MASS-PRODUCTION COST ESTIMATION FOR AUTOMOTIVE FUEL CELL SYSTEMS

DOE H_2 PROGRAM REVIEW

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FC 018

Overview

Timeline

- Base Period: Feb ‘06 to Jan ‘08
  - 100% complete
- Option Year 1: Feb ‘08 to Jan ‘09
  - 100% complete
- Option Year 2: Feb ‘09 to Jan ‘10
  - 100% complete
- Option Year 3: Feb ‘10 to Jan ’11

Barriers

- Manufacturing costs
- Materials costs (particularly precious metal catalysts)

DOE Cost Targets

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

Timeline

- Total Project Funding:
  - $407k (2 year base period)
  - $160k (option year 1)
  - $166k (option year 2)
  - $150k (turbocompressor task)
  - $276k (option year 3)

Collaborations

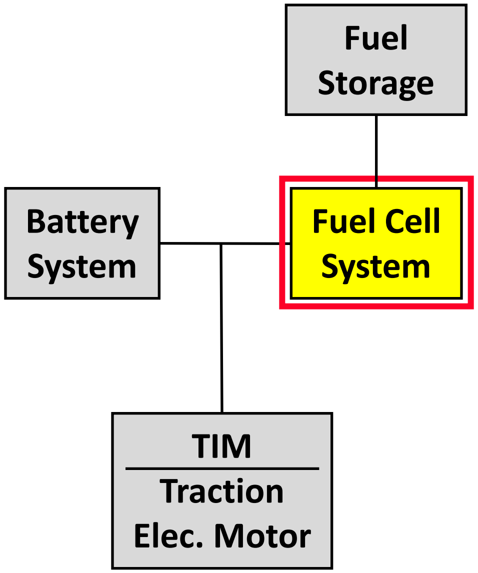
- Extensive interaction with industry/researchers to solicit design & manufacturing metrics as input to cost analysis.

Project Objectives

1. **Identify the <u>lowest cost system design and manufacturing methods</u> for an 80 kW_e direct-H_2 automotive PEMFC system based on 2 technology levels:**
   - Current (2010) status technology
   - 2015 projected technology

2. **Determine costs for these 3 tech level systems at 5 production rates:**
   - 1,000 vehicles/year
   - 30,000 vehicles/year
   - 80,000 vehicles/year
   - 130,000 vehicles/year
   - 500,000 vehicles/year

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



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

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General Cost Analysis Rules

- 80 kW_{net} system (88 kW_{gross} for 2010 system)
- 1k to 500k annual system production
- U.S. labor rates: $45/hr (fully loaded)
- $1,100/troy oz. Pt cost used for consistency

Some costs *NOT* included:

- 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
  - purchased components (membrane, GDL, compressor) have a manufacturer markup
  - but there is no markup to the Fuel Cell Manufacturer/Assembler

DTI's DFMA®-Style Costing Methodology

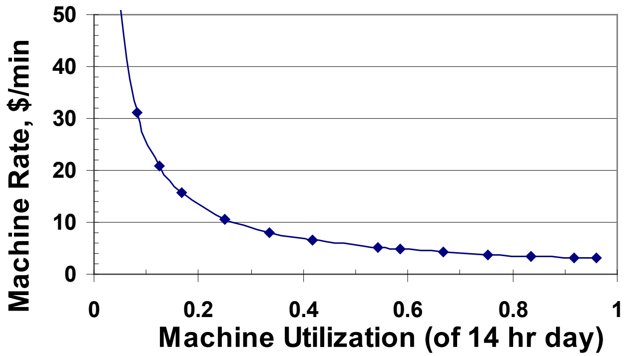
- **DFMA® (Design for Manufacturing and Assembly) is a registered trademark of Boothroyd-Dewhurst, Inc.**
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Co. design/costing method for past 20+ years
- **DTI practices are a blend of:**
  - "Textbook" DFMA®, industry standards & practices,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

Maint./Spare Parts
Utilities
Miscellaneous
} **Operating Expenses**

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

Key Technical Targets Define System

Tech. Targets that drive analysis:		Previous Years (2008, 2009)		2010	2015
Stack Efficiency @ Rated Power	%	55%	55%	55%	55%
MEA Areal Power Density @ Peak Power	mW/cm^2	715	833	833	1,000
Total Pt-Group Catalyst Loading	$mg\ PGM/cm^2$	0.25	0.15	0.15	0.15
Key Derived Performance Parameters:					
System Gross Electric Power (Output)	kW	90.2	87.8	87.9	87.3
Active Area	cm^2	339	286	286	237
Cell Voltage @ Peak Power	V/cell	0.676	0.676	0.676	0.676
Operating Pressure (Peak)	atm	2.3	1.69	1.69	1.5

Red text indicates a change from previous year.

- **A few key DOE Technical Target values are used to anchor system definition**
- **All other system parameters flow from DTI calculations & judgment**
- **2010 values for key parameters (power density & catalyst loading) remain at 2009 levels**

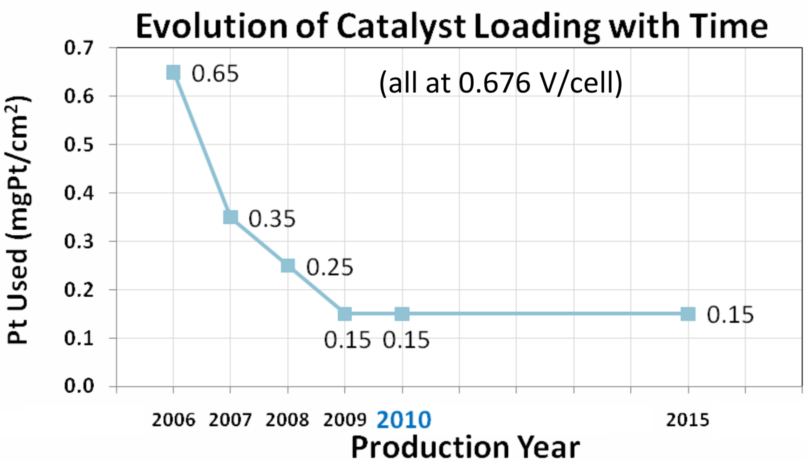
Key Changes Since 2009 AMR

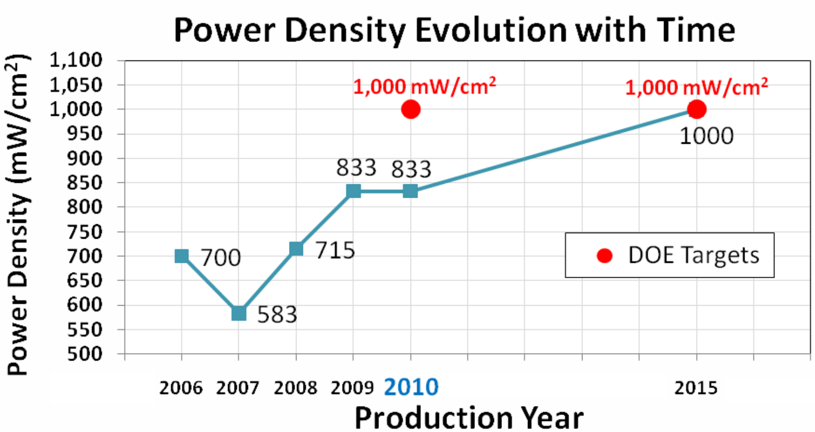
Change	Reason	+/-	500k/year
Final 2008 Value			***$75.07***
Switched to 833 mW/cm^2 and 0.15 mg/cm^2	Technology improvement, DOE input	($10.28)	**$64.79**
Switched from water spray humidification to Membrane Humidifier	Technology improvement, Membrane Humid. becoming industry standard	($3.02)	**$61.77**
Switched from VertiCoater to NSTF	NSTF proven to be durable and yield high-performance	($0.03)	**$61.74**
Miscellaneous adjustments & improvements	Opportunities for improved analysis	$0.06	**$61.80**
Removed the Exhaust Loop from the 2009 system	Not needed with membrane humidifier	($1.42)	**$60.38**
Switched to 1 stack/system	Industry & Tech. Team suggestion	($0.55)	**$59.83**
Capital cost for Stack Conditioning test stand increased to $357,000	Independent Review Panel suggestion	$0.10	**$59.93**
New Inline Filter for Gas Purity Excursions	Independent Review Panel suggestion	$0.28	**$60.21**
New Flow Diverter Valve	Independent Review Panel suggestion	$0.19	**$60.40**
Updated to Honeywell cost estimate for CEM & Motor Controller	Significant analysis improvement, much higher confidence level	$0.19	**$60.59**
Corrected to 3M design conditions (833 mW/cm^2, 2.5 air stoichiometry, 1.69 atm), Membrane Humidifier enlarged	Performance charateristics now tied to appropriate polarization curves	$0.37	**$60.96**
Final 2009 Value	-$14.11/kW$_{net}$ since 2008		***$60.96***
Reconfigured Ejector System	Industry input -> removed prop. valve & press. transducer, added OPCO & check valves, relies on H_2 storage system for some pressure regulation	($4.83)	**$56.13**
Improved System Controller DFMA Analysis	Improved Cost Analysis by adding greater detail	($1.70)	**$54.43**
Lowered channel depth of stamped plates from 0.92 to 0.5 mm	Industry input, allows gasket material reduction	($1.03)	**$53.39**
Changed Temperature at Peak Power from 80°C to 90°C	Improved durability allows higher peak temperature	($0.50)	**$52.89**
Changed Membrane Humidifier to larger model	Previous model not large enough to handle mass flow	$0.40	**$53.29**
Added Demister and Air Precooler	Added requirement after ANL review	$0.80	**$54.09**
Added Part and Material Yields across all components	Added part yields at component level, homogenized methodology	$0.08	**$54.17**
Low-Temperature Coolant Loop reconfigured & reinserted	Needed for Air Precooler & CEM, but only 39% of LTL cost is included	$0.77	**$54.94**
Improved Wiring Analysis	Improved and updated wire lengths and specifications	($0.84)	**$54.10**
CEM costs scaled to better reflect operating parameters	New data from Honeywell, improved cost analysis	($0.65)	**$53.45**
Assorted BOP Changes	Improved Cost Analysis (H_2 piping, air tubing, mass air flow sensor, etc.)	($2.22)	**$51.23**
Miscellaneous Costs	Improved Cost Analysis (improved calculations, error fixes, etc.)	$0.07	**$51.31**
Final 2010 Value	-$9.65/kW$_{net}$ since 2009		***$51.31***

