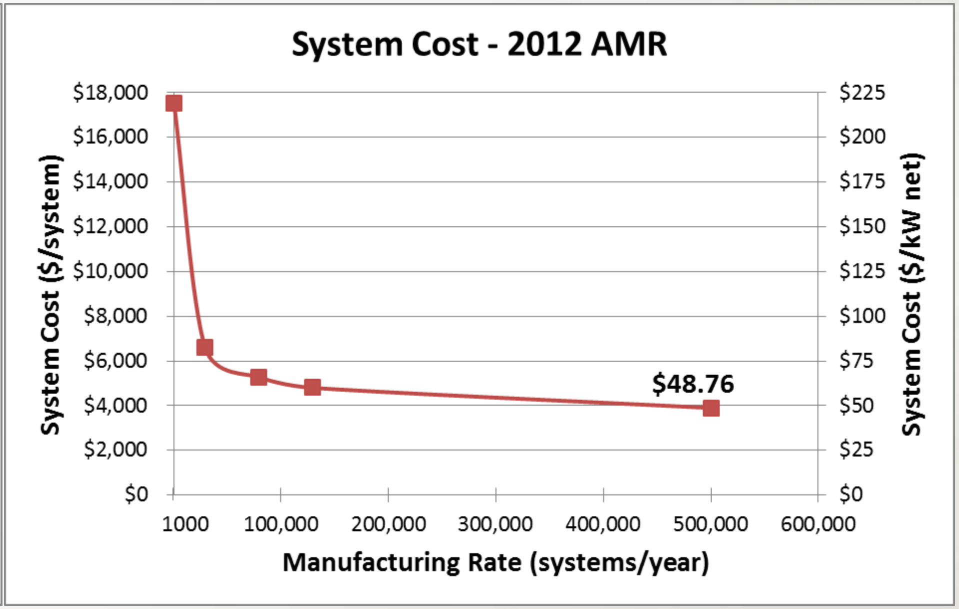
Accomplishments: 2012 Automotive Changes from Previous Year

Change	Reason	Change from previous value	Cost $/kW (at 500k sys/year)
2011 AMR Preliminary Cost Value		N/A	$47.81
Press force calculations & capital cost parameters for bipolar plate stamping	Analysis altered to account for swageing of material, as opposed to simple bending.	$0.06	$47.87
Gasket injection molding calculations	Model refined and molding cavity count re-optimized	$0.31	$48.18
GDL Thickness reduced from 300 μm to 150 μm	Response to industry review	-$0.25	$47.93
Final system assembly calculations refined and expanded	Response to industry review	-$0.16	$47.78
Piping configuration/costing updated & expanded	Response to industry review	$0.66	$48.43
Air temperature sensor added to system to monitor coolant exit conditions	Response to industry review	$0.06	$48.49
Purge valve upgraded to multi-function model	Response to industry review	$0.33	$48.82
Hot pressing process removed and replaced with crimping roller process prior to cutting & slitting	Hot pressing incompatible with NSTF catalyst deposition, new method required for combining membrane & GDL layers	-$0.06	$48.76
Final 2012 AMR Value		**$0.95**	**$48.76**

- **Changes from last year consist of a series of small cost impact refinements/improvements.**

