Fuel Cell Transportation Cost Analysis

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Project ID #FC018

Overview

Timeline

- Project start date: 9/30/11
- Project end date: 9/30/16
- % complete: 40% (year 3 of 5)

Budget

- Total Funding Spent*: $437k
  - **SA: $348K**
  - **ANL: $55K**
  - **NREL: $34k**
- Total project funding value:
  - **$1M** (includes FFRDC)

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

- Project Lead: Strategic Analysis Inc.
- Argonne National Laboratory (ANL)
- National Renewable Energy Laboratory (NREL)

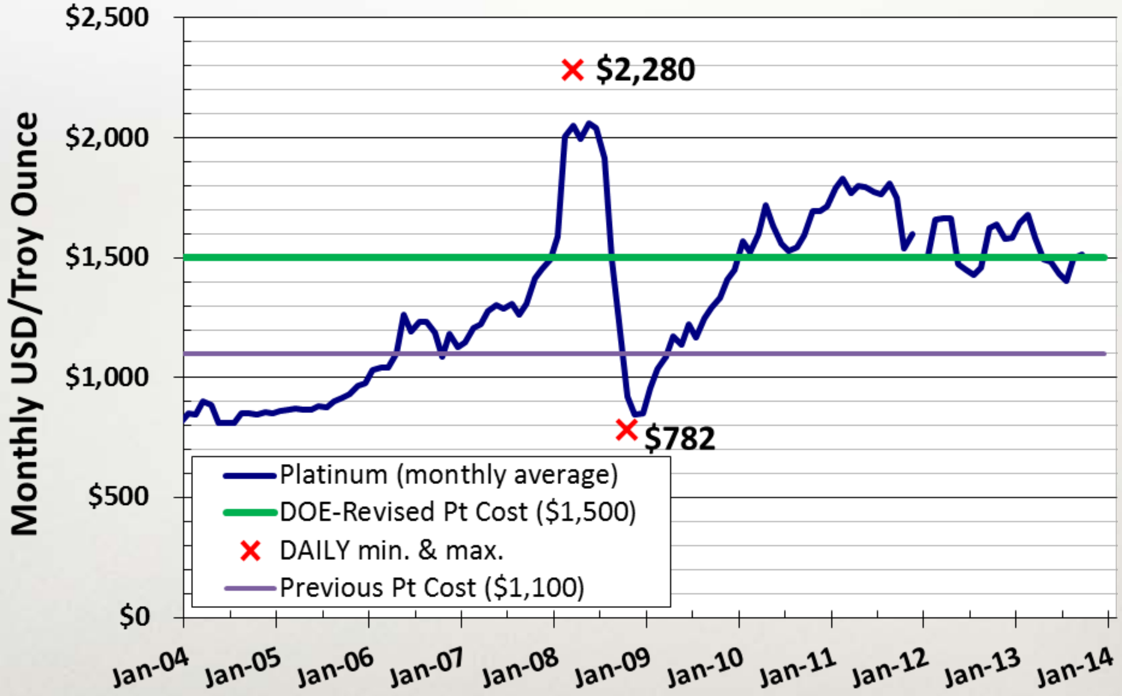
* As of 3/31/2014

Outline of Activities Since Last Year

- **Completion of 2013 Automotive & Bus Power Systems Cost Report** (only some changes implemented before 2013 AMR)
  - Updated ANL PEM polarization performance
  - Modelled plate Frame Membrane Humidifier (instead of tubular humid.)
  - Modelled Twin Lobe Air Compressor for bus (Eaton-style)
  - Updated Platinum (Pt) cost from $1,100/troy ounce (tr. Oz.) to $1,500/tr. Oz.
  - Imposed a heat loss constraint ($Q/\Delta T$) and re-optimization for low cost
  - Conducted side examinations:
    - Gore Inc. low-cost Membrane Electrode Assembly (MEA) fabrication cost analysis
    - Automotive Twin Lobe Air Compressor (Eaton-style)
- **Examination of Alternative Catalyst System**
  - De-alloyed Platinum-Nickel-Carbon (PtNiC) catalyst (Based on Johnson Matthey approach)
- **Review of Nano Structured Thin Film (NSTF) Pt-Co-Mn Catalyst Polarization Performance**

For 2013: Platinum Cost Adjusted to $1,500/tr. oz. to align with Market changes

		Pt Cost ($1,100/tr.oz.)						Pt Cost ($1,500/tr.oz.)					
Production Rate (Sys/yr)		1,000	10,000	30,000	80,000	100,000	500,000	1,000	10,000	30,000	80,000	100,000	500,000
Stack Cost	$/stack	$14,109	$4,055	$2,968	$2,416	$2,338	$1,909	$14,368	$4,312	$3,224	$2,672	$2,594	$2,164
	$/kWnet	$176.36	$50.69	$37.10	$30.20	$29.22	$23.86	$179.60	$53.90	$40.31	$33.40	$32.42	$27.05
System Cost	$/system	*$22,167*	*$8,031*	*$6,450*	*$5,298*	*$5,079*	*$4,131*	$22,426	$8,287	$6,706	$5,554	$5,335	$4,387
	$/kWnet	$277.09	$100.38	$80.62	$66.22	$63.49	$51.64	$280.33	$103.58	$83.82	$69.42	$66.68	$54.83



Higher Pt Cost adds about $3/kW to 2013 system cost.

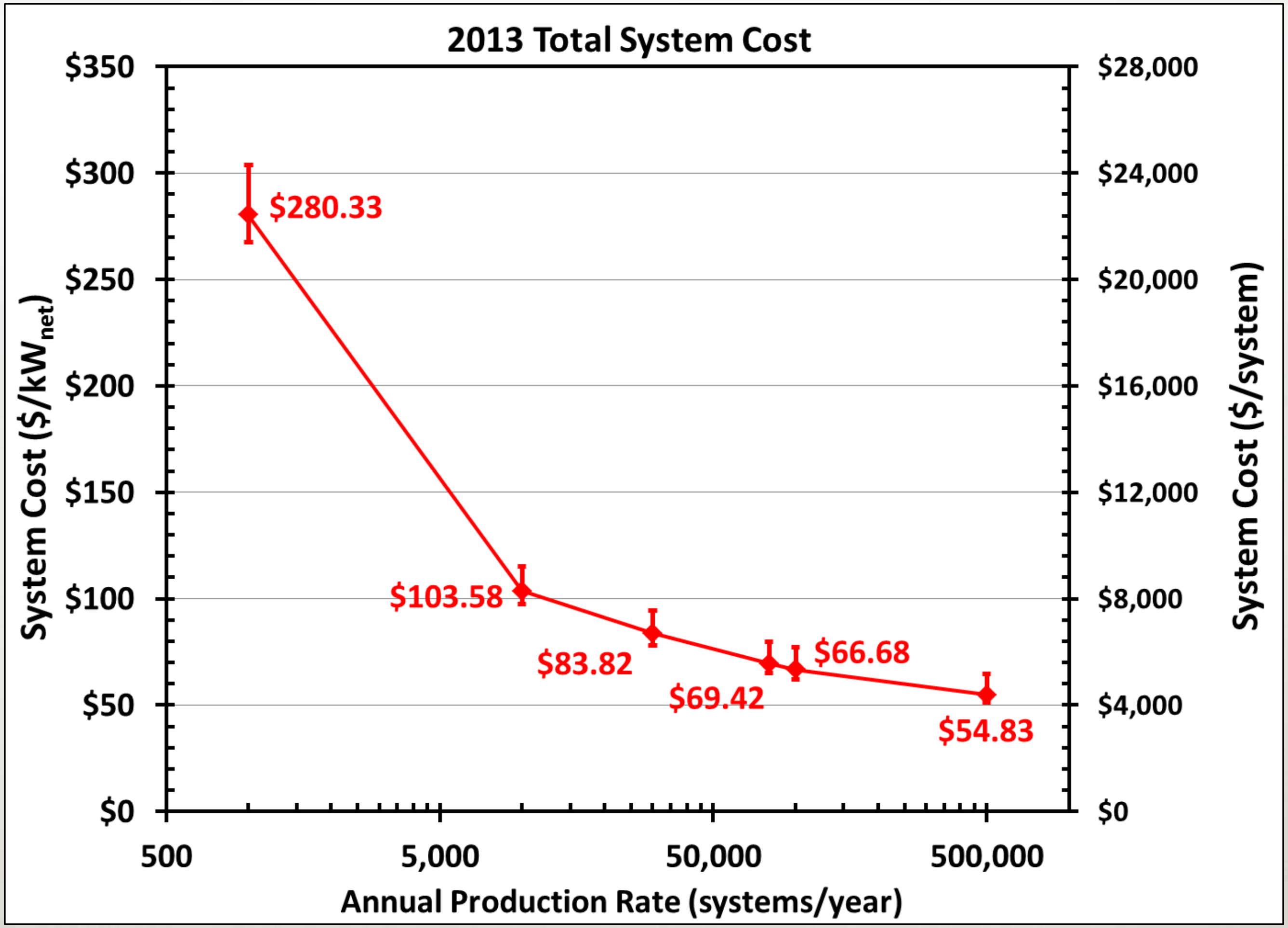
For 2013: Heat loss constraint imposed based on limiting car radiator's $Q/\Delta T$

- **Q = Radiator heat rejection duty**
  - accounts for temperatures of inlet/outlet streams, stack efficiency, and extent of liquid product water production
- **ΔT = Temperature difference**
  - difference between the stack coolant exit temperature (92.3°C) and worst case ambient air (40°C)
- **$Q/\Delta T$ is a measure of radiator size.**
  - Radiator frontal surface area is limited by vehicle frame.
  - Depth of radiator is limited by pressure drop across radiator core(s)
- **Previous assumptions exceeded the DOE 2017 Target of $Q/\Delta T<1.45$.**
  - 2012 $Q/\Delta T \sim 1.7$
- **$Q/\Delta T$ now computed by Argonne National Lab (ANL) performance model**

Imposition of $Q/\Delta T$ limits adds about $3/kW to system cost.