System Comparison

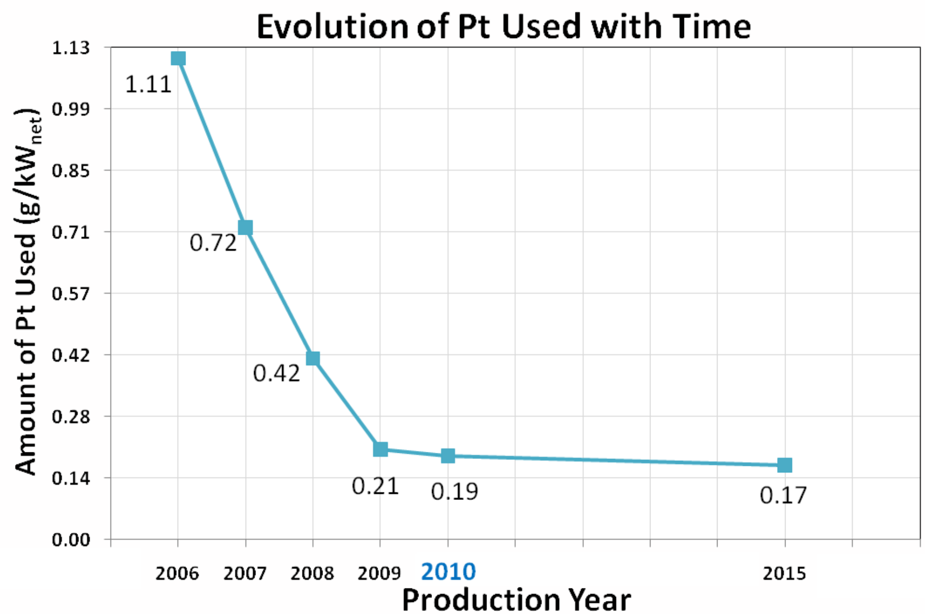
	2008 Technology	2009 Technology	2010 Technology	2015 Technology
Power Density (mW/cm²)	715	**833**	833	**1,000**
Total Pt loading	0.25	**0.15**	0.15	0.15
Operating Pressure (atm)	2.30	**1.69**	1.69	**1.5**
Peak Stack Temp. (°C)	80	80	**90**	**99**
Active Cells per Stack	372	372	**369**	369
Membrane Material	Nafion on ePTFE	Nafion on ePTFE	Nafion on ePTFE	**Advanced High-Temperature**
Radiator/ Cooling System	Aluminum Radiator, Water/Glycol coolant, DI filter	Aluminum Radiator, Water/Glycol coolant, DI filter	Aluminum Radiator, Water/Glycol coolant, DI filter	**Smaller** Aluminum Radiator, Water/Glycol coolant, DI filter
Bipolar Plates	Stamped SS 316L with Coating	Stamped SS 316L with Coating	Stamped SS 316L with Coating	Stamped SS 316L with Coating
Air Compression	Twin-lobe compressor, twin-lobe expander	**Centrifugal Compressor, Radial Inflow Expander**	Centrifugal Compressor, Radial Inflow Expander	Centrifugal Compressor, **No Expander**
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Microporous layer applied on top	Carbon Paper Macroporous Layer with Microporous layer applied on top	Carbon Paper Macroporous Layer with Microporous layer applied on top	Carbon Paper Macroporous Layer with Microporous layer applied on top
Catalyst Application	Double-sided vertical die-slot coating of membrane	**Nanostructured Thin Film (NSTF)**	Nanostructured Thin Film (NSTF)	Nanostructured Thin Film (NSTF)
Air Humidification	Water Spray Injection	**Polyamide Membrane**	Polyamide Membrane	**None**
H_2 Humidification	None	None	None	None
Exhaust Water Recovery	SS Condenser (Liquid/Gas HX)	**None**	None	None
MEA Containment	Injection molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E	Injection molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E	Injection molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E	Injection molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E
Coolant & End Gaskets	Laser Welding/ Screen-Printed Adhesive Resin	Laser Welding/ Screen-Printed Adhesive Resin	Laser Welding/ Screen-Printed Adhesive Resin	Laser Welding/ Screen-Printed Adhesive Resin
Freeze Protection	Drain water at shutdown	Drain water at shutdown	Drain water at shutdown	Drain water at shutdown
H_2 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)	2 for FC system 1 for passenger cabin (not in cost estimate) 1 for fuel sys (not in cost estimate)	**None**
End Plates/ Compression System	Composite molded end plates with compression bands	Composite molded end plates with compression bands	Composite molded end plates with compression bands	Composite molded end plates with compression bands
Stack Conditioning	5 hours of power conditioning	5 hours of power conditioning	5 hours of power conditioning	**3 hours of power conditioning**

Power Density & Platinum Loading





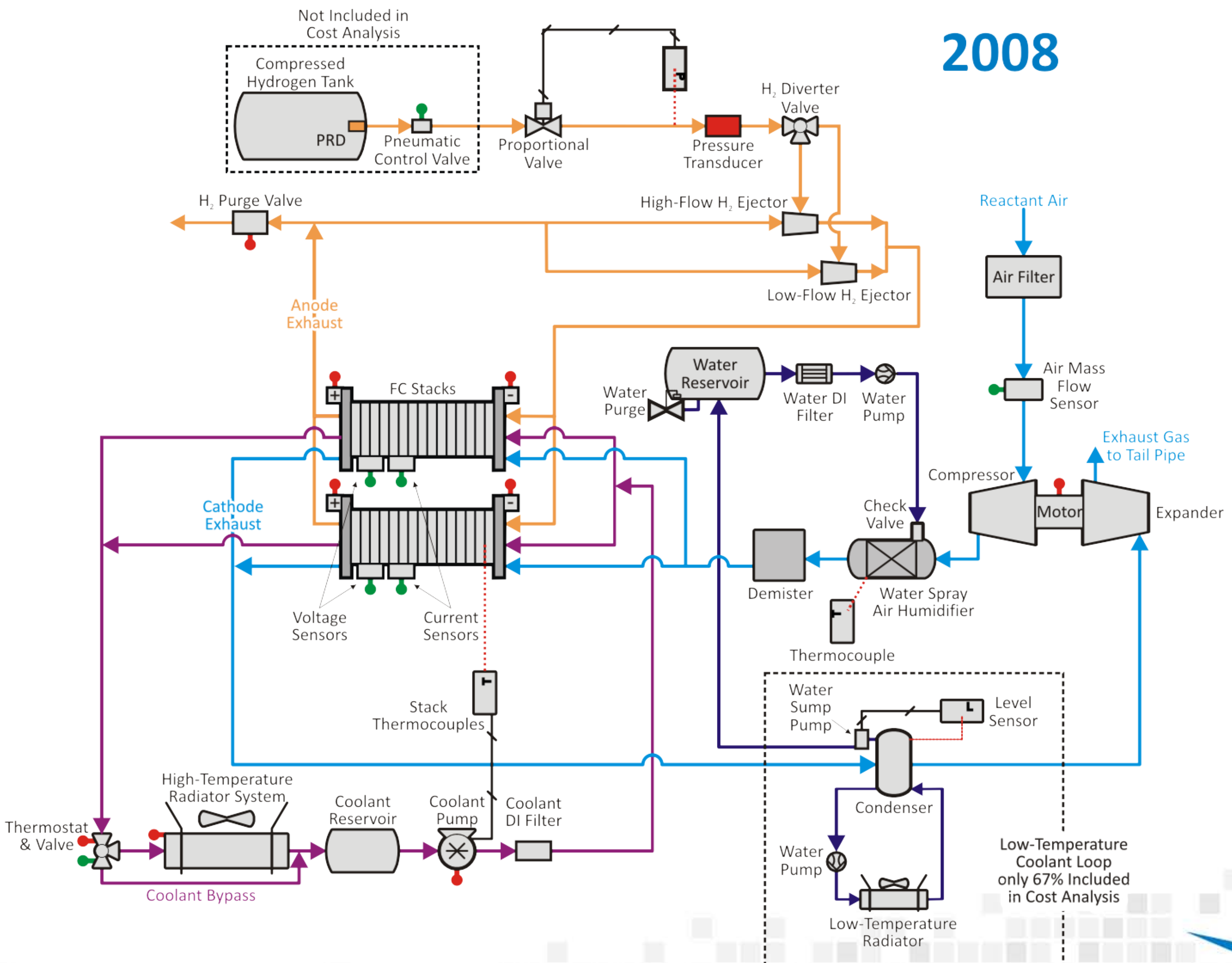
- Areal catalyst loadings have been decreasing
- Catalyst loading reductions appear to be slowing down
- Focus has switched to durability/robustness



Possible significant future improvements:

- Power density increases
- Switch to non-Pt catalyst

Simplification is Key to Cost Reduction



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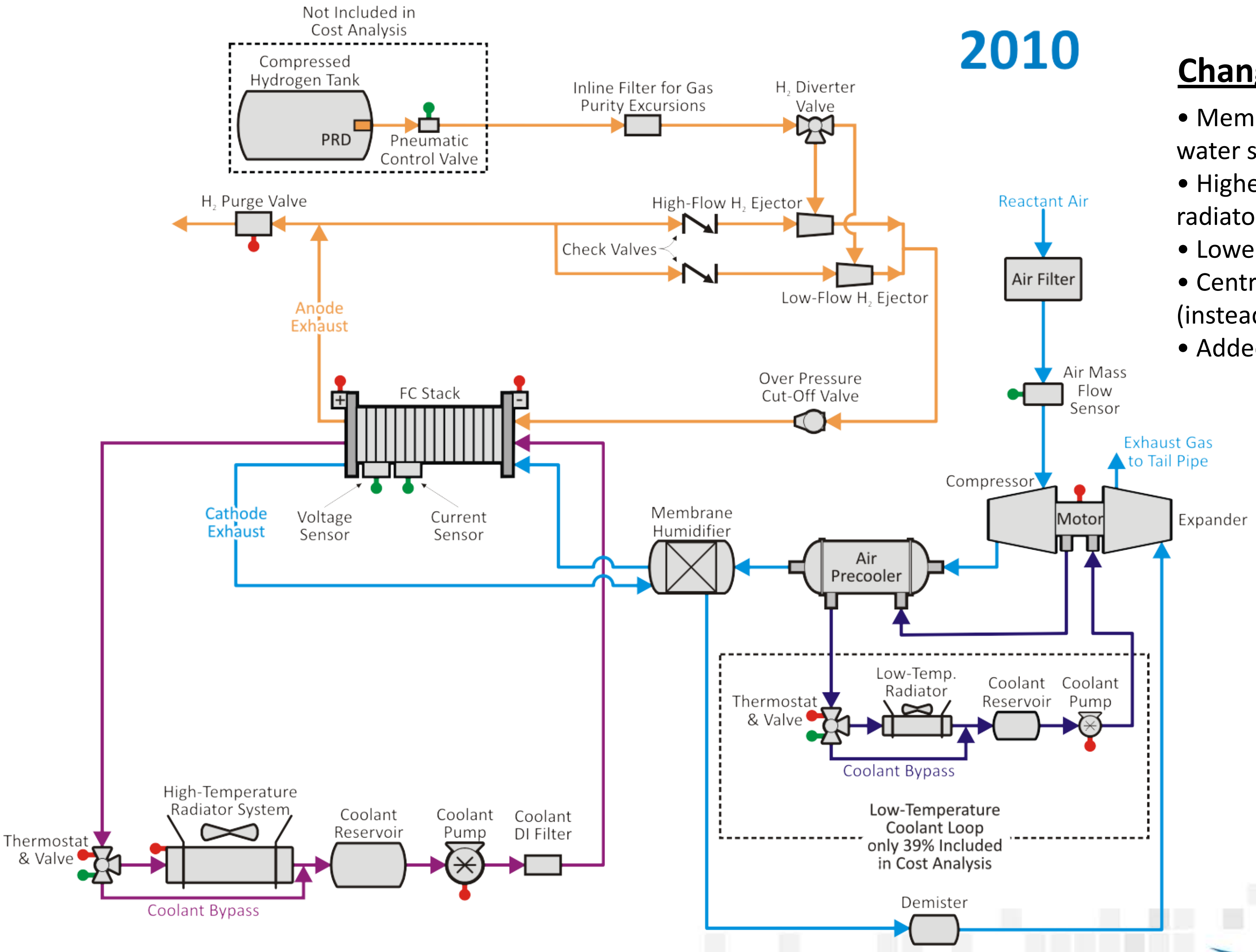

Changes since 2008:

- Membrane humidifier instead of water spray humidification
- Higher temperature, smaller radiators
- Lower pressure
- Centrifugal compressor/expander (instead of twin-lobe compressor)
- Added air precooler and demister

For printable schematics, see the "Additional Slides" at the end of the presentation