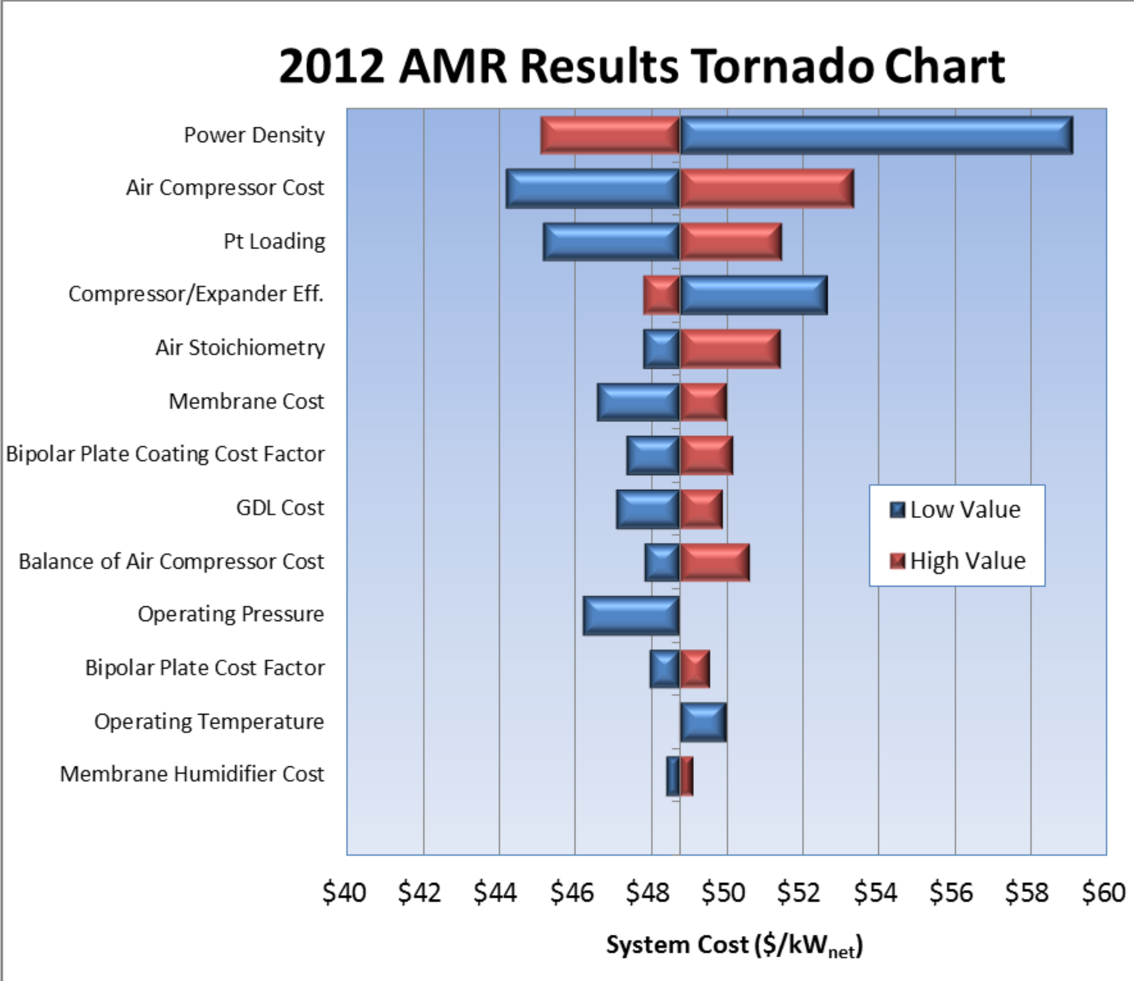
Accomplishments:
2012 Automotive System and Stack Costs