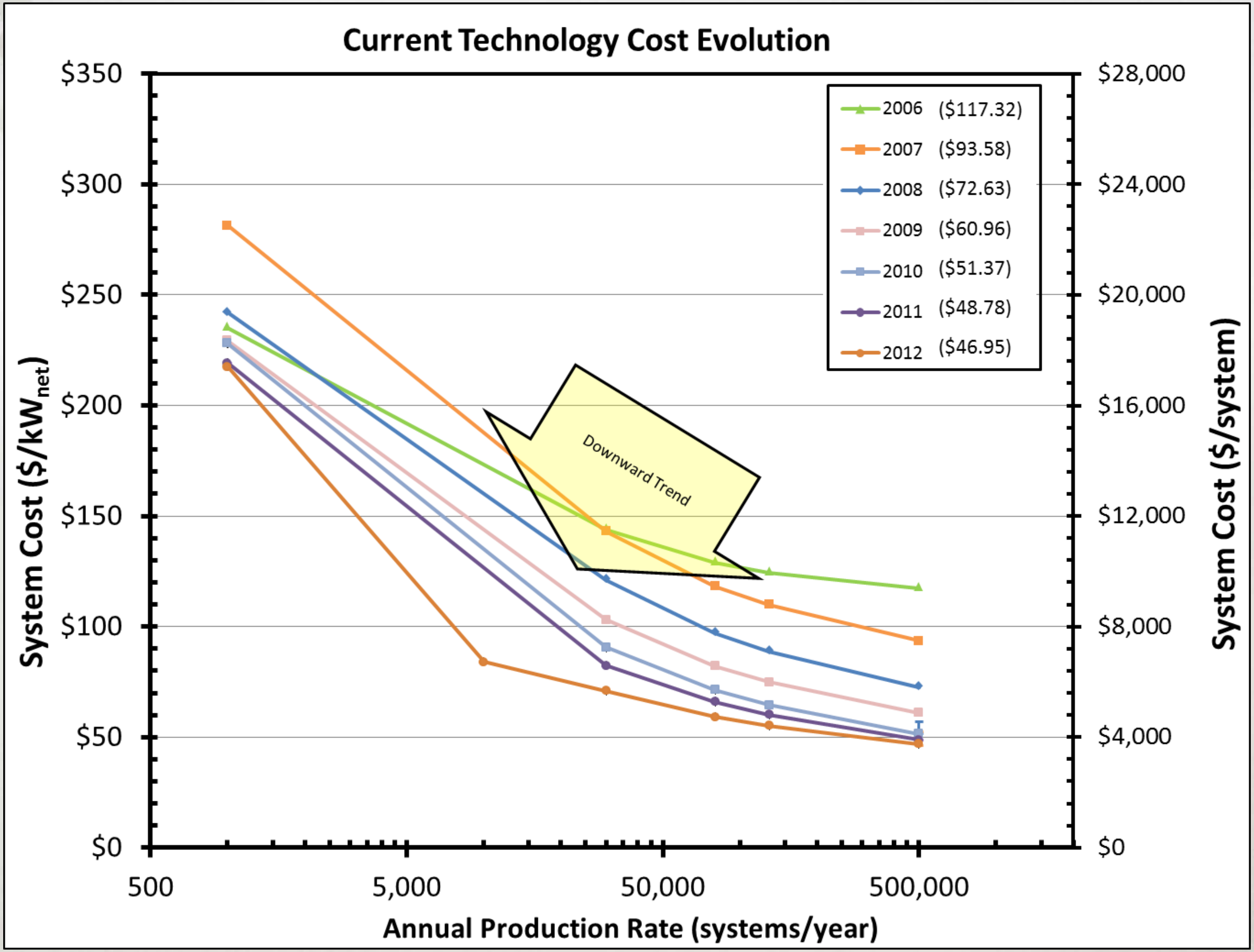
2013 Final Automotive FC Cost estimate

- **$55/kW$_{electric, net}$ at 500k systems/year**
  - **Approximately $3/kW added due to Q/ΔT limit**
  - **Approximately $3/kW added due to Pt price increase**
  - **Approximately $2/kW added due to all other changes (material costs, polarization, etc.)**



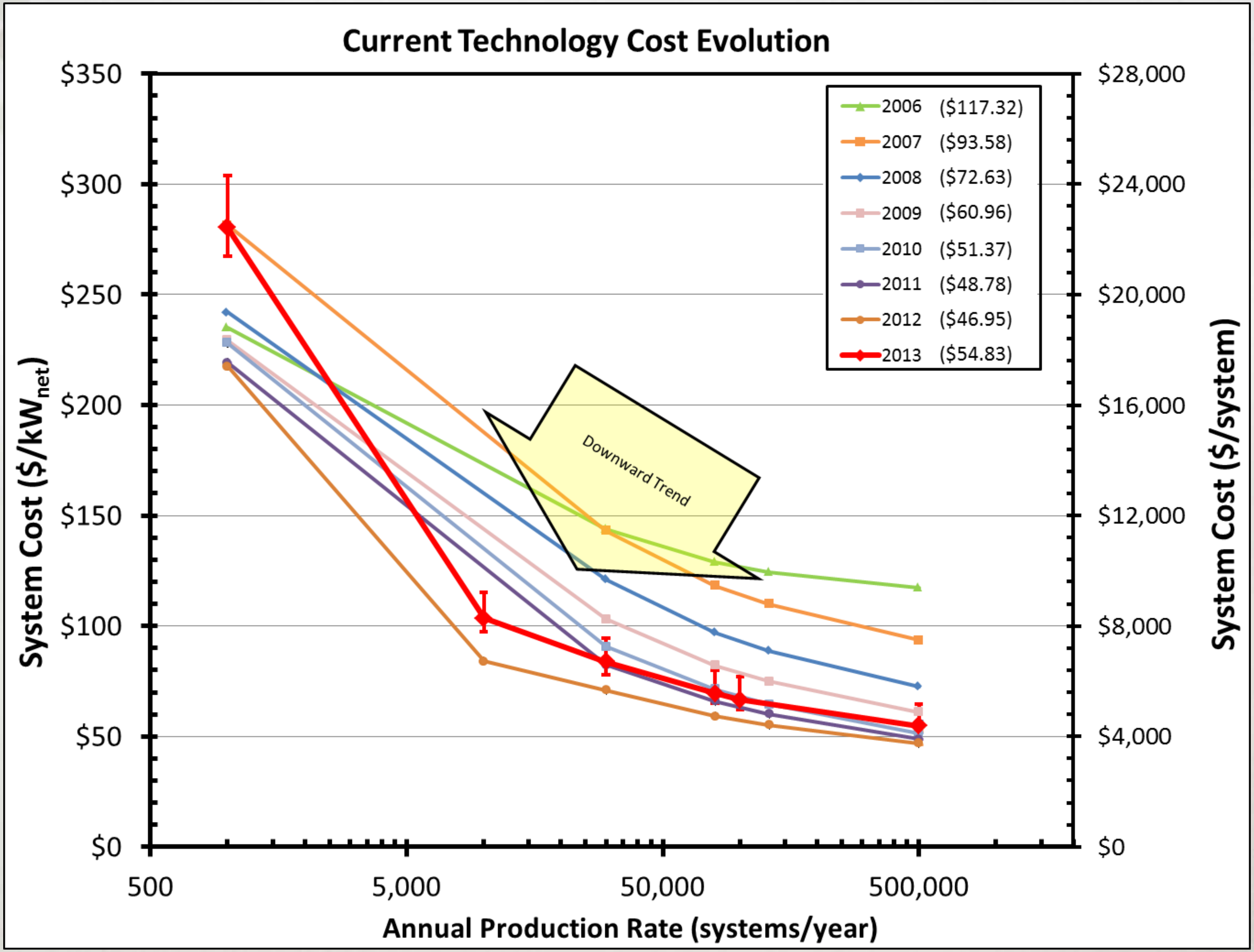
Summary of Auto System Cost from 2006 to 2013

System cost rises in 2013. (Explanation in back-up slides.)



Summary of Auto System Cost from 2006 to 2013

System cost rises in 2013. (Explanation in back-up slides.)



For 2013: Examination of Twin-Lobe Air Compressor

- Baseline automotive system cost is based on use of:
  - Centrifugal Compressor- Radial In-flow Expander with integrated motor
- DOE is funding Eaton to develop an alternative CEM based on:
  - Twin-lobe compression/expansion technology
- DFMA®-Style Cost analysis conducted to explore expected costs

Exterior view of the Eaton R340 supercharger
Source: http://www.hybridcars.com/demand-increased-fuel-economy-drives-eaton-develop-new-automotive-technology-28637/

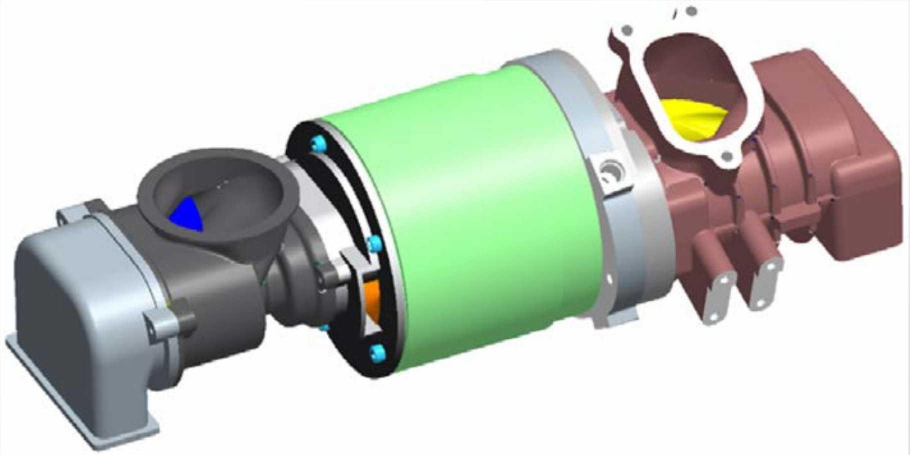
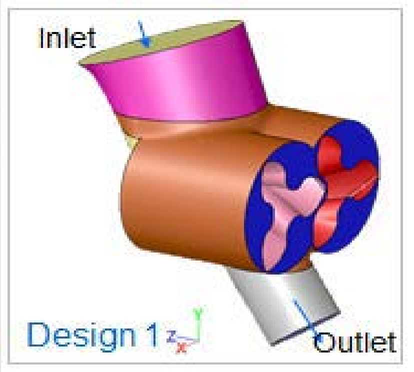