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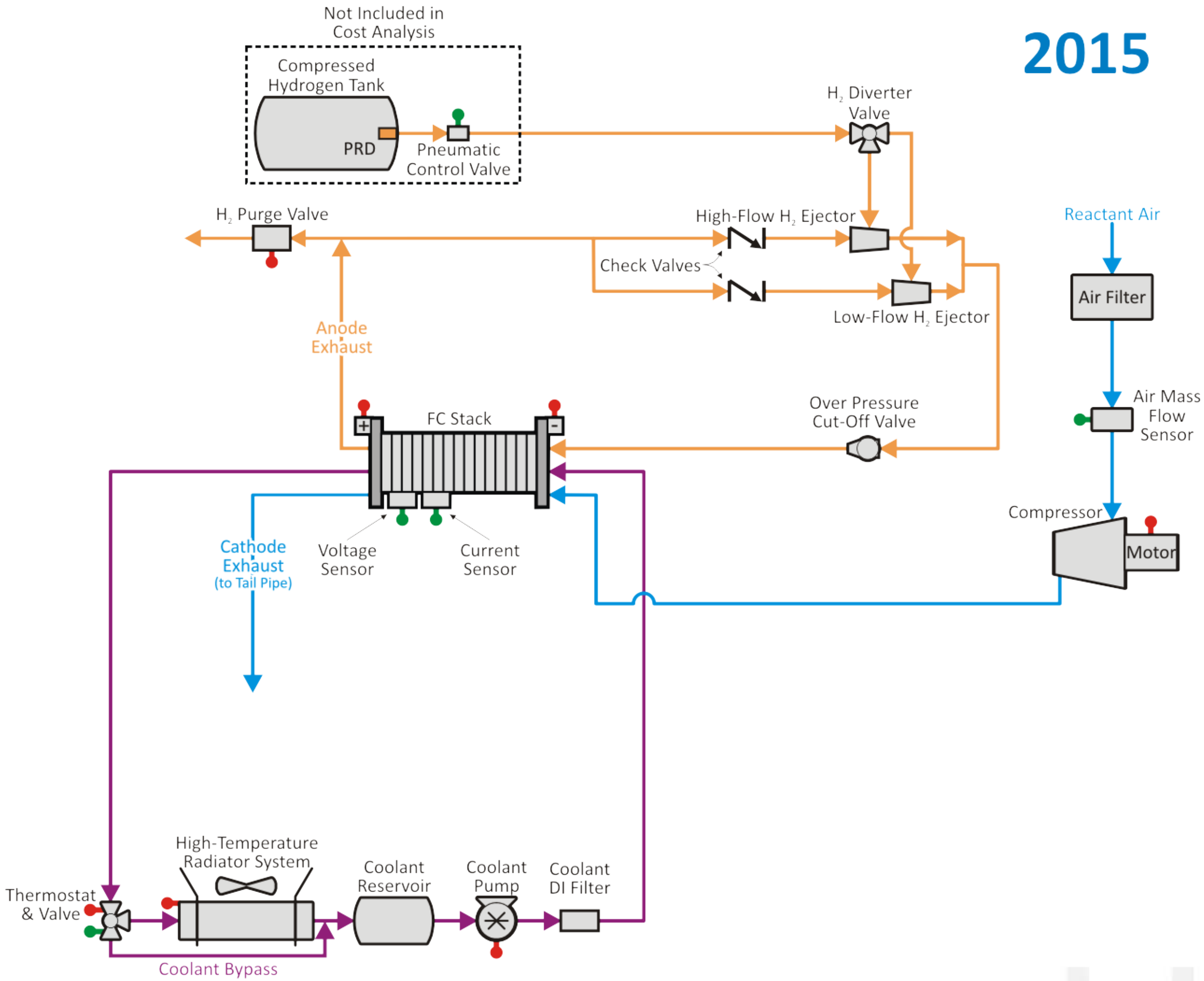


Changes since 2008:

- Membrane humidifier instead of water spray humidification
- Higher temperature, smaller radiator
- Lower pressure
- Centrifugal compressor/expander (instead of twin-lobe compressor)
- Added air precooler and demister

Changes for 2015:

- Higher temperature, smaller radiator
- No humidification
- Lower pressure
- Smaller compressor
- No expander

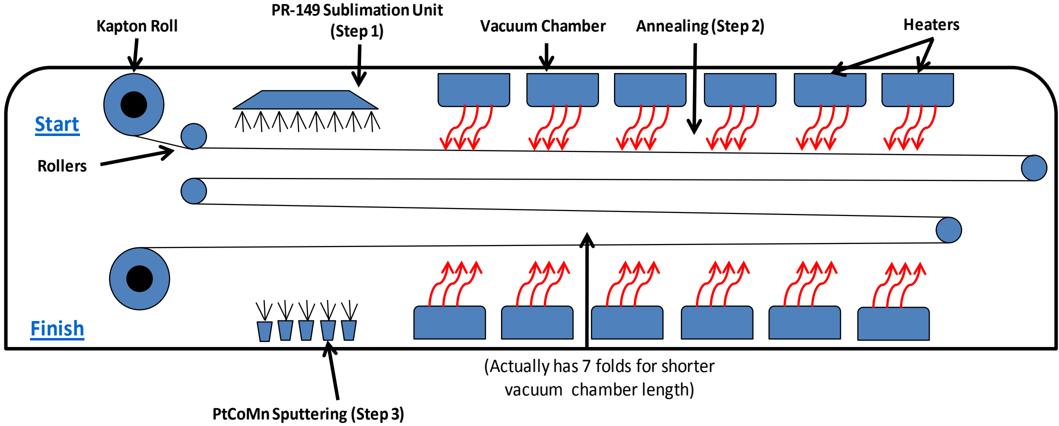
For printable schematics, see the "Additional Slides" at the end of the presentation

NanoStructured Thin Film (NSTF) Catalysts
New for 2009

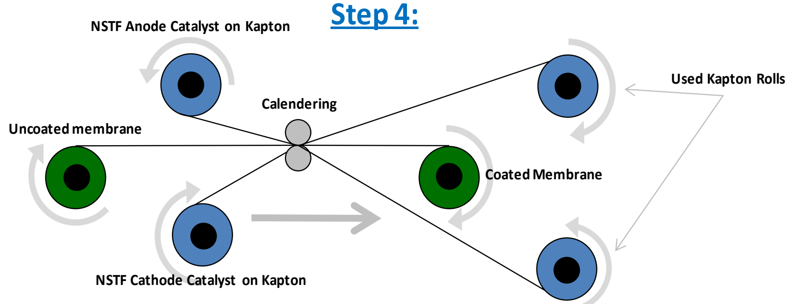
- DFMA® analysis conducted
- Process based on open-literature description of 3M process
- Assumptions discussed/vetted with 3M
- Cost results are consistent with 3M proprietary price projections
- 4-step roll-to-roll process:
  1) Sublimation of PR-149 (Perylene Red pigment 149) onto DuPont Kapton® polyimide web
  2) Vacuum annealing
  3) Platinum or metallic alloy is vapor deposited onto the crystalline nanostructures
  4) Roll-to-roll transfer of catalyst from Kapton® to membrane

- Capital cost is surprisingly low even for high capacity system

Steps 1-3:



Step 4:



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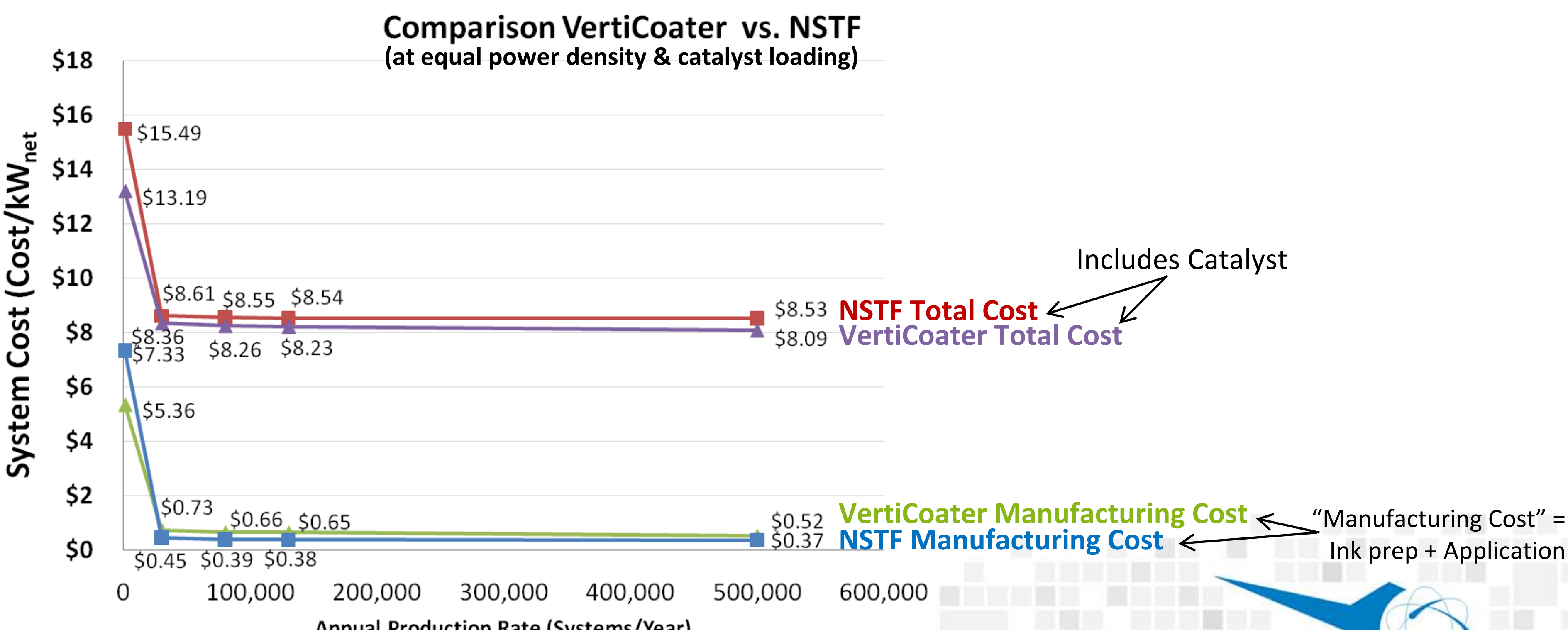
NanoStructured Thin Film (NSTF) Catalysts
New for 2009

Compared to VertiCoater method **(roller application method used in 2008 analysis):**