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

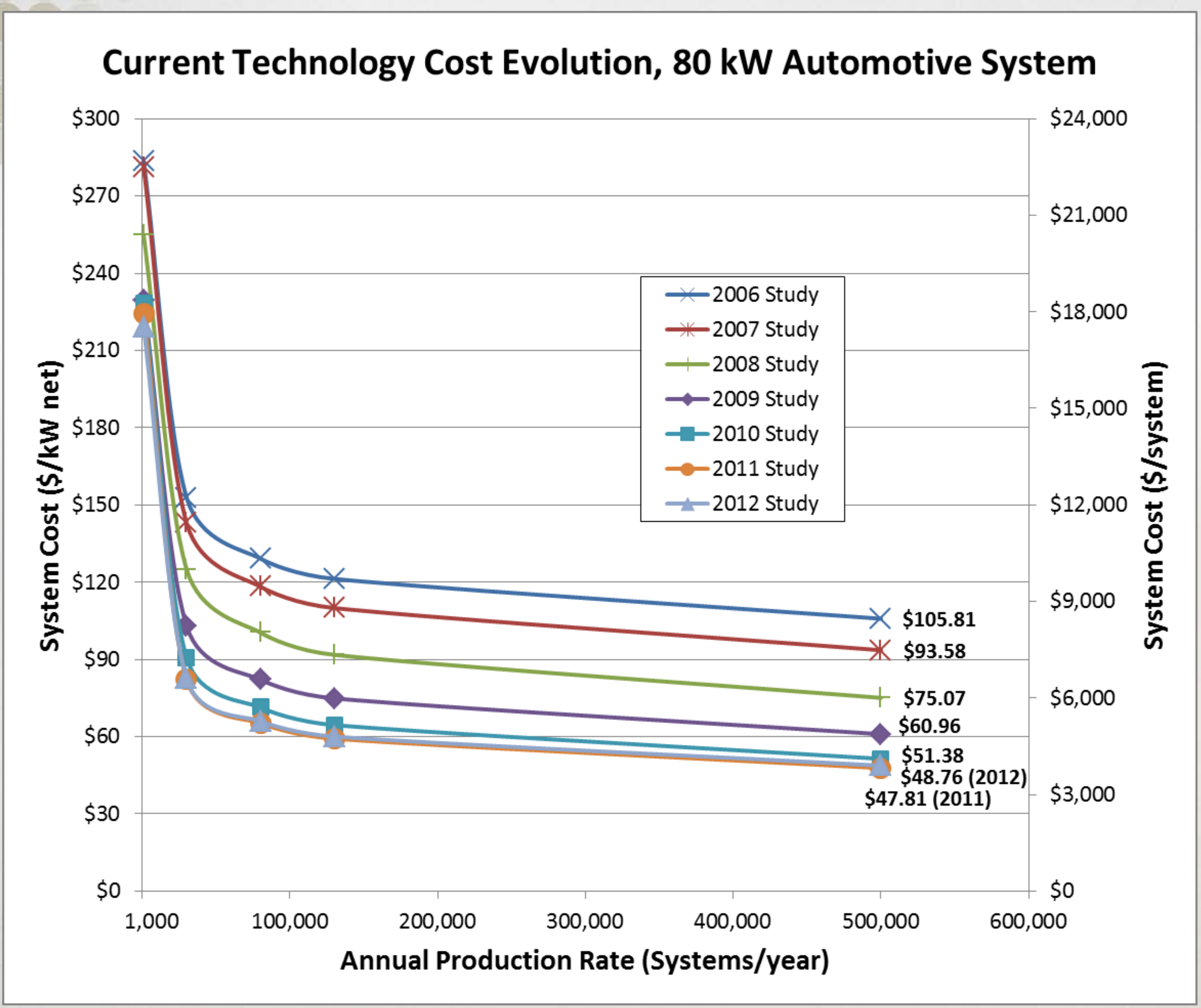
Tornado Chart



System Cost ($/kWnet), 500,000 sys/year				
Parameter	**Units**	**Low Value**	**Base Value**	**High Value**
Power Density	mW/cm^2	700	**1110**	1400
Air Compressor Cost	$/system	$366.48	**$732.95**	$1,099.43
Pt Loading	mgPt/cm^2	0.1	**0.186**	0.25
Compressor/Expander Eff.	%	50%	**64%**	69%
Air Stoichiometry		1.3	**1.5**	2.0
Membrane Cost	$/m^2	$2.50	**$23.21**	$34.82
Bipolar Plate Coating Cost Factor		0	**1**	2
GDL Cost	$/m^2	$3.00	**$11.03**	$16.55
Balance of Air Compressor Cost	$/system	$73.15	**$146.30**	$292.60
Operating Pressure	atm	1.5	**3**	3
Bipolar Plate Cost Factor		0.75	**1.00**	1.25
Operating Temperature	°C	80	**95**	95
Membrane Humidifier Cost	$/system	$29.51	**$59.01**	$88.52
2012 AMR System Cost			**$48.76**	

- **Power density remains dominant cost parameter.**
- **Air compressor error bands large due to diversity of approach/opinion within community.**

Automotive Fuel Cell System Trend



- Previous years of analysis allow analysis of cost trends.
- A downward trend is observed.
- Projected cost slightly rises from 2011 to 2012 based on analysis refinement.