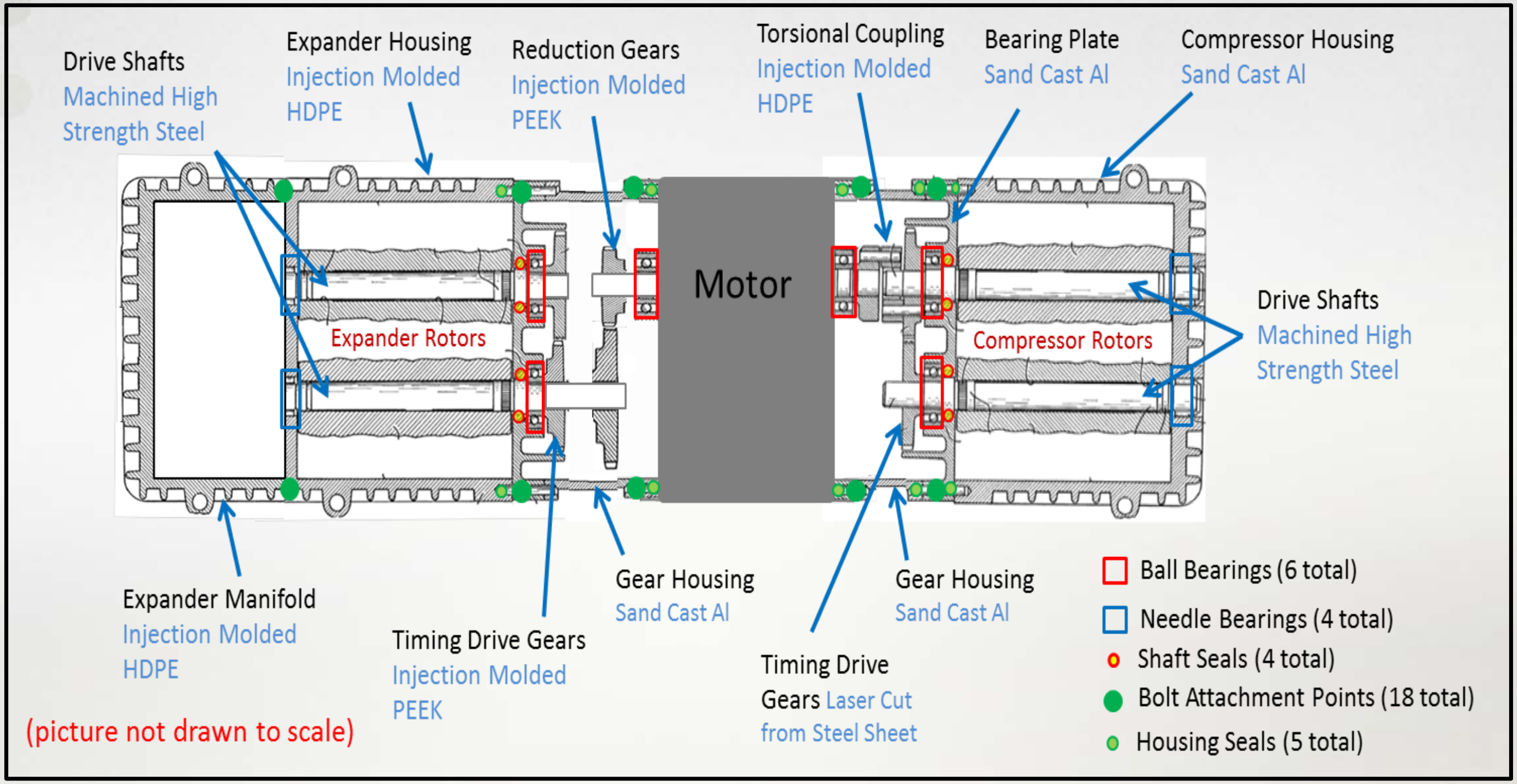
Image of Eaton 5-shaft CEM design.
Source: 2013 Annual Progress Report, "Roots Air Management System with Integrated Expander", Eaton Corporation.



Eaton supercharger meshed geometry showing internal twin lobe interaction
Source: 2013 Annual Merit Review, "Roots Air Management System with Integrated Expander", Dale Stretch, Eaton Corporation, 14 May 2013.

CEM=compressor-motor-expander
DFMA®=Design for Manufacturing & Assembly

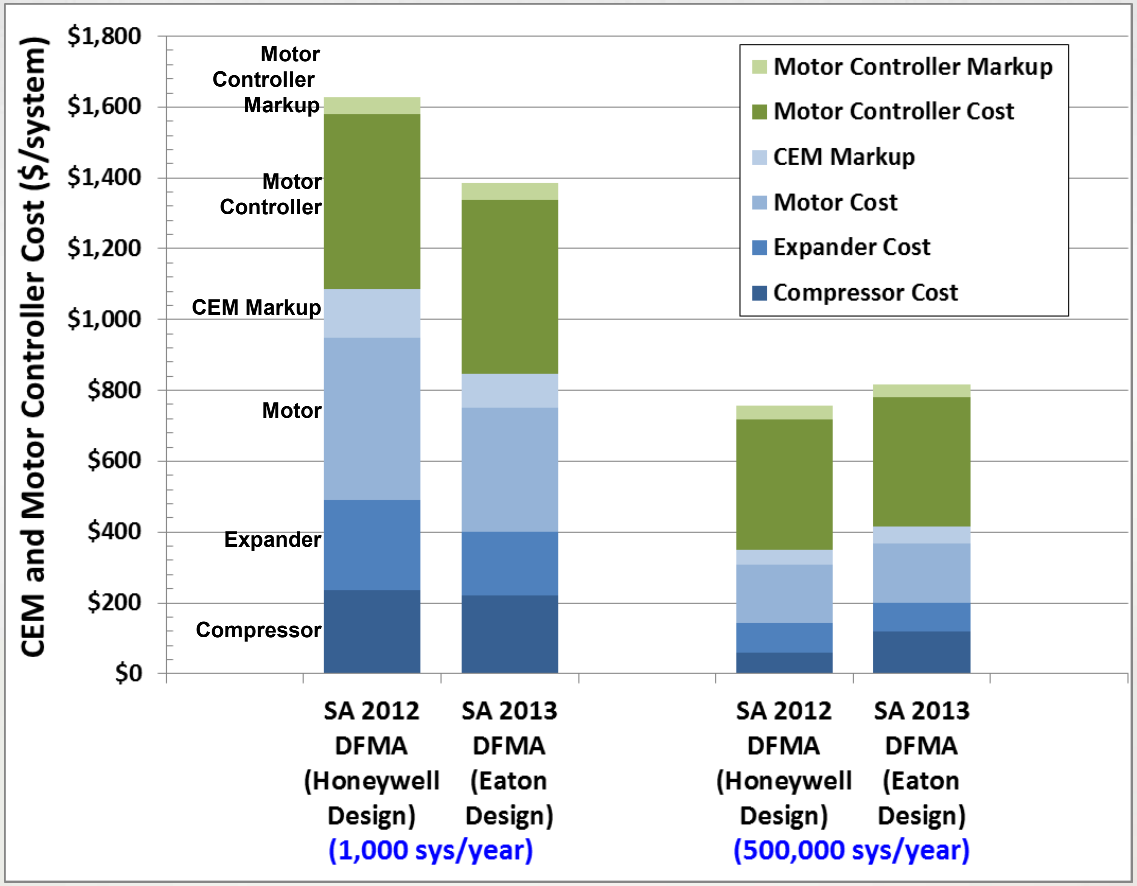
Twin-Lobe Compressor Concept for Cost Analysis



Schematic of cross-sectional view of SA's concept for Eaton 5-shaft CEM design.
Source: Drawing derivation from US patent 4,828,467: Richard J. Brown, Marshall, Mich. "Supercharger and Rotor and Shaft Arrangement Therefor", Eaton Corporation, Cleveland, Ohio, May 9, 1989.

Full DFMA analysis conducted on this design concept.

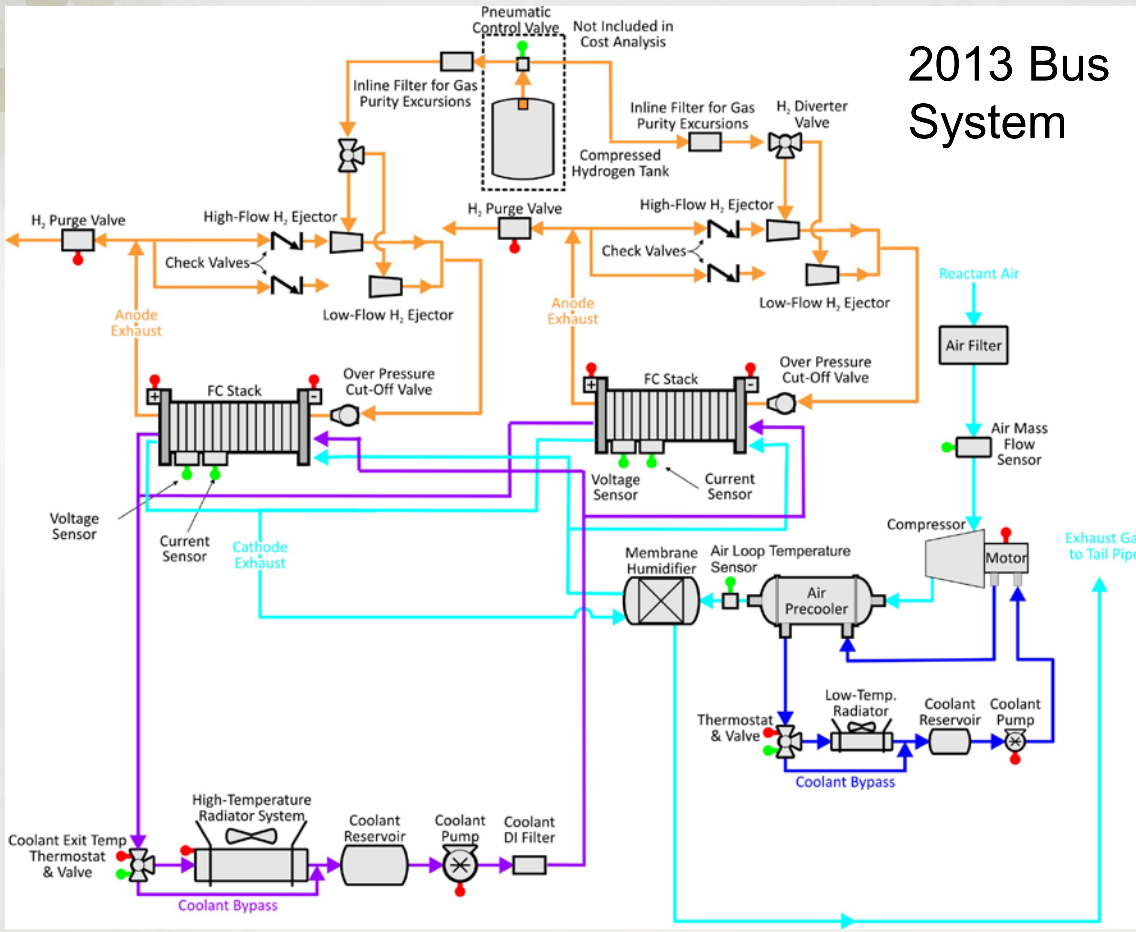
Twin Lobe CEM Cost Results



- Twin Lobe and Centrifugal compressors appear similar in total cost.
- Controller is large cost fraction of both designs.
- Motor costs merit further scrutiny. (Eaton motor based on scaled quotes rather than DFMA.)