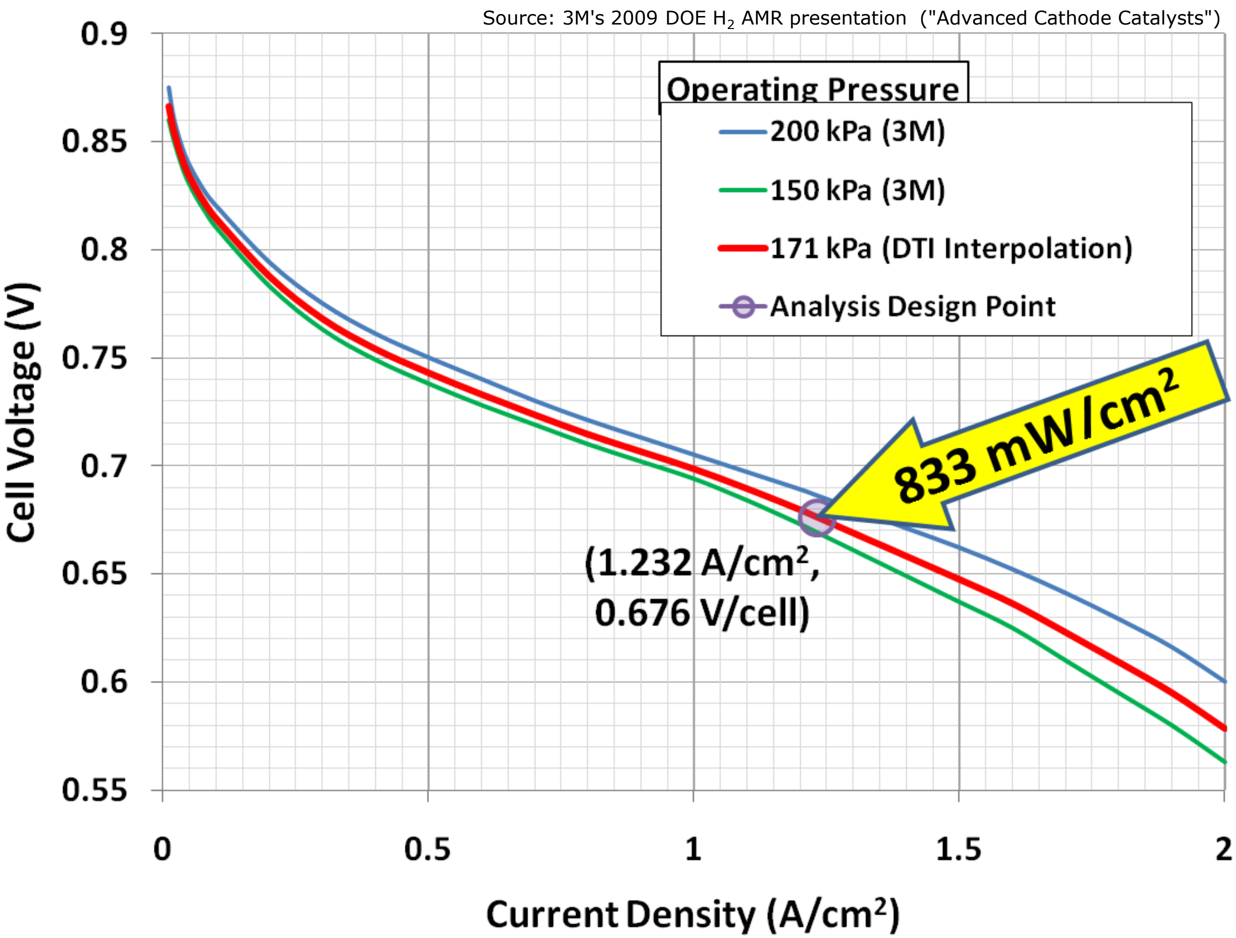
- The NSTF method assumes a PtCoMn ternary catalyst
- For a given power density & catalyst loading, the NSTF application method **($8.53/kW$_{net}$)** is slightly **more expensive** than previous **($8.09/kW$_{net}$)**
- However, NSTF catalyst *enables* the improved power density & catalyst loading used for 2009 & 2010 systems; yields a net **$10.28/kW$_{net}$** savings



Cell Performance based on Latest 3M Data

New for 2009

- For 2009, performance parameters switched from Tech Team specifications to latest 3M NSTF polarization data
- 3M: No change in performance between 2009 & 2010
- Design point selection:
  - **0.676 V/cell**
  - **171 kPa**
  - **833 mW/cm²**
  - **0.15 Pt/cm²** (anode + cathode)
  - **2.5** air stoichiometry
  - **67%** relative humidity
  - **80°C**
- This ensures consistency between our assumed performance and the components specified



Membrane Air Humidifier

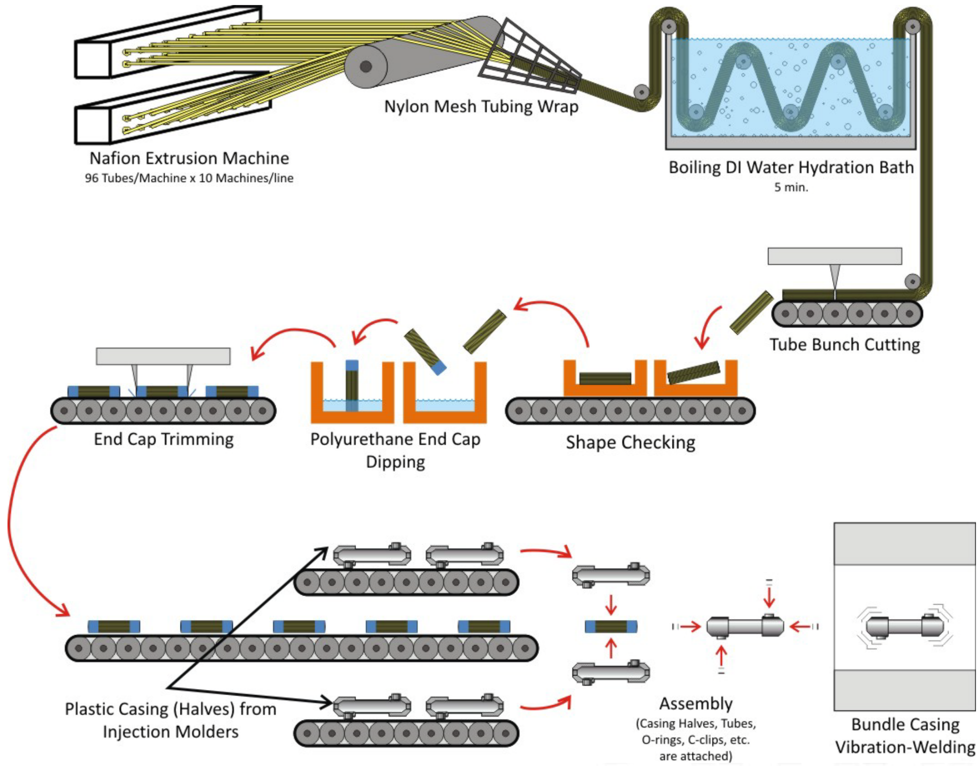
New for 2009

- **Sizing and materials based on membrane humidifier from Perma Pure, LLC**
- **Replaces water-spray humidification system used in 2008 analysis**

<u>**Manufacturing Assumptions:**</u>

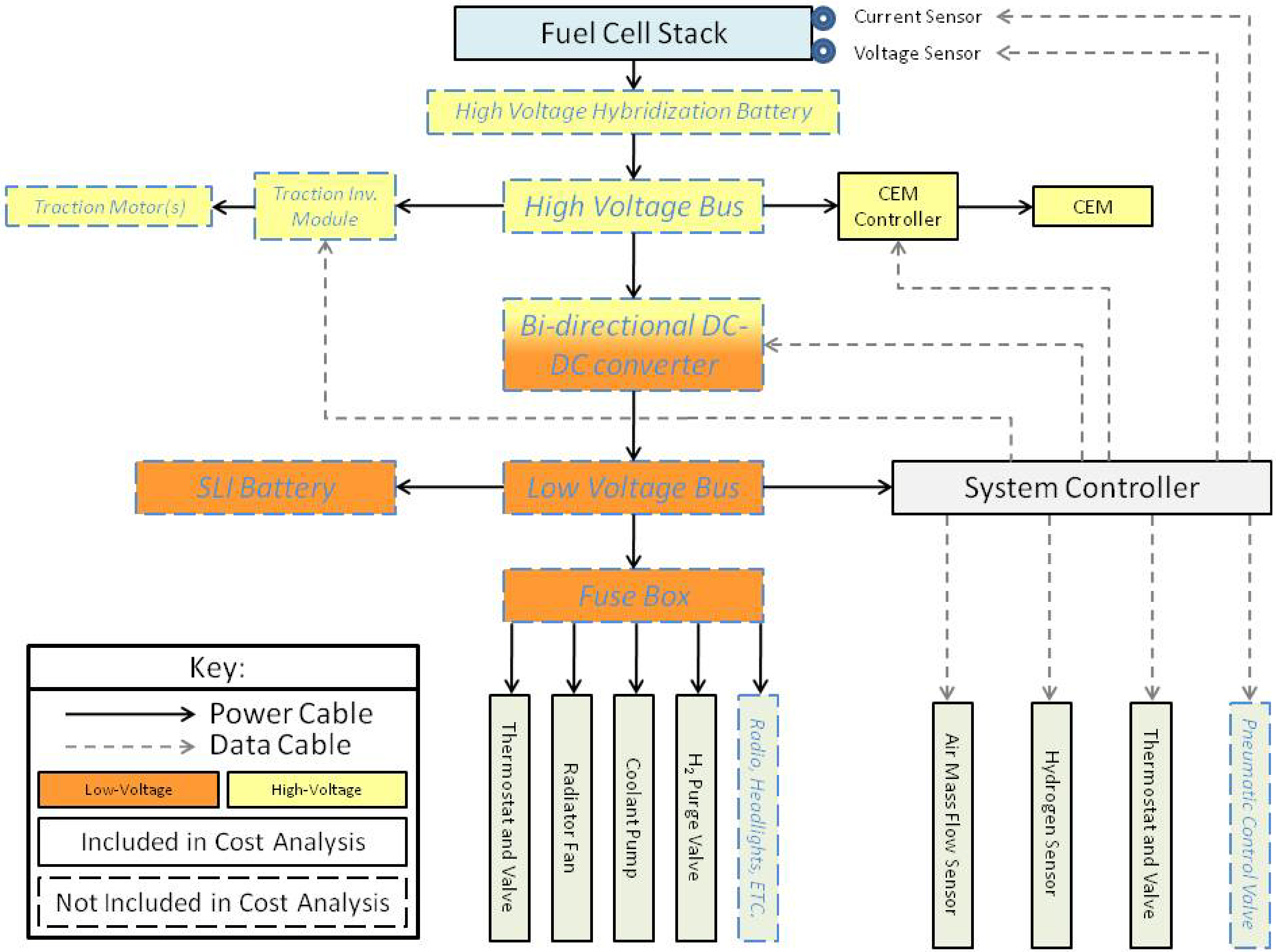
- Nafion® extrusion, 45 cm/min
- 5 minute DI water bath dwell time
- 30 second polyurethane end cap set time
- 30 second vibration welding time for casing

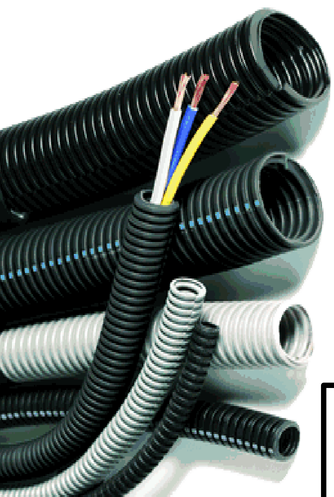
Membrane Humidifier Cost (500k systems/year):	**\$94.57 each** **$1.18/kW_{net}$**



Detailed Wiring Analysis

- Wiring examined in greater detail for 2010 update
- Power, amperage and length requirements carefully examined for each component
- Cable length determined by configuration layout
- Wire/connector pricing from waytekwire.com
- Reduction of **$0.84/kW$_{net}$** from 2009

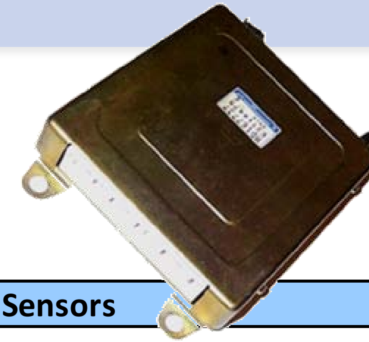




Wiring System Cost (500k systems/year): **$74.40** **$0.93/kW$_{net}$**

New System Controller (ECU) Analysis

Improved for 2010



- **New DFMA®-Style Analysis**
- **Comes from discussion and collaboration with DOE**
- **Reduces Cost of ECU by $1.70/kW$_{net}$ compared to previous cost estimate**