Collaborations

- **Argonne National Labs**
  - System design and modeling support
  - Specify key system parameters and range of sensitivity studies
  - SA calculations and point designs verified against ANL modeling
- **National Renewable Energy Laboratory**
  - Expertise on manufacturing and quality control systems
- **Industry Collaborators**
  - Ford, Ballard, NexTech, Catacel, Enersys Innovation, PNNL
  - Vet results and provide manufacturing process insight
  - Stationary reformer design based on concept supplied by Industry

Proposed Future Work:

- Stationary Solid Oxide FC System
- Bus Systems
  - 150 kW systems
  - Manufacturing rates of 1k, 10k, 30k, 80k, 130k, 500k
- Explore differences between light duty vehicle and bus systems
  - Peak installed power
  - System lifetime
  - Number of start/stop cycle over system lifetime,
  - Layout of system components due to available volume
  - Differences in system component form (cell aspect ratio)
  - Drive cycle impact on LCC and resulting FC operating parameter optimization
- Life Cycle Cost Analysis

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Summary

- Overview
  - Cost analysis of stationary, automobile, and bus fuel cell systems
  - Final stage of auto & stationary project
  - In year 1 of 5 year transportation project
- Relevance
  - Cost analysis used to assess practicality of proposed storage system, determine key cost drivers, and provide insight for direction of R&D priorities
- Approach
  - Process based cost analysis methodologies (e.g. DFMA)
- Accomplishments
  - Low and High Temperature PEM stationary systems analysis complete
  - 2011 Automobile analysis complete
  - 2012 Automotive analysis underway
  - In progress analysis of Solid Oxide stationary system
- Collaborations
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
  - Ballard/NexTech provide system design input for stationary systems.
- Future Work
  - Conclude Solid Oxide and final pass of stationary systems
  - Conclude analysis of automobile and bus systems

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Technical Backup Slides

Stationary System Overview

- **Cost of system is highly dependent on specific application and configuration.**
- **Therefore, we have made the following assumptions**
  - **Operation on Natural Gas**
    - **Cost of operation on Propane would be quite similar but fuel compressor might not be needed, and sizing of reactor would slightly change**
  - **Natural Gas supply pressure**
    - **For 1kW and 5kW systems: NG gas supplied at 2 psig (thereby requiring a NG compressor)**
    - **For 25kW and 100kW systems: NG supplied at 15 psig (thereby requiring only a pressure regulator)**
  - **Design for Water Neutral Operation**
    - **System assumes an initial charge of DI water**
    - **Condenser on flue gas is used to recover all future system water needs**
    - **In hot/dry climate, additional water might be necessary (and water cleanup up subsystem)**
  - **Moderate climate is assumed**
    - **No extreme cold heat tracing is added to the system**
  - **Fuel Cell stack is oil cooled**
  - **Combined Heat and Power (CHP) operation**
    - **System configurations assumed usable heat from both the stack and from the reactor**
    - **Quantity and Quality of excess heat from these two streams are quite different**
    - **System cost includes two CHP heat exchangers:**
      - **1) Liquid/Liquid Heat exchanger (Fuel Cell Oil Coolant to Building Liquid Coolant)**
      - **2) Gas/Liquid Heat exchanger (Reactor Flue Gas to Building Liquid Coolant)**
    - **Further details of the heat transfer to the building have not been modeled**

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Low Temp PEM FC System Configuration Assumptions