- Total CEM cost dominated by motor controller cost at higher volumes.
- Eaton CEM costs are lower than Honeywell's at the low production volume (1k sys/yr) and higher at the high production volume (500k sys/yr).
- Both systems modeled with equal efficiency. Eaton system testing planned for FY14.
- Potential for Eaton controller cost reduction: currently carried at same cost even though at very different rpm's (Eaton: 20krpm, Honeywell: 165krpm).

2013 Bus Cost Results



Key Parameters:

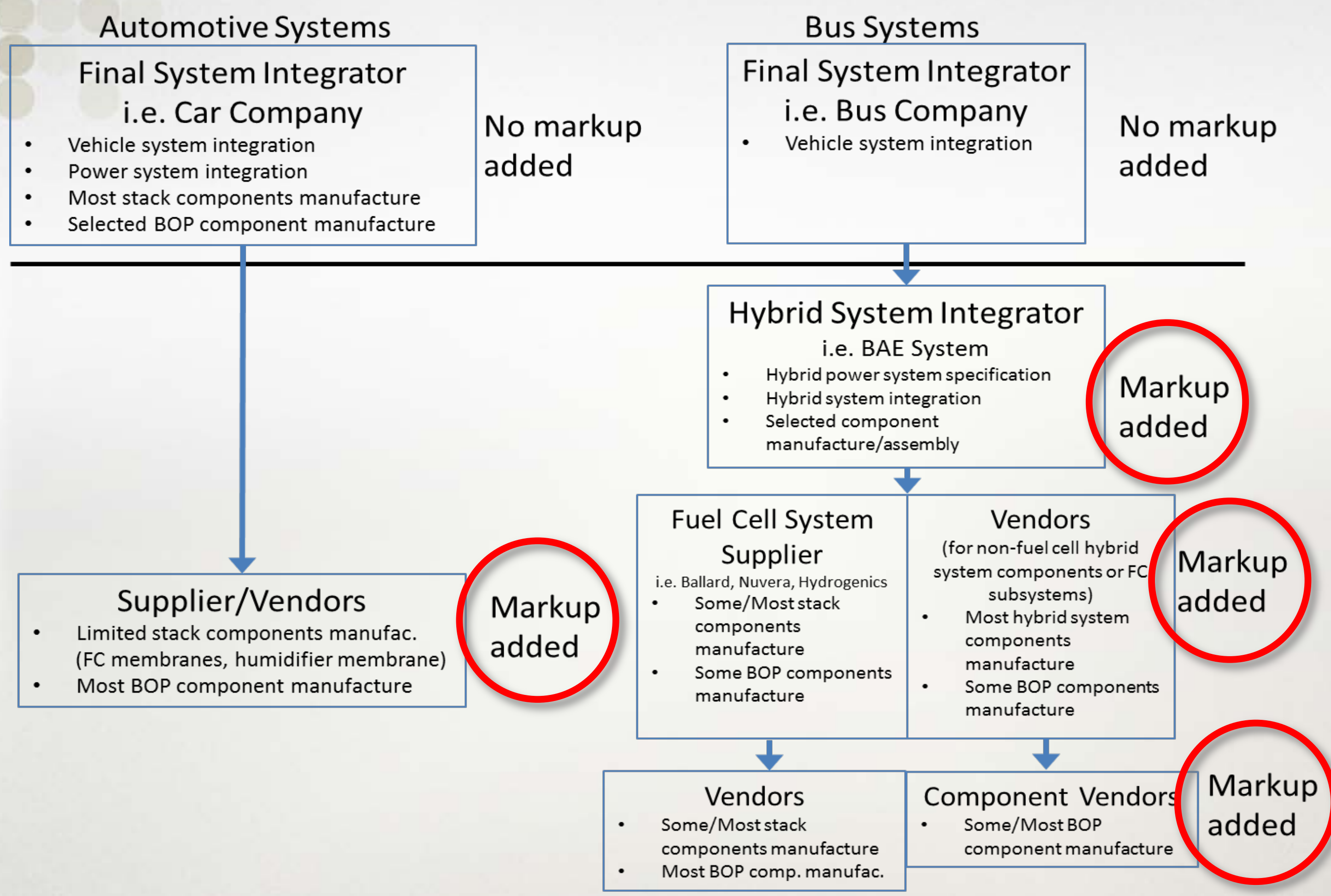
- 160 kW_{net}
- Two stacks
- 0.4 $mgPt/cm^2$ (total)
- 1.8 atm, 2.1x air stoic.
- 601 mW/cm^2 at 0.676 volts/cell

New for 2013 analysis:

- Expansion of annual production rates
  - 200, 400, 800, and 1,000 systems/year
- Re-evaluation of bus business/mark-up structure
- Use of Eaton-style twin lobe compressor

Automobile and Bus Business Structures Differ

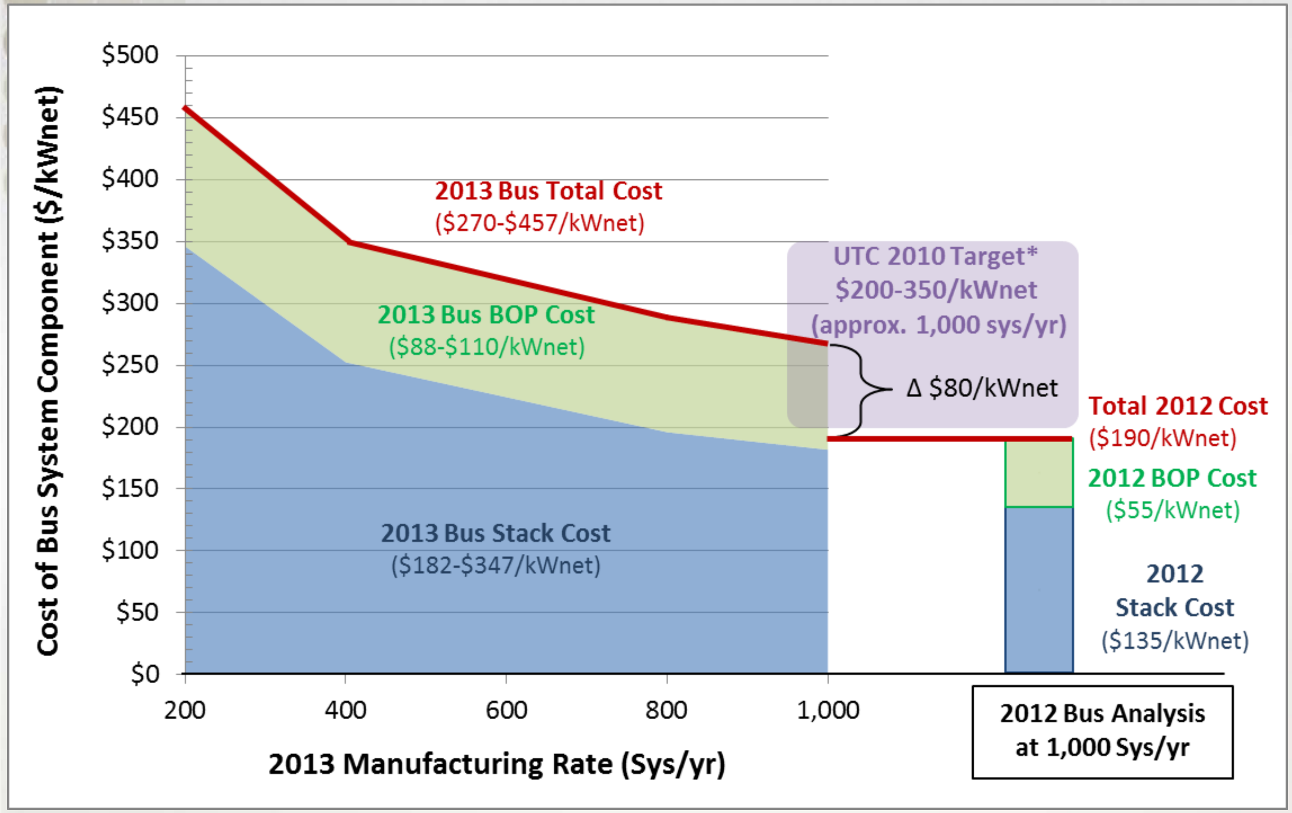
Assumptions Regarding Extent of Vertical Integration



- Per DOE past directive, cost estimates do not include markup for the final system integrator.
- Markup covers overhead, General & Admin, profit, scrap, R&D expenses.
- Markup typically reported as a % of base manufac./assy cost.

FC bus marketplace modeled on existing bus market.
Multiple levels of markup are expected.