ECU Requirements	
Name	**Signal**
Inputs	
Air Mass Flow Sensor	Analog
H_2 Pressure Sensor (upstream of ejector)	Analog
H_2 Pressure Sensor (stack inlet manifold)	Analog
Air Pressure Sensor (after compressor)	Analog
Stack Voltage (DC bus)	Analog
Throttle Request	Analog
Current Sensors (drawn from motor)	Analog
Current Sensors (output from stack)	Analog
Signal for Coolant Temperature	Analog
H_2 Leak Detector	Digital
Outputs	
Signal to TIM	Analog
Signal to CEM	Analog
Signal to Ejector 1	PWM
Signal to Ejector 2	PWM
High Voltage System Relay	Digital
Signal to Coolant Pump	PWM
Signal to H_2 Purge Valve	Digital
Total Analog	**11**
Total Digital	**3**
Total PWM	**3**
Total Inputs/Outputs	**17**

Engine Control Unit (ECU) and Associated Sensors			
Component	**Description**	**Cost at 500k systems/year**	**Cost Basis**
Main Circuit Board	2 layer punchboard	$8.01	$5.34 for single layer of 6.5"x4.5" punchboard, Q=500, Assume 25% discount for Q=500K
Input Connector	Wire connector for inputs	$0.18	$0.23 each in Q=10k, reduced ~20% for Q=500k
Output Connector	Wire connector for outputs	$0.20	$0.23 each in Q=10k, reduced ~20% for Q=500k
Embedded Controller	25 MHz, 25 channel microprocessor board	$32.50	Digi-Key Part No. 336-1489-ND, $50@Q=1, assumed 35% reduction for Q=500k
Mosfets (17 total, 1 each per I/O)	P-channel, 2W, 49MOhm @5A, 10V	$3.74	Digi-Key Part No. 785-1047-2-ND, $0.2352@Q=3k,$0.2184@Q=12k
Misc. Board Elements	Capacitor, resistors, etc.	$4.25	Estimate based on $0.25 component for each input/output
Housing	Shielded plastic housing, watertight	$5.00	Estimate based on comparable shielded, electronic enclosures. Includes fasteners.
Assembly	Assembly of boards/housing	$5.83	Robotic assembly of approx. 50 parts at 3.5sec each, $2/min assembly cost.
Contingency	10% of all components	$5.97	Standard DFMA additional cost to capture unenumerated elements/activities.
Markup	25% of all Components	$16.42	Manufacturers Markup
ECU Subtotal		**$82.11**	
Current Sensor (for stack current)	~400A, Hall Effect transducer	$10.00	Based on LEM Automotive Current Transducer HAH1BV S/06, 400A.
Current Sensor (for motor current)	~400A, Hall Effect transducer	$10.00	Based on LEM Automotive Current Transducer HAH1BV S/06, 400A.
Voltage Sensor	225-335V	$8.00	Rough estimate based on a small Hall Effector sensor in series with a resistor
ECU + Sensors Total		**$110.11**	

ECU and Sensors Cost (500k systems/year): **$110.11** **$1.38/kW$_{net}$**

Interaction with Argonne National Laboratory

New for 2010

- **Key accomplishment has been collaboration/validation with Rajesh Ahuwalia at Argonne to validate our system designs**
  - **Added a demister**
    - **Removes liquid water from cathode stream before expander**
  - **Added a pre-cooler between air compressor & membrane humidifier**
    - **ANL analysis shows membrane humidifier works best with ~55°C input**
  - **Minor adjustments of operating parameters & assumptions**
  - **No major component or architectural changes**

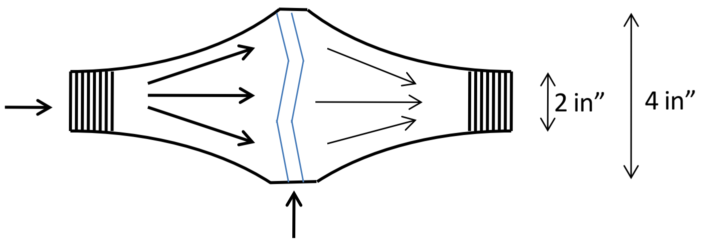
Pre-cooler ($0.73/$kW_{net}$)

WWW.FROZENBOOST.COM

Precooler Parameters				
System Pressure		1.5 atm	1.75 atm	2 atm
Air flow rate	g/s	85.5	87.5	88.4
Air temperature	°C	100	120	139
Heat duty	kW	4	5.4	6.9
Coolant flow rate	g/s	790	860	930
Coolant temperature	°C	50	55	60
Frontal area	cm^2	100	100	100
Depth	cm	9.3	12.5	12
Volume	L	4	4.5	4.4
Weight	kg	3.6	3.8	3.6

- Designed to reduce temp. of compressed air to 55 C before membrane humidifier, which could be damaged by high temp.
- Pre-cooler design based on liquid/air cross-flow pre-cooler design of frozenboost.com intercooler, sealed for heat duty
- 100% aluminum, 24 fins/inch

Demister ($0.08/$kW_{net}$)



- Removes water from cathode exhaust before inlet to expander
- Polypropylene housing with nylon mesh water filter
- Two ends of housing unscrew for filter replacement

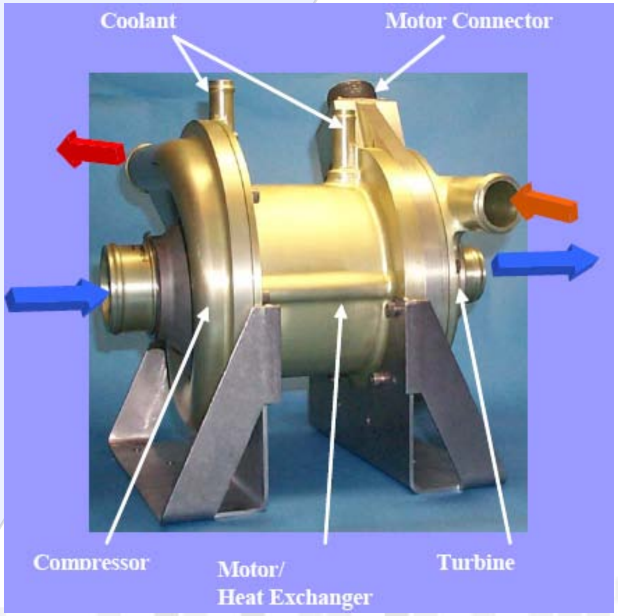
Detailed CEM Cost Study with Honeywell

New for 2009

- CEM = Compressor-Expander-Motor
- CEM has a large impact on total system cost:
  - **16.0%** of system cost (2010, 500k systems/year)
  - **6.5%** of gross power (2010, 500k systems/year)

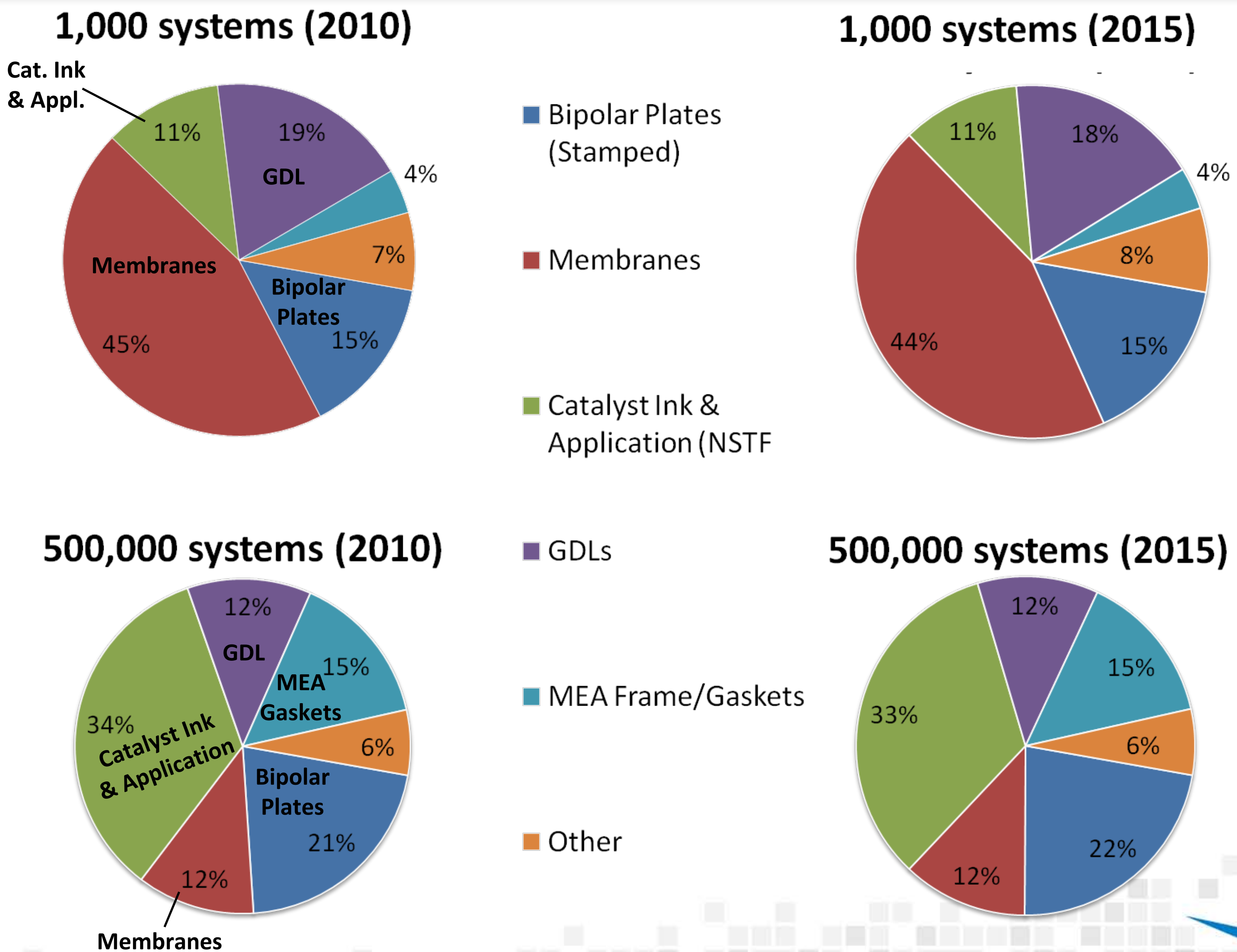
	Current (100k rpm)	Near Future (165k rpm)	Future (165k rpm)
With Expander	Design 1	Design 2 (2010 tech)	Design 3
Without Expander	Design 4	Design 5	Design 6 (2015 tech)

- Based on Honeywell CEM proprietary detailed design drawings and controller design
- Tailored to fit DTI system
- Developed 6 CEM configurations, plus the associated control electronics
- Analysis based on vendor quotes and DFMA®
  - 1k to 500k systems/year examined
- Updated for 2010 to scale with pressure & power requirements



		CEM			Motor Controller			
Design	Sys/year	Cost	Assembly	Markup	Cost	Assembly	Markup	
Design 2 Near-Future Turbocharger 165k rpm	1,000	$868.25	$23.00	15%	$408.92	$7.67	10%	$1,483.18
	30,000	$353.11			$340.11			$815.08
	80,000	$251.59			$328.94			$686.04
	130,000	$247.03			$314.23			$664.63
	500,000	$240.44			$303.39			$645.12

Stack Component Cost Distribution



- **Membrane** dominates cost at low production
- **Catalyst Ink** dominates cost at high production