Technology Type		Stationary Low Temp PEM							
Annual Production Rate	systems/year	100				1,000			
System Net Electric Power (Output)	kWnet	1	5	25	100	1	5	25	100
System Voltage @ Peak Power	V	24	120	250	250	24	120	250	250
Active Width	cm	10.60	10.66	11.69	16.54	10.60	10.66	11.69	16.54
Active Height	cm	7.07	7.11	7.80	11.03	7.07	7.11	7.80	11.03
Active Cells per Stack	cells/stack	36	178	185	370	36	178	185	370
Cell Voltage @ Peak Power	V/cell	0.676	0.676	0.676	0.676	0.676	0.676	0.676	0.676
Stacks per System	stacks/system	1	1	4	4	1	1	4	4
System Gross Electric Power (Output)	kWgross	1.10	5.50	27.50	110.00	1.10	5.50	27.50	110.00
MEA Areal Power Density @ Peak Power	mW/cm2	408	408	408	408	408	408	408	408

Annual Production Rate	systems/year	10,000				50,000			
System Net Electric Power (Output)	kWnet	1	5	25	100	1	5	25	100
System Voltage @ Peak Power	V	24	120	250	250	24	120	250	250
Active Width	cm	10.60	10.66	11.69	16.54	10.60	10.66	11.69	16.54
Active Height	cm	7.07	7.11	7.80	11.03	7.07	7.11	7.80	11.03
Active Cells per Stack	cells/stack	36	178	185	370	36	178	185	370
Cell Voltage @ Peak Power	V/cell	0.676	0.676	0.676	0.676	0.676	0.676	0.676	0.676
Stacks per System	stacks/system	1	1	4	4	1	1	4	4
System Gross Electric Power (Output)	kWgross	1.10	5.50	27.50	110.00	1.10	5.50	27.50	110.00
MEA Areal Power Density @ Peak Power	mW/cm2	408	408	408	408	408	408	408	408

High Temp PEM FC System Configuration Assumptions

Technology Type		Stationary High Temperature PEM							
Annual Production Rate	systems/year	100				1,000			
System Net Electric Power (Output)	kWnet	1	5	25	100	1	5	25	100
System Voltage @ Peak Power	V	21.84	109.2	104	209.52	21.84	109.2	104	209.52
Cell Active Width	cm	14.56	14.56	33.36	33.36	14.56	14.56	33.36	33.36
Cell Active Length	cm	9.71	9.71	22.24	22.24	9.71	9.71	22.24	22.24
Active Cells per Stack	cells/stack	42	210	200	403	42	210	200	403
Cell Voltage @ Peak Power	V/cell	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520
Stacks per System	stacks/system	1	1	1	2	1	1	1	2
System Gross Electric Power (Output)	kWgross	1.19	5.93	29.67	119.57	1.19	5.93	29.67	119.57
MEA Areal Power Density @ Peak Power	mW/cm2	200	200	200	200	200	200	200	200
Total FC Subsystem Cost	$/kWnet	$3,506	$1,506	$815	$681	$2,508	$1,125	$715	$551
Total Stacks Cost	$/kW (Net)	$1,762	$1,085	$706	$643	$1,080	$774	$622	$518

Annual Production Rate	systems/year	10,000				50,000			
System Net Electric Power (Output)	kWnet	1	5	25	100	1	5	25	100
System Voltage @ Peak Power	V	21.84	109.2	104	209.52	21.84	109.2	104	209.52
Cell Active Width	cm	14.56	14.56	33.36	33.36	14.56	14.56	33.36	33.36
Cell Active Length	cm	9.71	9.71	22.24	22.24	9.71	9.71	22.24	22.24
Active Cells per Stack	cells/stack	42	210	200	403	42	210	200	403
Cell Voltage @ Peak Power	V/cell	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520
Stacks per System	stacks/system	1	1	1	2	1	1	1	2
System Gross Electric Power (Output)	kWgross	1.19	5.93	29.67	119.57	1.19	5.93	29.67	119.57
MEA Areal Power Density @ Peak Power	mW/cm2	200	200	200	200	200	200	200	200
Total FC Subsystem Cost	$/kWnet	$2,052	$966	$507	$381	$1,828	$745	$417	$327
Total Stacks Cost	$/kW (Net)	$789	$655	$425	$352	$695	$465	$343	$301