2013 Bus Power System Cost Results: $270/kW_{net}$ (at 1k sys/year)



Parameter Change from 2012 to 2013	Approx. Δ in Cost ($/kW$_{net}$) at 1,000 sys/yr
Change in Polarization	+$15
Added Eaton-Style Compressor/Motor	+$15
Added Markup	+$50
Total	**$80/kW$_{net}$**

- Lower manufacturing rates investigated for 2013 analysis
- Δ $80/kWnet between 2012 and 2013 total bus power system cost based on change in polarization curve, added Eaton Compressor/Motor, and added Markup .

* 2010 DOE AMR Joint DOE/DOT Bus Workshop, “Progress and Challenges for PEM Transit Fleet Applications”, Tom Madden, UTC, 7 June 2010: 2010 UTC Preliminary Bus Fleet Cost Target: $200-350/kW in 1,000’s per year.

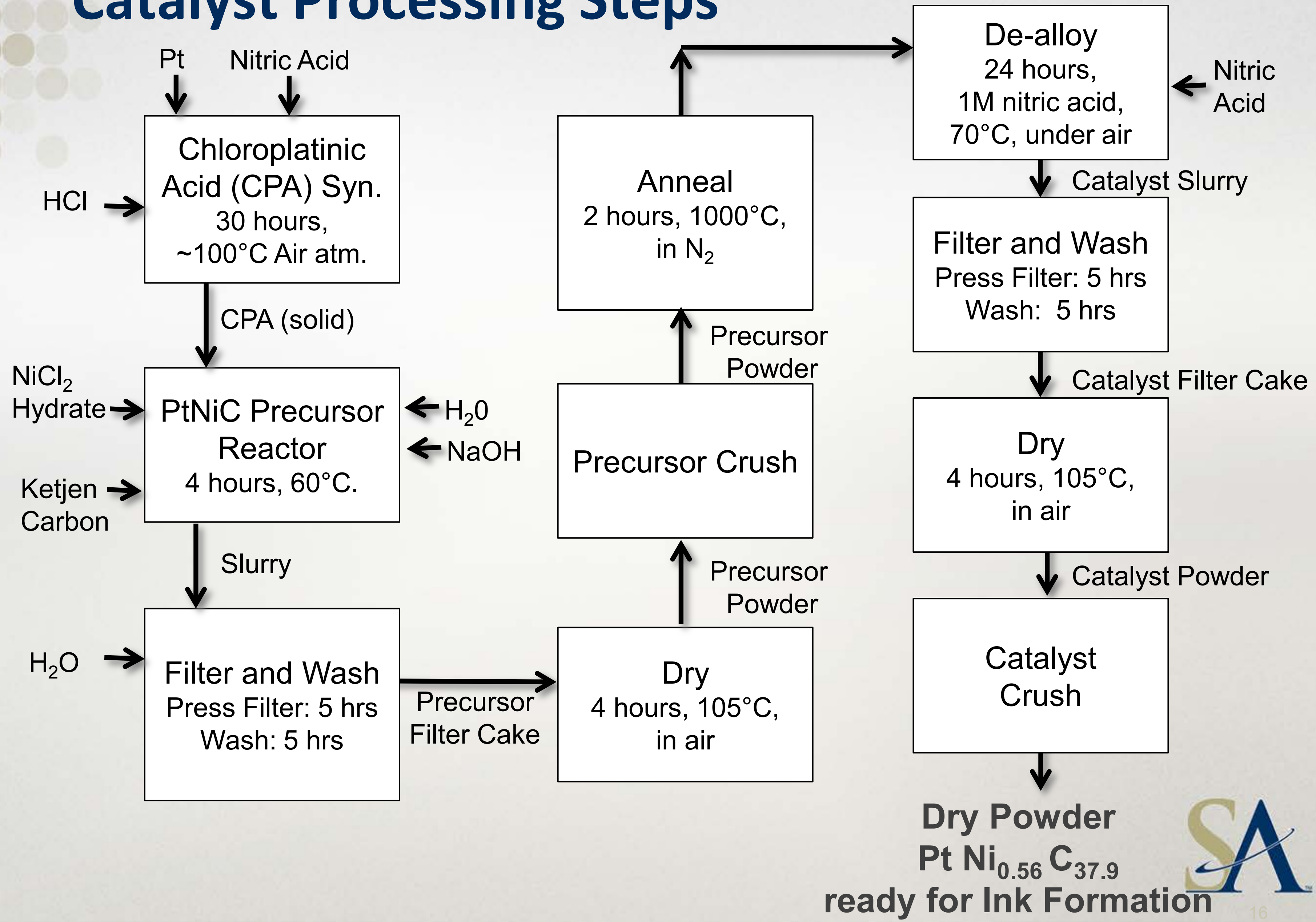
Approach

Recent Catalyst Systems (funded by DOE)

Catalyst	PtCoMn (Ternary)	PtNi (on Carbon) (Binary)		
Development Group	3M	3M	3M	Johnson-Matthey
Synthesis Method	NSTF	NSTF, De-alloyed	Wet Syn., De-alloyed	Wet Syn., De-alloyed
Application Method	NSTF	NSTF	Inking	Inking
Polarization Experimental Data	Extensive 3M experimental data 2002-2012	Limited 3M exp. data since 2012	Limited 3M exp. data since 2012	Limited JM experimental data
Polarization Modeling	ANL (neural and non-neural net modeling)	ANL modeling in-process	NA	ANL modeling in-process
	2009-2014 Cost Analysis Baseline			2014 Alternate Manufacturing Examination

NSTF= 3M's nano-structured, thin film catalyst

DFMA Cost Analysis: De-alloyed PtNiC Catalyst Processing Steps



Summary of Key Assumptions/Observations

- **Analysis based on non-proprietary data**
  - **Open source descriptions of Johnson Matthey process**
- **Methods still being refined/improved, but as-modeled synthesis thought to capture essence of eventual process**
- **Not much catalyst needed**
  - 86 grams per system (for 80kWnet)
  - Only 86 kg/year (at 1k sys/year) & 43 Metric Tonnes (at 500k sys/year)
- **All batch processes**
- **Markup added for the Catalyst Producer:**
  - **70% markup at 1k systems per year**
  - **40% markup at 500k systems per year**
  - **Larger than average automotive markups expected due to limited competition, IP position, etc.**

Additional Key Assumptions

- **Chloroplatinic Acid (CPA) Reaction:**
  - Net (stoic.): $Pt + 4\ HNO_3 + 6\ HCl \rightarrow H_2PtCl_6 + 4\ NO_2 + 4\ H_2O$
  - Substantial excess acids used:
    - Excess Nitric Acid: 3.7x
    - Excess Hydrochloric Acid: 6.4x
  - 100% conversion of Pt into CPA

- **Precursor Reaction:**
  - Net: $(H_2PtCl_6 + 358H_2O) + 3(NiCl_2\text{-}6(H_2O) + 27H_2O) + 37.9(\text{Carbon} + 114H_2O) +$ $8\ NaOH \Rightarrow PtNi_3C_{37.9}$ + Waste Products
  - 98% (baseline) conversion of CPA into Precursor

- **Filter Presses for both filtration and wash steps**

- **Final De-alloyed Catalyst : Pt $Ni_{0.56}C_{37.9}$**

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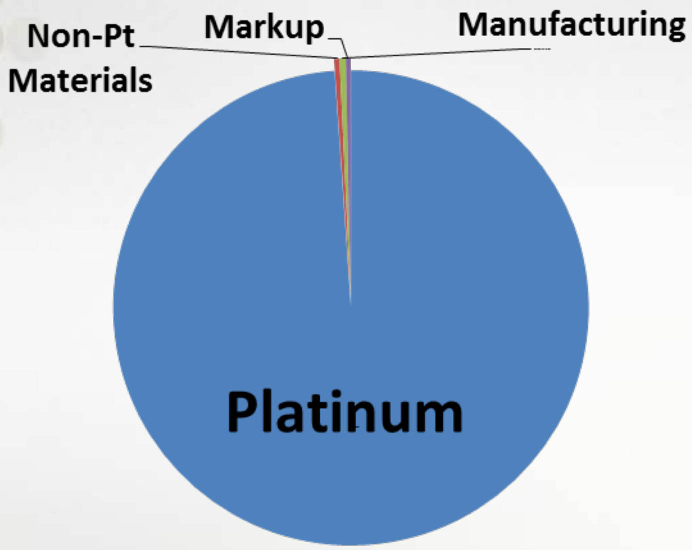
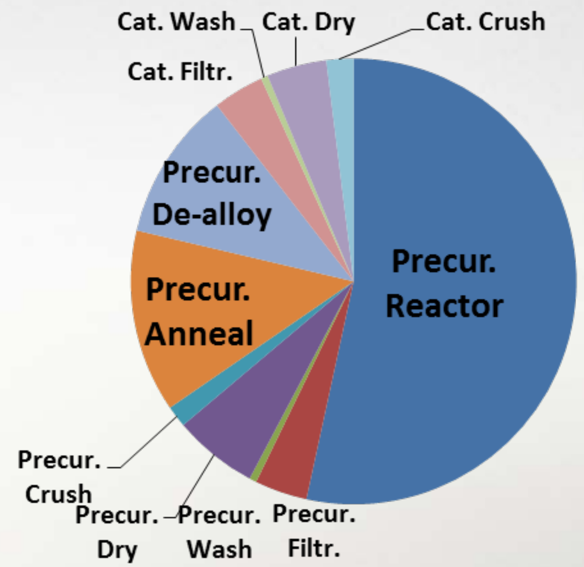
De-alloyed PtNiC Catalyst Cost Summary: 500ksys/year

Breakdown of Entire Catalyst Synthesis



Breakdown of Manufacturing Step Costs



- 86 grams catalyst per system
- Pt cost dominates
- Precursor Reactor step is 53% of manufacturing cost
- Precursor Reactor, Annealing, and De-alloy combine to almost 80%

At 1k Systems/Year
(excluding Pt)

- \$802/system
- \$9,322/kg catalyst
- \$10/kW$_{net}$

At 500k Systems/Year
(excluding Pt)