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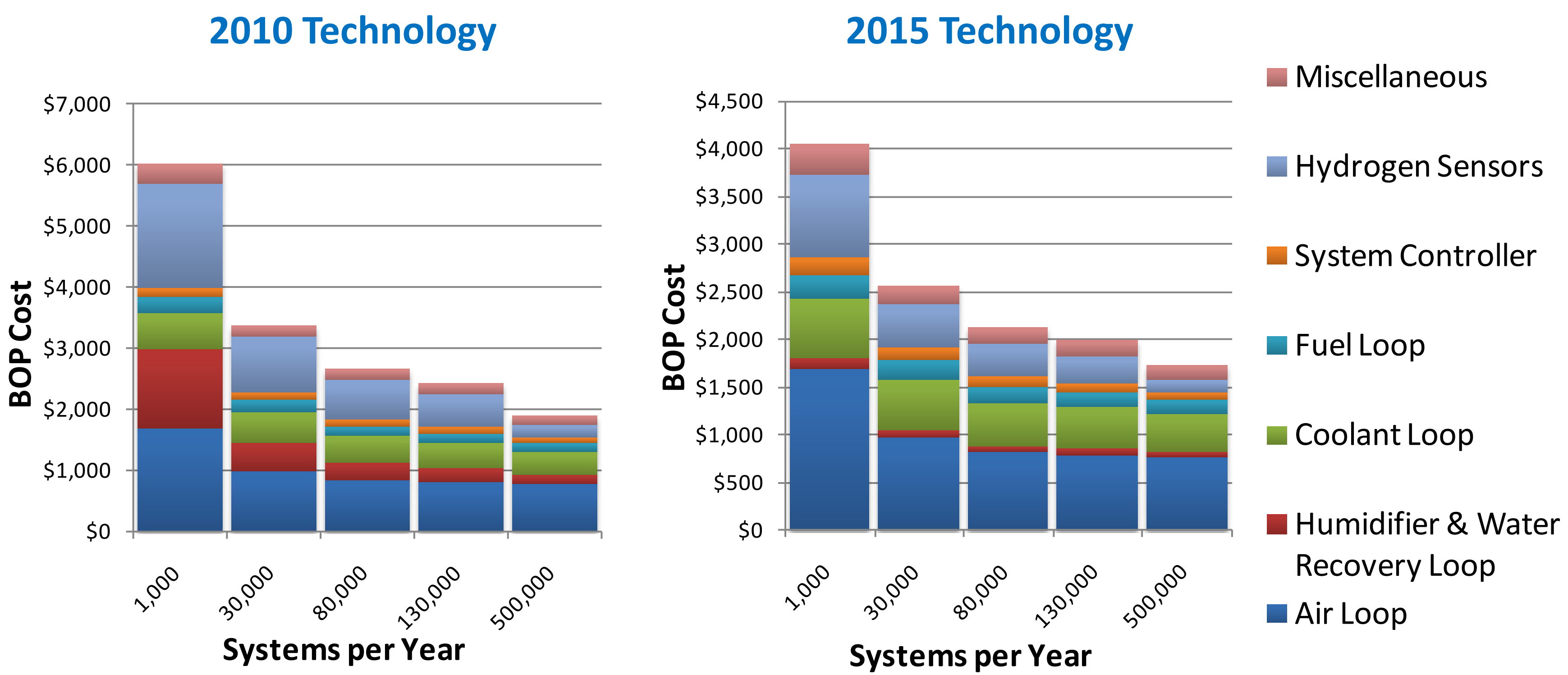
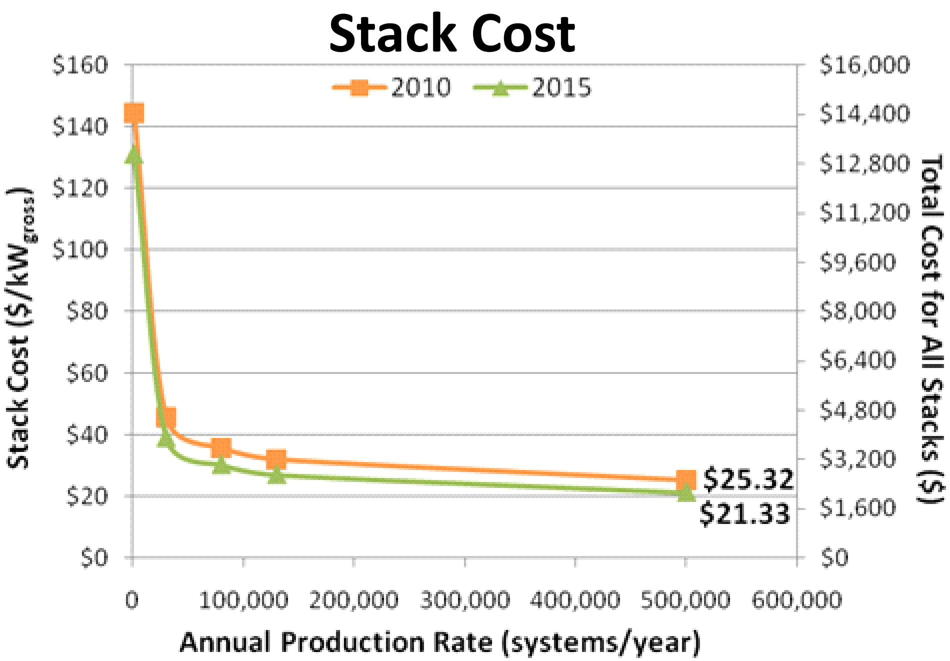
Balance of Plant

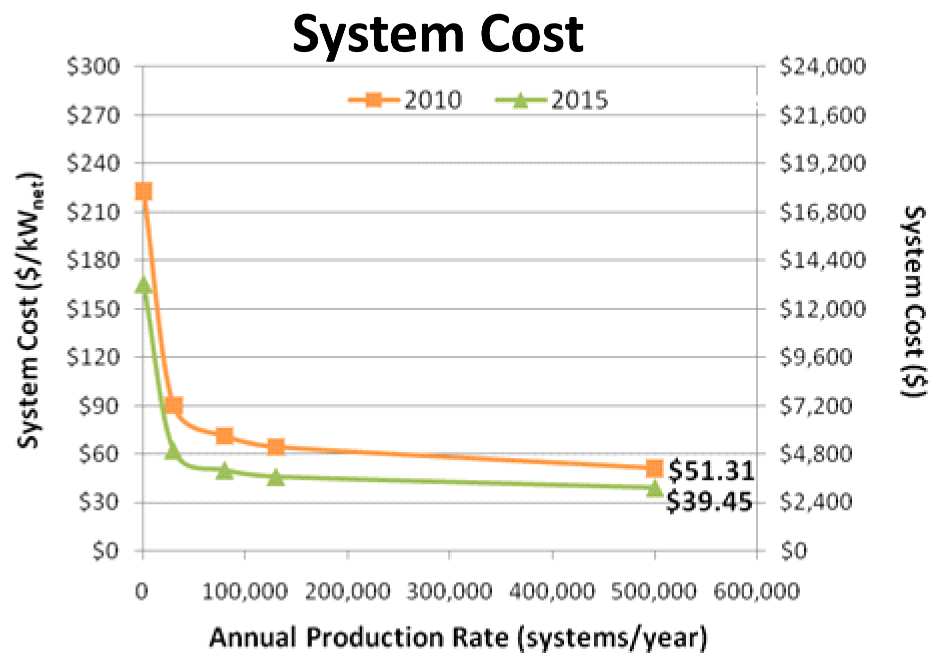


- Increases in manufacturing rate leads to largest savings.
- Air Compressors and Sensors are the two categories that have the largest $ decline, together yielding 70% of the BOP cost decline from low production to high production.

- Technology changes yield lesser BOP savings and comes in form of reduced/eliminated components.
- Simplifications of Air & Humidifier loops yield majority of technology improvement savings.

Stack & System Costs vs. Annual Production Rate





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

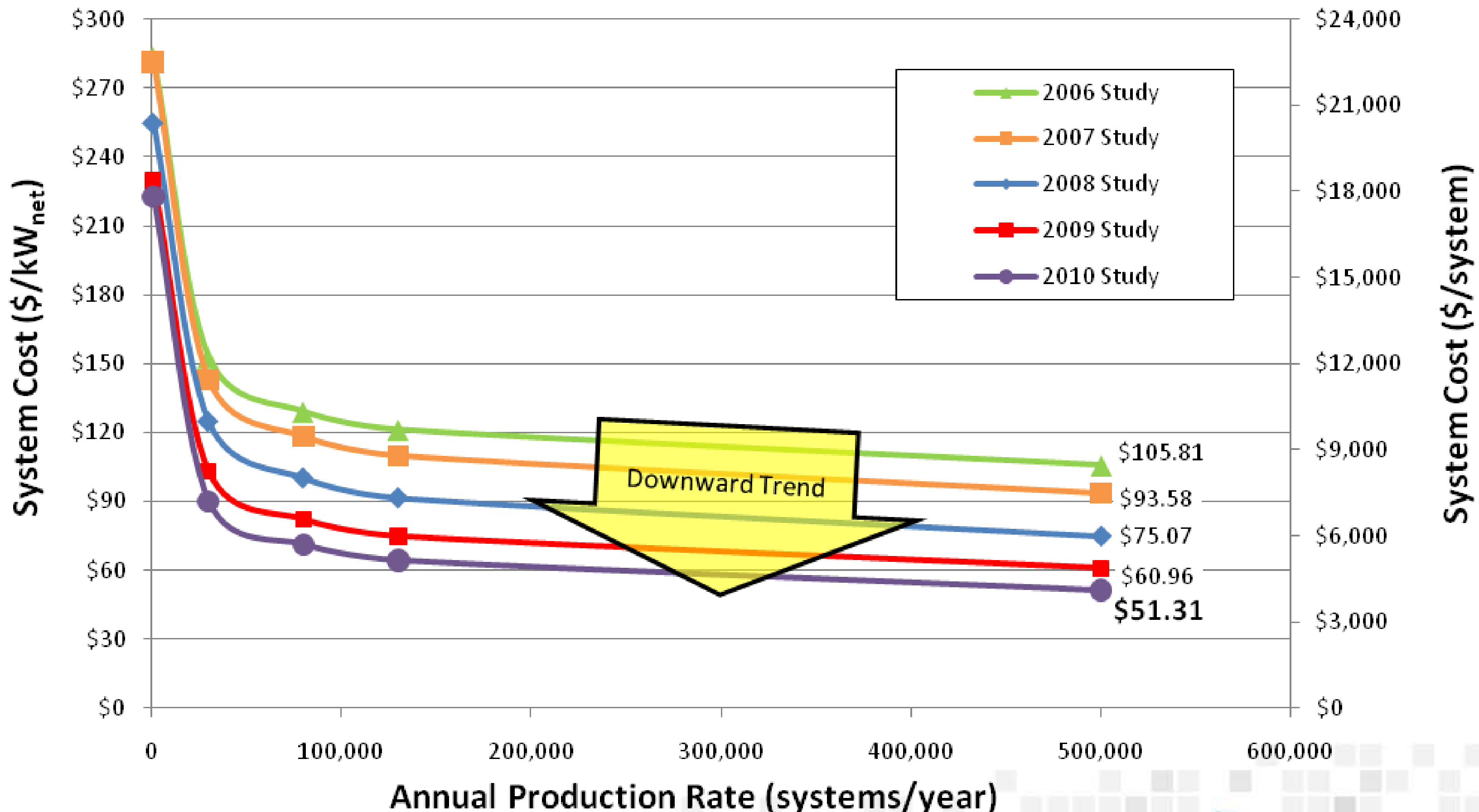
			2010	2015
DOE Target:	Stack Cost	$\$/kW_{e\,(net)}$	**$25**	**$15**
Study Estimate:	Stack Cost	$\$/kW_{e\,(net)}$	**$25**	**$21**
DOE Target:	System Cost	$\$/kW_{e\,(net)}$	**$45**	**$30**
Study Estimate:	System Cost	$\$/kW_{e\,(net)}$	**$51**	**$39**