- \$14/system
- \$169/kg catalyst
- \$0.18/kW$_{net}$

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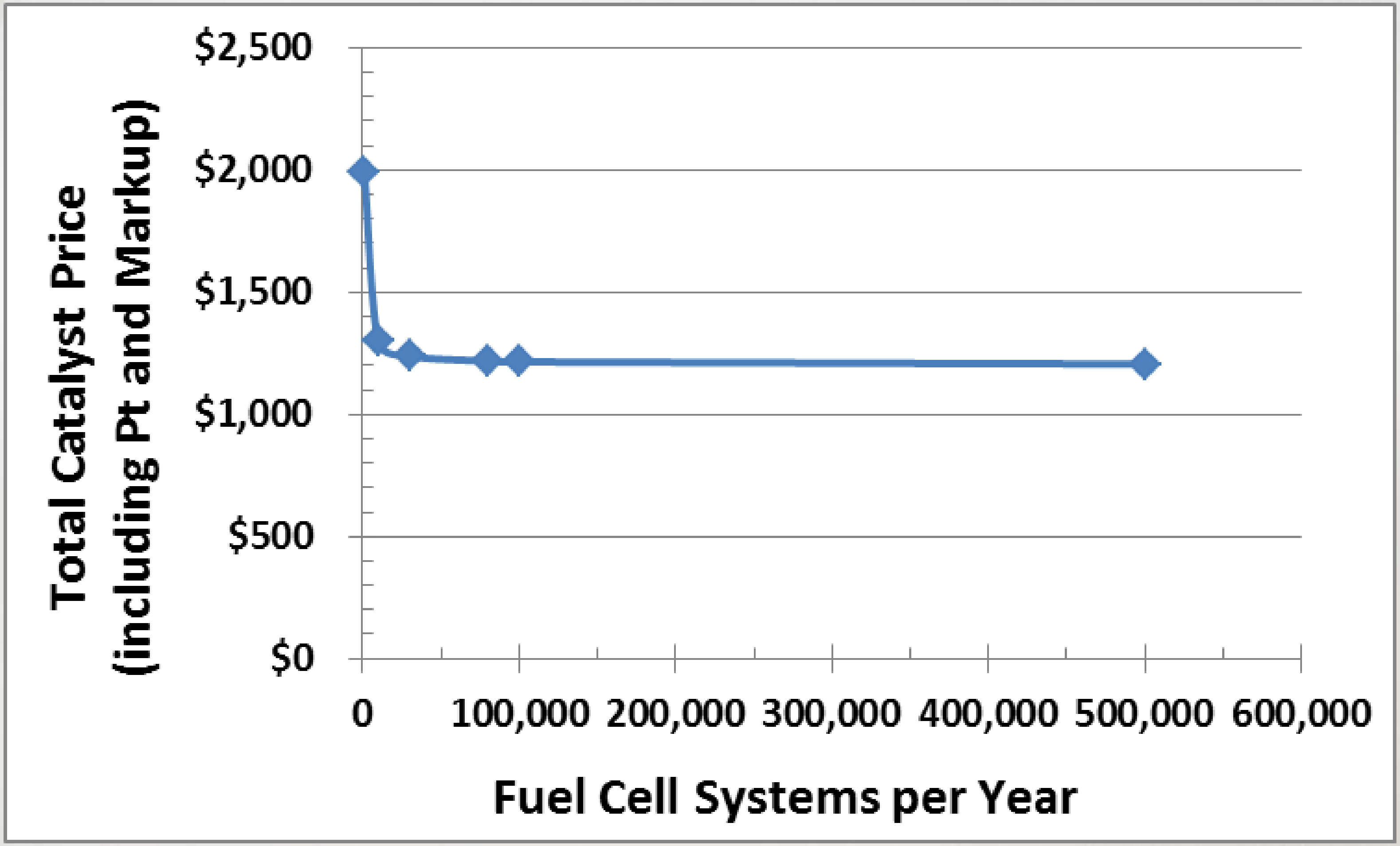
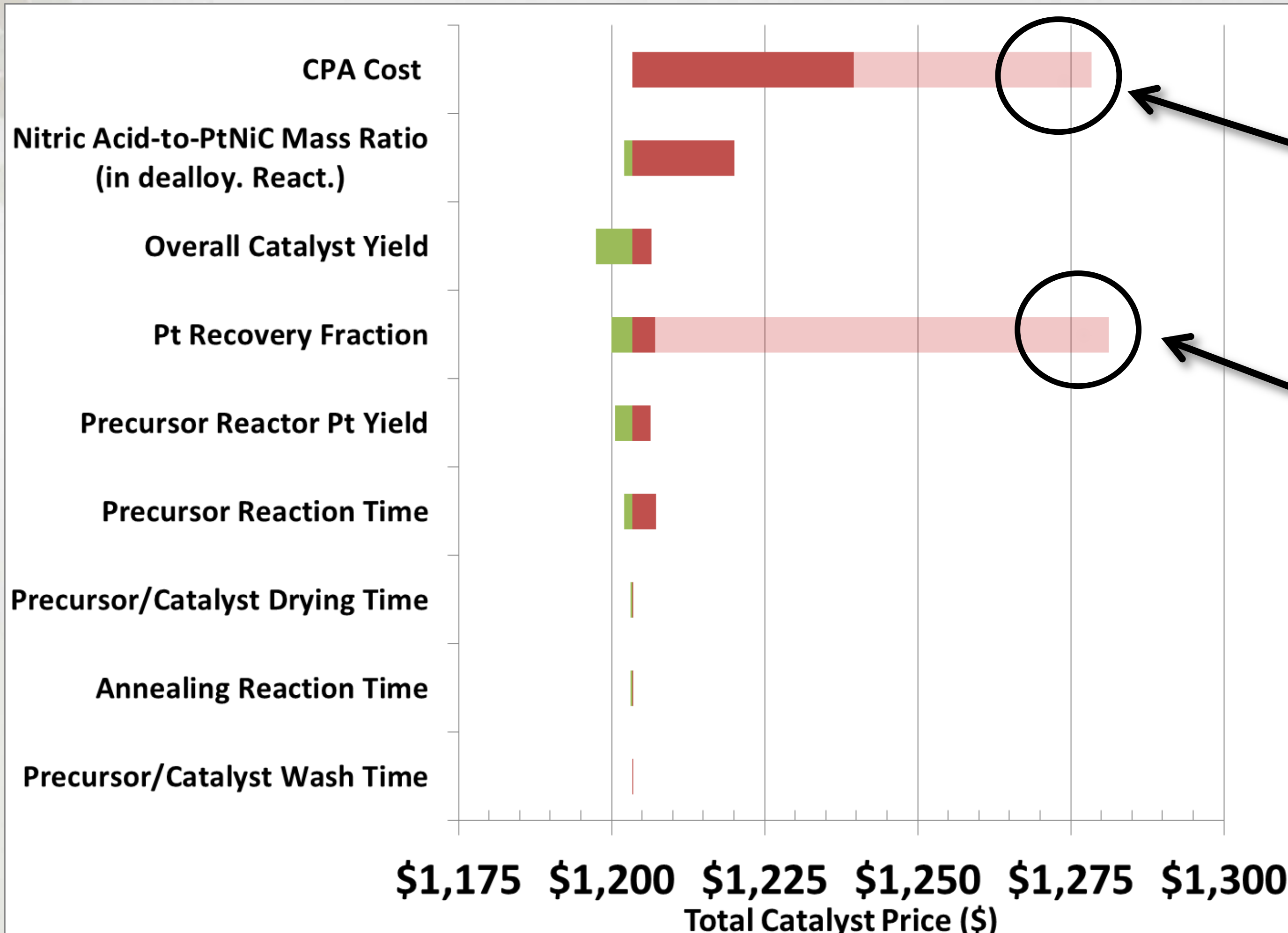
Expected Catalyst Price to Fuel Cell Fabricator

$1,190/system Pt price at all production rates.



- Knee in curve is at ~20k systems/year.
- Price drops steeply due to initially very small processing batch sizes.

Tornado Chart (at 500k systems/year)



Extremely high CPA cost ($1/g) adds ~0.93/kW to baseline cost

No Pt Recovery (0%) adds ~$0.97/kW to baseline

- Many parameters have only small impact.
- Recovery of Pt is vital. Needs to be 80%+.
- Important to assess the cost of CPA at high production rates.
  (Current (low vol.) vendor quotes ($1/g) are much higher than DFMA projections.)

De-alloyed PtNiC Catalyst Next Steps

- **Total Cost: Catalyst + Application**

  Catalyst Application Includes:
  - Ink preparation
  - Die slot coating onto Decal
  - Decal transfer via hot calendaring

- **Comparison of De-alloyed PtNiC to Ternary NSTF Catalyst**
  - Incorporate ANL polarization model of JM-type catalyst (in-progress)
  - Optimize operating parameters to define the lowest cost system
  - Compare on a $/kW basis

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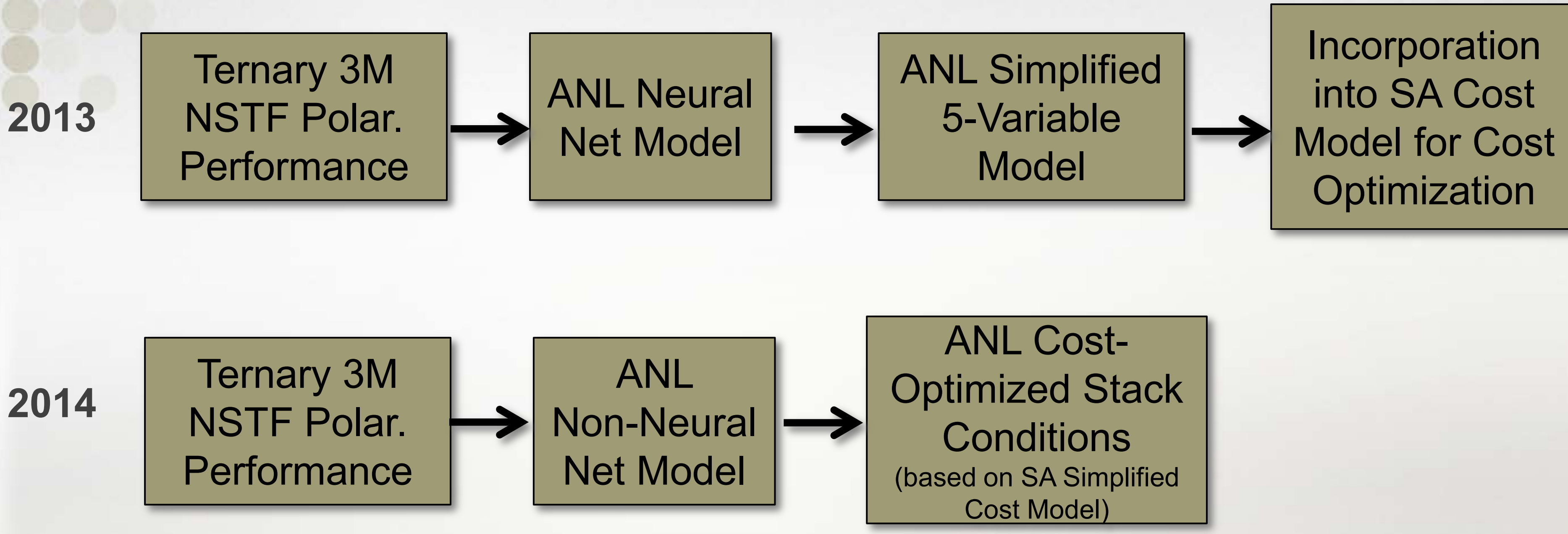
Review of Polarization Data: Determination Process