2010 targets nearly met

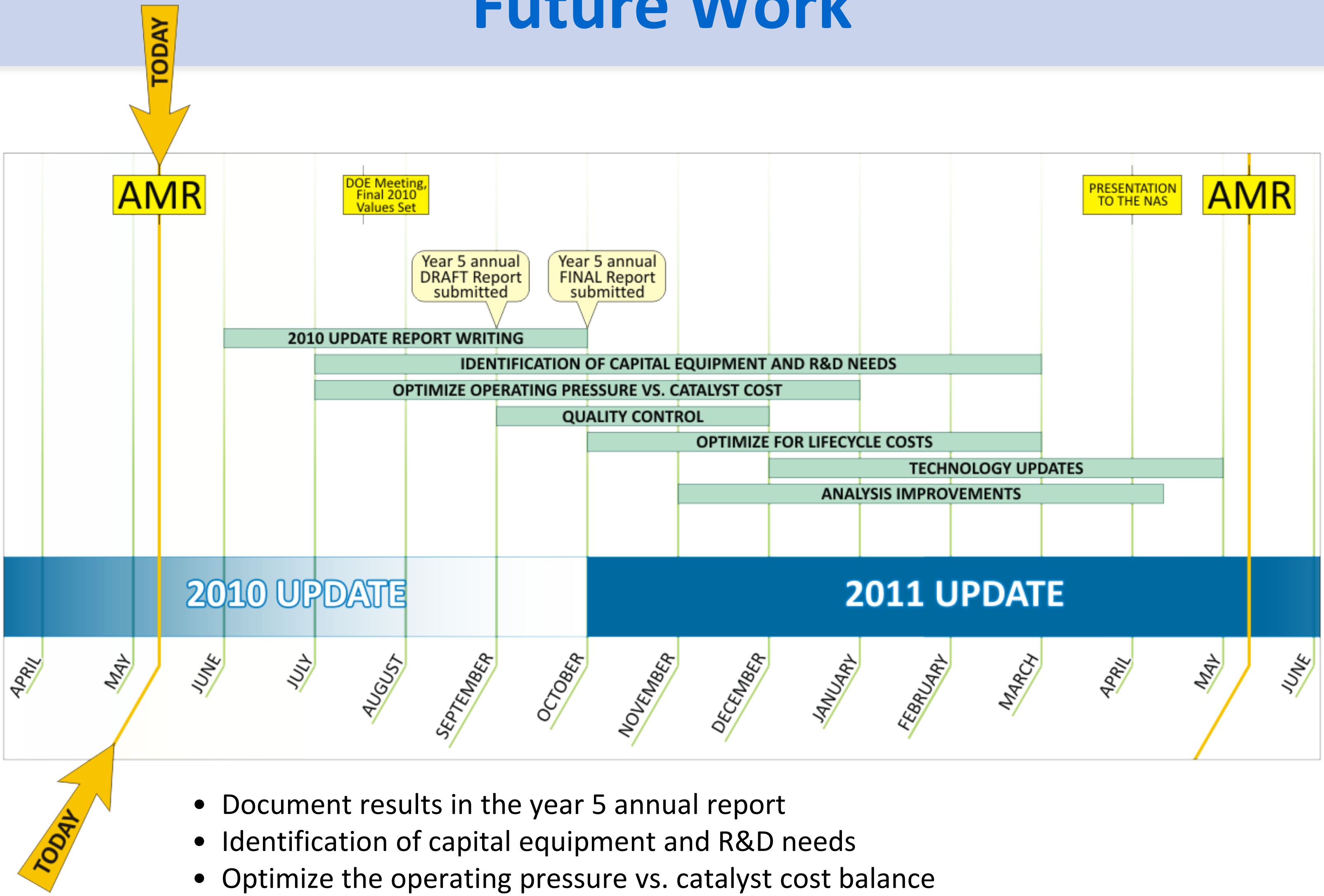
Progress in the Analysis

Since 2006:

The current technology cost projection has dropped by 52% (at 500,000 sys/year) due to a combination of technology improvement and analysis refinement



Future Work



- Document results in the year 5 annual report
- Identification of capital equipment and R&D needs
- Optimize the operating pressure vs. catalyst cost balance
- Enhance quality control analysis
- Perform lifecycle cost analysis

End of Presentation

Thank you.

Additional Slides

The following slides are provided for further clarification

DTI's DFMA®-Style Costing Methodology (Cont'd)

Machine Rate $/min * Annual Minutes of Equipment Operation → Manufacturing Machine Cost

Labor Rate, $/min * Annual Minutes of Labor → Manufacturing Labor Cost

Manufacturing Machine Cost + Manufacturing Labor Cost → **Manufacturing Cost**

Machine Rate, $/min * Annual Minutes of Equipment Operation → Assembly Machine Cost

Labor Rate, $/min * Annual Minutes of Labor → Assembly Labor Cost

Assembly Machine Cost + Assembly Labor Cost → **Assembly Cost**

Function of: Initial Tooling Cost, Refurbishment Cost, Cycles before refurbishment → Avg. Annual Tooling Cost/ Parts per Year → **Tooling Cost**

Function of: Part Dimensions, Trimming Losses → Sum of Materials Consumed → **Material Cost**

(**Manufacturing Cost** + **Assembly Cost** + **Tooling Cost** + **Material Cost**) * **Markup Factor** (as appropriate, see next page) = **Total Annual Cost**

Total Annual Cost / **Units per Year** = **Cost per Unit**

Markup Basics

- **Traditional automotive "markup" Includes:**
  - General & Administrative (G&A)
  - Research & Development (R&D)
  - Profit
  - Scrap

- **Markup are applied to each step of manufacture/assembly to appropriately compensate performer for legitimate incurred costs and for adding value.**

- **Many layers of markup are incurred if part/component passes through many entities on its way to final assembly**
  - Vertically integrated businesses will have fewer "markup costs" than horizontally integrated businesses

- **Different markup percentages are incurred if value is added rather than if component is just "passed through"**

Application of Markup

- **DTI cost study applies markup as follows:**
  - **No fuel cell system OEM markup is applied**
    - OEM is entity that sells final FC System (i.e. Ballard, UTC, GM, etc.)
  - **We assume vertical integration for fuel cell stack**
    - Stack is manufactured and assembled in-house by OEM
    - Thus there is no markup on stack manufacture and assembly
      - **Exception to Rule:** Membrane fabricated by Tier 1 Supplier so there is manufacturing markup to that supplier
  - **BOP components are purchased from vendors**
    - Thus there is manufacturing and component assembly markup to that supplier
  - **Purchased materials & components contain supplier markup**
  - **No markup is associated with the final system assembly**

Purchased Materials & Components

All materials and components listed in red are purchased from a tier 1 supplier, and thus include an ***implicit manufacturer markup***

Fuel Cell Stack

- Flow Plates (Stamping)
  - Stainless Steel 316L Sheet
- MEA
  - Membranes
    - ePTFE Substrate
    - Ionomer
  - GDLs
    - Macroporous Layer
      - Macroporous Substrate
      - PTFE
      - Solvent
        - Methanol
        - DI Water
    - Microporous Layer
      - Carbon Powder (Vulcan XC-72)
      - PTFE
      - Solvent
        - Methanol
        - DI Water
- End Gaskets
  - Type A Resin
- Endplates
  - Thermoset Resin (LYTEX 9063)
- Current Collectors
  - Copper Sheet
  - Copper Rod
- Compression Bands

Cost of membrane determined by DFMA® analysis. Assumed to be purchased from supplier so Tier 1 markups are applied.

Macroporous Substrate based on vendor quote with markup subtracted from quote to reflect OEM if made by OEM.

Balance of Plant

- Mounting Frames
  - [All Sub-Components]
- Air Loop
  - Air Compressor, Expander, Motor
    - [All Sub-Components]
  - [All Other Sub-Components]
- Humidifier & Water Recovery Loop
  - Air Humidifier Assembly
    - [All Sub-Components]
  - [All Other Sub-Components]
- Coolant Loop
  - [All Sub-Components]
- Fuel Loop
  - [All Sub-Components]
- System Controller/Sensors
  - [All Sub-Components]
- Miscellaneous BOP
  - Wiring
    - [All Sub-Components]
  - Belly Pan
    - [All Sub-Components]
  - [All Other Sub-Components]