New ANL Model for 2014: Allows relaxation of previous humidity constraint



- SA also re-validating modeling results by comparing to 3M experimental data.
- Difference between models (at same conditions) thought to be the result of experimental data scatter.
- Past ANL analysis shows substantial cell-to-cell, run-to-run voltage variation.
  - Can be Δ33mv from average voltage (at 1A/cm^2)
  - This equates to ~Δ\$2/kW
- Analysis is ongoing to better understand the impact of voltage uncertainty as we switch from one model to the other.

2014 Automotive System Preliminary Optimization*

	2013 Optimized Conditions	2014 Optimized Conditions
Cell Voltage	0.695 volts/cell	**0.660 volts/cell**
Current Density	992 mA/cm^2	**971 mA/cm^2**
Power Density	692 mW/cm^2	**641 mW/cm^2**
Peak Stack Pressure	2.5 atm	2.5 atm
Total Catalyst Loading	0.153 mgPt/cm^2	0.153 mgPt/cm^2
Peak Cell Temperature	97°C	**100°C**
Stack Inlet Relative Humidity(RH)/Dew Point (air)	92%, 86°C	**80%, 82°C**
Air Stoichiometric Ratio	1.5	1.5
Q/ΔT	1.45	1.45

New for 2014 analysis:

- Updated ANL (non-neural net) Ternary NSTF polarization model
- Re-optimized stack operating conditions
- Miscellaneous other adjustments

* Optimization of system operating parameters to achieve lowest system cost.

Conclusions

- 2013 Bus cost estimates consistent with Industry (UTC) projection ($270/kW$_{e\text{-}net}$ at 1,000systems/year)
- 2013 Auto cost significantly higher than 2012
  - + $3/kW added due to Q/ΔT limit
  - + $3/kW added due to Pt price increase
  - + $2/kW added due to all other changes
  - 2013 Total System Cost: $55/kW$_{net}$ (at 500k systems/year)
- 2014 Auto cost expected to be similar to 2013
  - No major configuration changes
  - Polarization performance being re-assessed
- De-alloyed PtNi on Carbon catalyst appears to be cost effective alternative to NSTF PtCoMn
  - Impact of power density differences still to be assessed

Proposed Future Work

- Auto Systems
  - Continue 2014 update
  - Validate stack modeling results against experimental data
  - Re-optimize stack operating conditions using new 2014 polarization model (which relaxes past year RH constraints)
  - Complete de-alloyed PtNiC cost: application to membrane
  - Compare de-alloyed PtNiC system cost to baseline NSTF system
  - Perform detailed cost analysis on high impact BOP components
  - Document results in final report
- Bus Systems
  - Incorporate auto changes into bus analysis (to extent appropr.)
  - Vet results with bus/fuel-cell industry
  - Document results in final report

Collaborations

Institution	Activities and Contributions
Argonne National Lab (ANL) • Rajesh Ahluwalia • Xiaohua Wang • Deborah Myers	• Stack polarization modeling • System design and modeling support • Cross validate assessment of system optimal oper. parameters • Humidifier membrane area modeling/sizing • De-alloyed catalyst consultation
National Renewable Energy Laboratory (NREL) • Michael Ulsh • Leslie Eudy	• Expertise on manufacturing and quality control systems • Consultation on fuel cell bus systems and vertical integration

Industry Collaborators
 	
Technology Developers
Ford
Ballard
Gore
dPoint Technologies
Faraday Technologies
Eaton
Johnson Matthey
GM
 	
Vendors/ Suppliers
FFP Sys Inc. (press filter)
Frontier Industrial Technology Inc.
Wisconsin Ovens
Machine Works
Andritz Kusters
AK Steel
Tejin Films
	• Gore, dPoint Technologies, and Faraday Technologies generously contributed information on the plate frame membrane humidifier.
	• Ballard provided input on bus fuel cell stack and bus issues.
	• GM and Johnson Matthey reviewed and provided feedback on JM-type catalyst manufacturing methods.
	• Numerous vendors/suppliers consulted for production specs, and pricing updates:
	    • ePTFE, pick & place/manufacturing robots, sheet steel, Mylar® films, adhesives, die-slot coating systems, drying ovens, calendaring equipment, JM catalyst batch processing (press filters, waste product removal and recycling services)
	    • Vetted results and provided manufacturing process insight

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Summary

- Overview
  - Annually updated cost analysis of automobile & bus fuel cell systems
  - Exploring subsystem alternative configurations
  - In year 3 of 5 year transportation project
- Relevance
  - Cost analysis used to assess practicality of proposed power system, determine key cost drivers, and provide insight for direction of R&D priorities
- Approach
  - Process based cost analysis methodologies (e.g. DFMA)
- Accomplishments
  - 2013 Automobile & Bus analysis complete (report available)
  - 2014 Automotive & Bus analysis underway
  - New subsystems analyzed:
    - Johnson Matthew style dispersed PtNi on Carbon catalyst
    - Eaton-style twin lobe compressor
- Collaborations
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
- Future Work
  - Conclude 2014 Auto & Bus analysis
  - Continue alternative catalyst analysis (incorporating power density differences)
  - Fully vet bus cost analysis with industry

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Acknowledgements

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The authors wish to thank the following individuals for their technical and programmatic contributions and oversight:

Mr. Jason Marcinkoski (Technology Development Manager)

Dr. Sunita Satyapal (Fuel Cell Technologies Office Director)

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Technical Back-Up Slides

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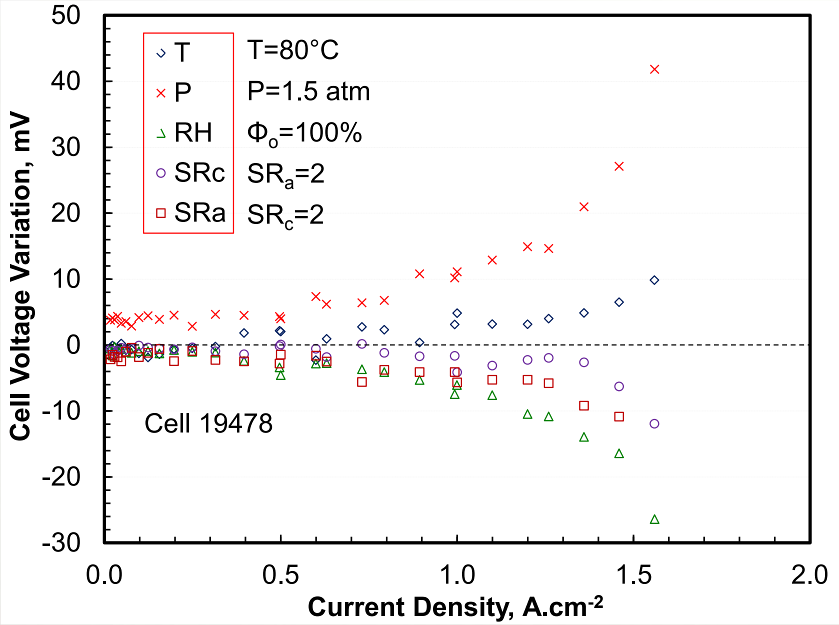
PtCoMn/NSTF Stack Model Development and Validation

Single cell data variability

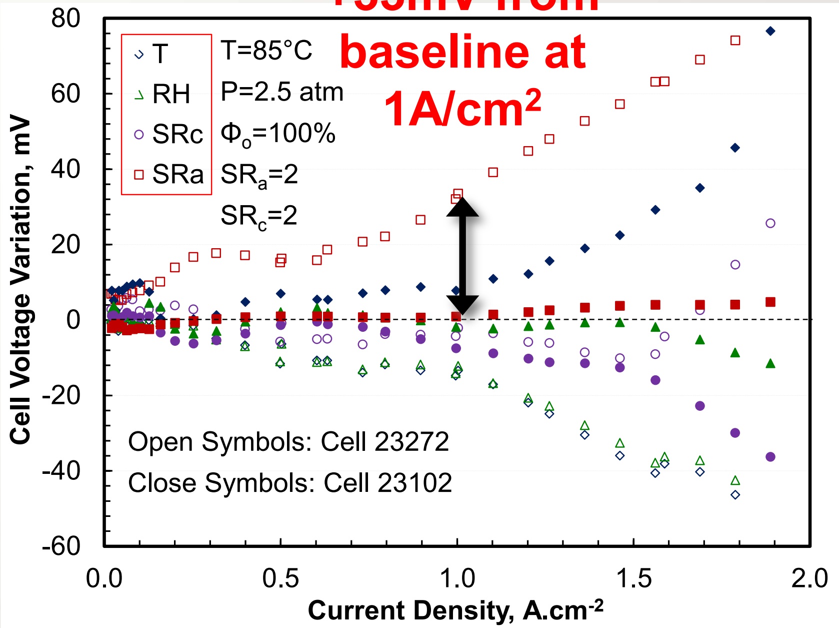
- Reference condition (1.5 atm, 80°C, 100% RH) visited multiple times in five series of tests performed in Cell 19478
- Error bar established as deviation from the measured average voltage as function of current density