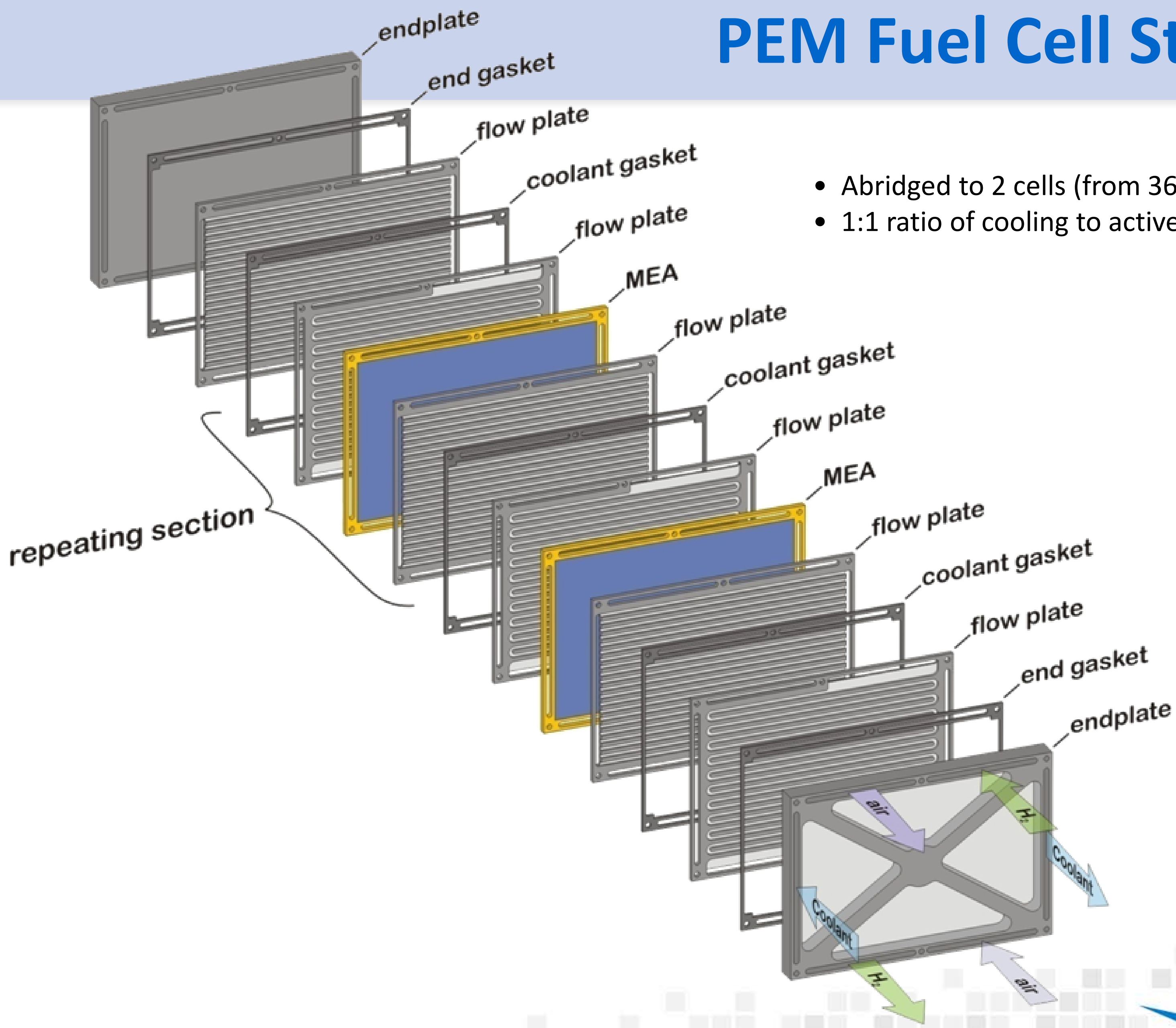
Detailed Wiring Costs

		2010				2015				2030			
Component	Type	Length (m)	Quantity	Cable Total	Connector Total	Length (m)	Quantity	Cable Total	Connector Total	Length (m)	Quantity	Cable Total	Connector Total
CEM	Power Cable, 7 Gauge	0.5	1	$1.64	$1.38	0.5	1	$1.64	$1.38	0.5	1	$1.64	$1.38
CEM Controller	Data Cable, 16 Gauge	0.5	1	$0.28	$2.00	0.5	1	$0.28	$2.00	0.5	1	$0.28	$2.00
Air Mass Flow Sensor	Data Cable, 16 Gauge	0.5	1	$0.28	$2.00	0.5	1	$0.28	$2.00	0.5	1	$0.28	$2.00
HTL Coolant Pump	Power Cable, 7 Gauge	1	1	$3.27	$1.38	1	1	$3.27	$1.38	1	1	$3.27	$1.38
HTL Thermostat and Valve	Power Cable, 12 Gauge	1	1	$0.56	$2.00	1	1	$0.56	$2.00	1	1	$0.56	$2.00
HTL Thermostat and Valve	Data Cable, 16 Gauge	1	1	$0.56	$2.00	1	1	$0.56	$2.00	1	1	$0.56	$2.00
HTL Radiator Fan	Power Cable, 7 Gauge	1	1	$3.27	$1.38	1	1	$3.27	$1.38	1	1	$3.27	$1.38
LTL Coolant Pump	Power Cable, 7 Gauge	1	1	$3.27	$1.38	1	0	$0.00	$0.00	1	0	$0.00	$0.00
LTL Thermostat and Valve	Power Cable, 12 Gauge	1	1	$0.56	$2.00	1	0	$0.00	$0.00	1	0	$0.00	$0.00
LTL Thermostat and Valve	Data Cable, 16 Gauge	1	1	$0.56	$2.00	1	0	$0.00	$0.00	1	0	$0.00	$0.00
H_2 Pressure Relief Device	Data Cable, 16 Gauge	1	1	$0.56	$2.00	1	1	$0.56	$2.00	1	1	$0.56	$2.00
Pressure Switch	Data Cable, 16 Gauge	1	1	$0.56	$2.00	1	1	$0.56	$2.00	1	0	$0.00	$0.00
H_2 Purge Valve	Power Cable, 12 Gauge	1	1	$0.56	$2.00	1	1	$0.56	$2.00	1	1	$0.56	$2.00
System Controller	Power Cable, 6 Gauge	0.25	1	$1.04	$1.38	0.25	1	$1.04	$1.38	0.25	1	$1.04	$1.38
H_2 Sensors	Data Cable, 16 Gauge	1	2	$1.12	$4.00	1	0	$0.00	$0.00	1	0	$0.00	$0.00
Current Collectors	Power Cable, OOOO Gauge	0.25	2	$8.32	$23.44	0.25	2	$8.32	$23.44	0.25	2	$8.32	$23.44
Stack Current Sensor	Data Cable, 16 Gauge	1	1	$0.56	$2.00	1	1	$0.56	$2.00	1	1	$0.56	$2.00
Stack Voltage Sensor	Data Cable, 16 Gauge	1	1	$0.56	$2.00	1	1	$0.56	$2.00	1	1	$0.56	$2.00
Total ($)		**16.25**	**20**	**$27.52**	**$56.34**	**11.25**	**15**	**$22.01**	**$46.96**	**12.25**	**16**	**$22.57**	**$48.96**
Total ($/kW$_{net}$)				**$0.34**	**$0.70**			**$0.28**	**$0.59**			**$0.28**	**$0.61**

Cable Type	Cost ($/m)	Connector Cost	Max Current (A)	Material
Data Cable, 16 Gauge	$0.56	$1.00	3.7	Copper
Power Cable, 6 Gauge	$4.15	$0.69	37	Copper
Power Cable, 7 Gauge	$3.27	$0.69	30	Copper
Power Cable, 12 Gauge	$0.67	$0.94	9.3	Copper
Power Cable, OOOO Gauge	$16.64	$5.86	302	Copper

- Total cost of **$1.04/kW$_{net}$** for 2010 analysis
- Down from **$1.77/kW$_{net}$** in 2009 analysis
- Wire fasteners add **0.19/kW$_{net}$** (and are bookkept under Wire/Tube/Pipe Fastener category)

PEM Fuel Cell Stack



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

Bill of Materials: Stack (2010 Technology)

	2010				
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)	87.91	87.91	87.91	87.91	87.91
Bipolar Plates (Stamped)	$1,684.28	$434.15	$439.95	$433.03	$429.07
MEAs					
Membranes	$5,184.51	$908.84	$562.23	$438.23	$230.78
Catalyst Ink & Application (NSTF)	$1,252.28	$700.37	$695.57	$698.62	$694.83
GDLs	$2,140.33	$1,111.35	$691.53	$537.04	$242.57
M & E Hot Pressing	$72.09	$9.98	$8.23	$8.36	$8.16
M & E Cutting & Slitting	$56.94	$4.42	$3.29	$3.02	$2.82
MEA Frame/Gaskets	$469.80	$319.59	$311.95	$308.29	$301.42
Coolant Gaskets (Laser Welding)	$185.48	$26.48	$29.43	$27.39	$25.54
End Gaskets (Screen Printing)	$149.48	$5.08	$1.97	$1.25	$0.54
End Plates	$87.43	$33.55	$28.91	$26.21	$19.86
Current Collectors	$16.79	$7.18	$5.99	$5.54	$5.07
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
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	$11,556.43	$3,663.54	$2,867.17	$2,567.50	$2,025.76
Total Stack Cost ($/$kW_{net}$)	$144.46	$45.79	$35.84	$32.09	$25.32
Total Stack Cost ($/$kW_{gross}$)	$131.46	$41.67	$32.62	$29.21	$23.04

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

Bill of Materials: Stack (2015 Technology)

	2015				
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)	87.27	87.27	87.27	87.27	87.27
Bipolar Plates (Stamped)	$1,634.29	$386.30	$392.11	$385.17	$380.72
MEAs					
Membranes	$4,657.35	$827.11	$507.81	$394.04	$204.21
Catalyst Ink & Application (NSTF)	$1,134.71	$578.48	$573.71	$572.51	$569.63
GDLs	$1,853.85	$916.89	$565.27	$440.78	$196.86
M & E Hot Pressing	$71.29	$6.83	$6.54	$5.94	$5.95
M & E Cutting & Slitting	$56.55	$3.90	$2.76	$2.50	$2.19
MEA Frame/Gaskets	$403.76	$263.06	$256.85	$253.61	$248.04
Coolant Gaskets (Laser Welding)	$184.80	$26.26	$24.78	$24.44	$23.90
End Gaskets (Screen Printing)	$149.48	$5.08	$1.97	$1.25	$0.53
End Plates	$77.96	$27.02	$23.58	$21.51	$16.46
Current Collectors	$15.08	$6.24	$5.16	$4.77	$4.36
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Assembly	$76.12	$40.69	$34.95	$33.62	$32.06
Stack Conditioning	$166.06	$35.11	$27.72	$24.98	$16.84
Total Stack Cost	$10,491.30	$3,130.97	$2,429.21	$2,170.63	$1,706.73
Total Stack Cost ($/kW$_{net}$)	$131.14	$39.14	$30.37	$27.13	$21.33
Total Stack Cost ($/kW$_{gross}$)	$120.21	$35.87	$27.83	$24.87	$19.56

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

Bill of Materials: Balance of Plant (2010 Technology)

	2010				
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)	87.91	87.91	87.91	87.91	87.91
Air Loop	$1,695.29	$990.72	$830.17	$802.46	$770.35
Humidifier and Water Recovery Loop	$1,297.97	$468.31	$309.37	$251.89	$158.70
High-Temperature Coolant Loop	$564.28	$478.15	$409.86	$387.20	$356.91
Low-Temperature Coolant Loop	$82.55	$73.70	$68.30	$64.50	$60.56
Fuel Loop	$251.94	$198.65	$170.49	$163.40	$152.96
System Controllers	$171.07	$136.85	$102.64	$95.80	$82.11
Sensors	$1,706.65	$893.00	$659.96	$543.45	$225.49
Miscellaneous	$336.34	$198.75	$176.07	$169.43	$161.32
Total BOP Cost	$6,106.09	$3,438.13	$2,726.86	$2,478.12	$1,968.41
Total BOP Cost ($/kW$_{net}$)	$76.33	$42.98	$34.09	$30.98	$24.61
Total BOP Cost ($/kW$_{gross}$)	$69.46	$39.11	$31.02	$28.19	$22.39

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

Bill of Materials: Balance of Plant (2015 Technology)

	2015				
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)	87.27	87.27	87.27	87.27	87.27
Air Loop	$1,318.59	$786.05	$651.31	$628.59	$604.72
Humidifier and Water Recovery Loop	$0.00	$0.00	$0.00	$0.00	$0.00
High-Temperature Coolant Loop	$582.52	$493.84	$423.56	$400.06	$368.65
Low-Temperature Coolant Loop	$0.00	$0.00	$0.00	$0.00	$0.00
Fuel Loop	$233.74	$180.46	$152.29	$145.20	$134.76
System Controllers	$171.07	$136.85	$102.64	$95.80	$82.11
Sensors	$28.00	$28.00	$28.00	$28.00	$28.00
Miscellaneous	$305.05	$172.38	$151.94	$145.88	$139.15
Total BOP Cost	$2,638.97	$1,797.59	$1,509.74	$1,443.53	$1,357.39
Total BOP Cost ($/kW$_{net}$)	$32.99	$22.47	$18.87	$18.04	$16.97
Total BOP Cost ($/kW$_{gross}$)	$30.24	$20.60	$17.30	$16.54	$15.55

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

Bill of Materials: System (2010 Technology)

	2010				
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)	87.91	87.91	87.91	87.91	87.91
Fuel Cell Stacks	$11,556.43	$3,663.54	$2,867.17	$2,567.50	$2,025.76
Balance of Plant	$6,106.09	$3,438.13	$2,726.86	$2,478.12	$1,968.41
System Assembly & Testing	$157.17	$112.84	$110.91	$111.05	$110.67
Total System Cost	$17,819.70	$7,214.51	$5,704.94	$5,156.67	$4,104.85
Total System Cost ($/kW$_{net}$)	$222.75	$90.18	$71.31	$64.46	$51.31
Total System Cost ($/kW$_{gross}$)	$202.71	$82.07	$64.90	$58.66	$46.69

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

Bill of Materials: System (2015 Technology)

	2015				
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)	87.27	87.27	87.27	87.27	87.27
Fuel Cell Stacks	$10,491.30	$3,130.97	$2,429.21	$2,170.63	$1,706.73
Balance of Plant	$2,638.97	$1,797.59	$1,509.74	$1,443.53	$1,357.39
System Assembly & Testing	$130.55	$93.72	$92.12	$92.24	$91.92
Total System Cost	$13,260.83	$5,022.28	$4,031.07	$3,706.40	$3,156.04
Total System Cost ($/kW$_{net}$)	$165.76	$62.78	$50.39	$46.33	$39.45
Total System Cost ($/kW$_{gross}$)	$151.94	$57.55	$46.19	$42.47	$36.16

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