Cell to cell data variability

- Same reference condition (2.5 atm, 85°C, 100% RH) visited multiple times in four series of tests performed in Cells 23272 and 23102
- Cell to cell variability established as deviation from the measured average voltage in the two cells as function of current density



+33mV from baseline at 1A/cm²



(Slide from Rajesh Ahluwalia, Argonne National Lab)

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De-Alloyed Catalyst Tornado Chart Limits
(at 500k systems/year)

Dealloyed Catalyst Sensitivity Analysis					
Parameter	Unit	Min. Parameter Value	Likeliest Value	Max. Parameter Value	Basis for Limits
Precursor/Catalyst Wash Time	hours	1	5	10	Min: a very fast "rinse" of the powder Max: a lengthy soaking
Annealing Reaction Time	hours	1	2	4	Min: 50% of baseline Max: 200% of baseline
Precursor/Catalyst Drying Time	hours	1	4	6	Min: 25% of baseline Max. 150% of baseline
Precursor Reaction Time	hours	2	4	10	Min: 50% of baseline Max: 200% of baseline
Precursor Reactor Pt Yield	%	96%	98%	100%	Min: unlikely to go below 96% Max. best possible
Nitric Acid Disposal Cost (in Dealloy React.)	$/kg	0.25	1.85	2.00	Min: Material cost of NaOH dneutralization. Baseline: derived from ROM price quotes. Max: Modest increase on baseline.
Pt Recovery Fraction	%	85%	89%	93%	Min: worst case is zero Pt recovery Baseline: based on 6% loss of Pt during recapture, $80/troy oz recapture cost (based on analogy to stack Pt recovery) Max: based on only 2% loss of Pt during recapture, $75/troy oz recapture cost (baed on analogy to stack Pt recovery) Ultra Max: 0% recovery
Overall Catalyst Yield	%	93%	95%	99%	Min: Est. worse case Baseline: Engineering judgment Max: Best case
Nitric Acid-to-PtNiC Mass Ratio (in dealloy. React.)	kg/kg	1.5	5.0	50	Min: Optmisitic lower level (but potentially possible) Max: High confidence level
CPA Cost	$/g	0.04	0.04	0.40	Min/Baseline: DFMA computed value Max: 10x baseline Ultra Max: Price quotes from vendors (at lower production quantities)

Automotive Changes from 2012 to 2013

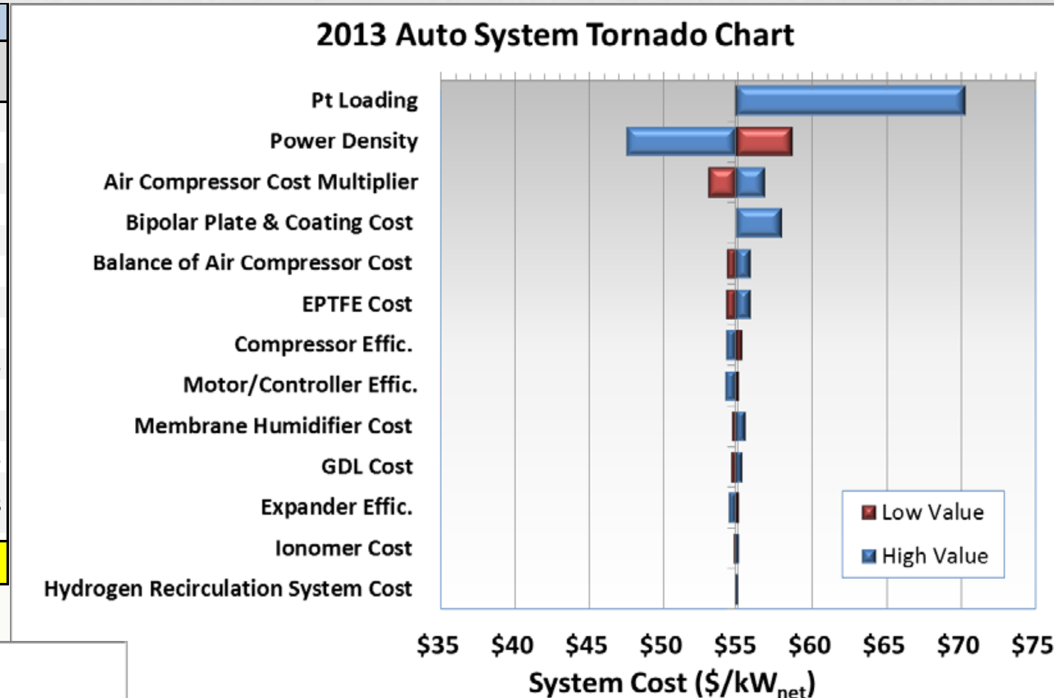
Key Changes:

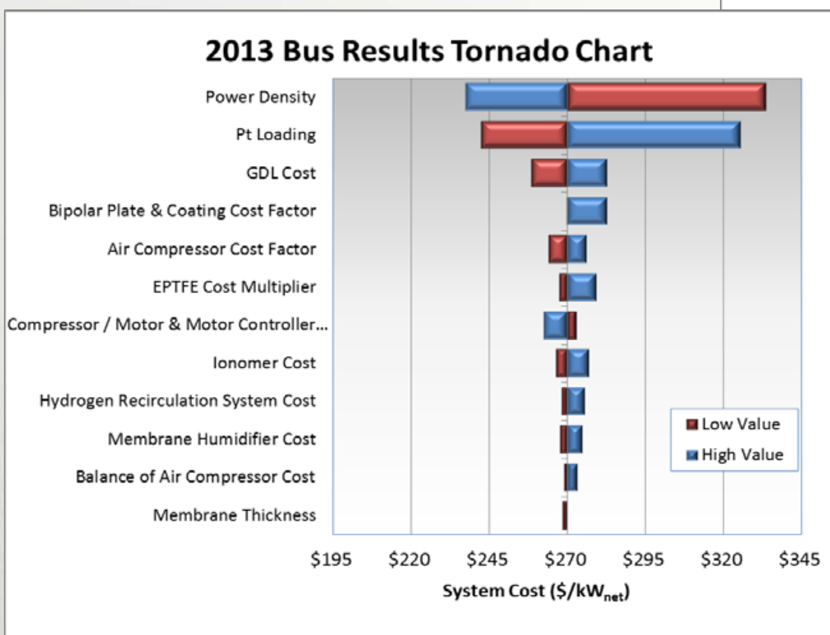
- Platinum cost increase (to reflect market conditions)
- Updated fuel cell performance (based on better modeling of stack conditions)
- Updated compressor/expander perf. (based on ANL modeling of status values)

Change	Reason	Change from previous value	Cost (500k sy/year, $/kW)
2012 Final Cost Estimate		NA	46.95
Plate Frame Humidifier	Switch to a much lower volume plate frame humidifier (as opposed to previous membrane tube humidifier).	$0.51	$47.46
Improved Catalyst Deposition Modeling	Re-examination of NSTF application including wastage and Pt recycling.	($0.20)	$47.26
Realigned Compressor and Expander Efficiencies	Adjusted the air compressor (75% to 71%), exh. Gas expander (80% to 73%), and motor (85% to 80%) efficiencies to match the status values modeled by ANL.	$1.87	$49.13
Updated Material Costs	Obtained new stainless steel and other material price quotations.	$0.13	$49.26
Updated Quality Control System	Re-examined quality control systems to ensure full functionality and improve cost realism.	$0.00	$49.26
Increased Platinum Cost	Increase in Pt base cost from $1100/troy once to $1500/troy ounce.	$3.19	$52.45
Other Misc. Changes	Updates made to improve and correct model i.e. LT and HT loop, CEM, and membrane adjustments.	($0.86)	$51.59
Updated Polarization Data, Stack Operating Condition Optimization, and Imposition of Radiator Area Constraints	Improved membrane electrode assembly (MEA) performance data based on expanded 3M NSTF experimental results. Performed stack condition optimization to achieve lowest system cost. Limited radiator Q/DT for volume management within the auto.	$3.24	$56.89
Final 2013 Value		$7.88	$54.83

Tornado Chart Results for 2013 Auto and Bus Systems

System Cost ($/kWnet), 500,000 sys/year				
Parameter	**Units**	**Low Value**	**Base Value**	**High Value**
Pt Loading	$mgPt/cm^2$	0.15	0.153	0.300
Power Density	mW/cm^2	588	692	1038
Air Compressor Cost Multiplier		0.80	1	1.20
Bipolar Plate & Coating Cost		1	1	1.5
Balance of Air Compressor Cost	$/system	$99.92	$149.81	$225
EPTFE Cost	$/m2	$3.00	$6.00	$10.20
Compressor Effic.	%	69%	71%	75%
Motor/Controller Effic.	%	78%	80%	90%
Membrane Humidifier Cost	$/system	$70.77	$94.36	$141.53
GDL Cost	$/m2	$2.79	$3.82	$4.97
Expander Effic.	%	71%	73%	80%
Ionomer Cost	$/kg	$46.63	$77.71	$155.43
Hydrogen Recirculation System Cost	$/system	$160.96	$241.32	$361.98
2013 Auto System Cost			**$54.83**	





2013 Bus System Cost ($/kWnet), 1,000 sys/year				
Parameter	**Units**	**Low Value**	**Base Value**	**High Value**
Power Density	mW/cm^2	420.7	**601**	823
Pt Loading	$mgPt/cm^2$	0.2	**0.4**	0.8
GDL Cost	$\$/m^2$	$76.99	**$105.47**	$137.11
Bipolar Plate & Coating Cost Factor		1	**1**	2
Air Compressor Cost Factor		0.8	**1**	1.2
EPTFE Cost Multiplier		0.667	**1.00**	2.20
Compressor / Motor & Motor Controller Efficiencies	%	69%/78%	**71%/80%**	75%/90%
Ionomer Cost	$/kg	$47.33	**$215.12**	$527.04
Hydrogen Recirculation System Cost	$/system	$600.20	**$899.86**	$1,799.71
Membrane Humidifier Cost	$/system	$391.00	**$782.00**	$1,563.99
Balance of Air Compressor Cost	$/system	$248.00	**$371.81**	$743.62
Membrane Thickness	µm	15	**25.4**	25.4
2013 Bus System Cost				**$269.95**

Monte Carlo Results for 2013 Auto and Bus Systems