V.A.3 Cost Analyses of Fuel Cell Stacks/Systems

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Objectives

The overall objective is to assess the high-volume (500,000 units/year) manufacturing cost for an 80 kW_e (net) direct-hydrogen polymer electrolyte membrane fuel cell (PEMFC) system for automotive applications. This past year's (2009-2010) objectives were:

- Estimate the bottom-up manufactured cost of the 2009 PEMFC system, assuming a nano-structured thin film catalyst (NSTFC)-based membrane electrode assembly (MEA) and a 30 micron perfluorosulfonic acid (PFSA) membrane.
- Perform sensitivity analyses on key stack and system parameters, assuming high-volume production (500,000 units/year) of the 2009 PEMFC system.
- Update the bottom-up manufactured cost for the PEMFC system based on updated stack performance assumptions and system configuration for 2010 – *preliminary* costs reported.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section (3.4.4) of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

(B) Cost

Technical Targets

This project evaluates the cost of automotive PEMFC technologies being developed by DOE contractors and other developers. Insights gained from this evaluation will help guide DOE and developers toward promising stack and system-level designs and approaches that could ultimately meet the DOE targets for PEMFC system cost, specific power, power density, and efficiency. DOE cost targets and high-volume cost estimates based on the 2009 status/2010 (*preliminary*) system configuration are shown in Table 1. Note that 2009 status is based on scenario S5 from Table 2, while the preliminary 2010 results are based on scenario S2-2 from Table 4 and Table 5.

TABLE 1. Progress towards Meeting Cost Targets for PEM Fuel Cell Systems for Transportation Applications

Component	Units	DOE 2010/2015 Targets	DOE 2009/2010 Targets	TIAX 2009 Status / *2010 Preliminary*
System[1]	$/kW$_e$	45 / 30	60 / 45	55.2 / *52.4*
Stack[2]	$/kW$_e$	25 / 15	/ 25	22.3 / *22.3*
Compressor Expander Motor (CEM)[1]	$/unit	400 / 200		982 / *832*
Membrane[2]	$/m^2	20 / 20		11.4 / *18.7*
Electrocatalyst[2]	$/kW$_e$	5 / 3		10.6 / *8.0*
MEA[2]	$/kW$_e$	10 / 5		16.5 / *13.7*
Bipolar Plates[2]	$/kW$_e$	5 / 3		2.9 / *6.2*

[1] Based on bottom-up high-volume manufacturing cost and an assumed 15% markup to the automotive original equipment manufacturer (OEM) for all major balance-of-plant (BOP) components.
[2] Assumes a vertically integrated stack manufacturing process by the OEM-based on bottom-up, high-volume manufacturing cost and assumes no markup for all major stack components.

Accomplishments

- Updated the bottom-up manufacturing cost for the 2009 PEMFC system configuration assuming current technology status, and high-volume production (500,000 units/year).
- Performed single-variable and multi-variable (Monte Carlo) sensitivity analyses on key stack and system parameters, for high-volume production (500,000 units/year).

- Participated in an independent peer review of our 2008 cost analysis methodology, assumptions and resulting cost projections.
- Developed *preliminary* bottom-up, high-volume manufacturing cost estimate for the 2010 PEMFC stack, assuming current technology status.

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Introduction

The DOE seeks to develop a durable fuel cell power system for transportation applications. Cost is a major challenge to the commercialization of automotive fuel cell power systems. The cost of fuel cell power systems must be reduced to less than $50/kW$_e$ for the technology to be competitive with automotive internal combustion engine power plants, which currently cost about $25-35/kW$_e$.

A rigorous, bottom-up analysis of projected high-volume manufacturing cost is required to accurately gauge the status and potential of fuel cell technology to meet the FreedomCAR and Fuel Partnership goals. TIAX LLC (formerly the Technology and Innovation group within Arthur D. Little) has assisted DOE with the development of cost projections for PEM fuel cells for transportation since 1999, analyzing reformate-based systems through 2004, followed by direct-hydrogen systems from 2005 through 2010.

Approach

We have applied an internally developed technology costing methodology that has been customized to accurately analyze and quantify the processes used in the manufacture of PEMFC stack and BOP components. TIAX has developed a proprietary, bottom-up, technology-based cost model which is used in conjunction with the Boothroyd-Dewhurst Design for Manufacturing and Assembly (DFMA®) software.

The approach starts with a technology assessment of the system configuration and components. Argonne National Laboratory (ANL) develops a fuel cell stack/system configuration and performance models that would represent the state-of-the-art for fuel cell vehicle technology in the current year. We perform a literature and patent search to explicate the component parts, specifications, material type and manufacturing process. Subsequently for each component, we develop a bill of materials based on the system specification/performance modeling provided by ANL, determine material costs at the assumed production volume, break down manufacturing processes into unit operations, and identify appropriate manufacturing equipment. We also perform single-variable and multi-variable (Monte Carlo) sensitivity analyses to identify the major cost drivers and the impact of material price and process assumptions on the high-volume PEMFC system cost results. Finally, we solicit feedback from the Fuel Cell Tech Team, developers and vendors on the key performance assumptions, process parameters, and material cost assumptions; we calibrate our model using this feedback.

Results

Throughout this document, we report a "factory cost", which is a bottom-up estimate of the high-volume manufacturing cost based on an 80 kW$_e$ net power PEMFC system, and an "OEM cost", which assumes a 15% markup (over the factory cost) to the automotive OEM for the BOP components. We assumed a vertically integrated process for the manufacture of the PEMFC stack by the automotive OEM, so no markup is included on the major stack components. Raw materials and purchased components implicitly include supplier markup.

In 2009, we updated the PEMFC system configuration, materials, processes, performance assumptions and component specifications [1,2]. Figure 1 shows the ANL 2009 PEMFC system configuration chosen for costing [1-3]. Table 2 is a summary of the stack performance assumptions and resultant high-volume manufactured cost of the 2009 PEMFC stack cost for six different scenarios modeled by ANL [3,4]. We assumed a baseline Pt cost of $1,100/tr.oz., and captured the impact of variability in Pt cost through the sensitivity analyses.

The high-volume 2009 PEMFC stack cost for six scenarios ranges from $19/kW$_e$ to $40/kW$_e$ [4]. Using S5 as the 2009 baseline scenario, the updated assumptions lowered the stack cost from $29/kW$_e$ in 2008 to $22.3/kW$_e$ in 2009. The low Pt loading with high power density is attributed to novel catalyst and support structure (i.e. NSTFC on organic whisker support). We based our cost assessment on ANL's single-cell modeling which is calibrated using data from an NSTFC-based short stack. The electrodes, primarily due to the Pt material, represent ~48% of the ~$22/kW$_e$ fuel cell stack manufactured cost in 2009.

We developed bottom-up manufacturing costs for the cathode and anode planar membrane humidifier, high-temperature (HT) and low-temperature (LT) radiators, hydrogen blower and CEM based on ANL specifications [3] and other patents [1,4]. We scaled vendor/catalog quotes for the air precooler, radiator fan, HT and LT coolant pumps, hydrogen demister, air demister, solenoid valves, flow orifice, and air/H_2 mixer. Table 3 is a summary of the projected high-volume OEM cost for the 2009 BOP subsystems and individual components [4].

Figure 2 shows the component/subsystem cost breakout for the 2009 PEMFC stack and system. BOP,

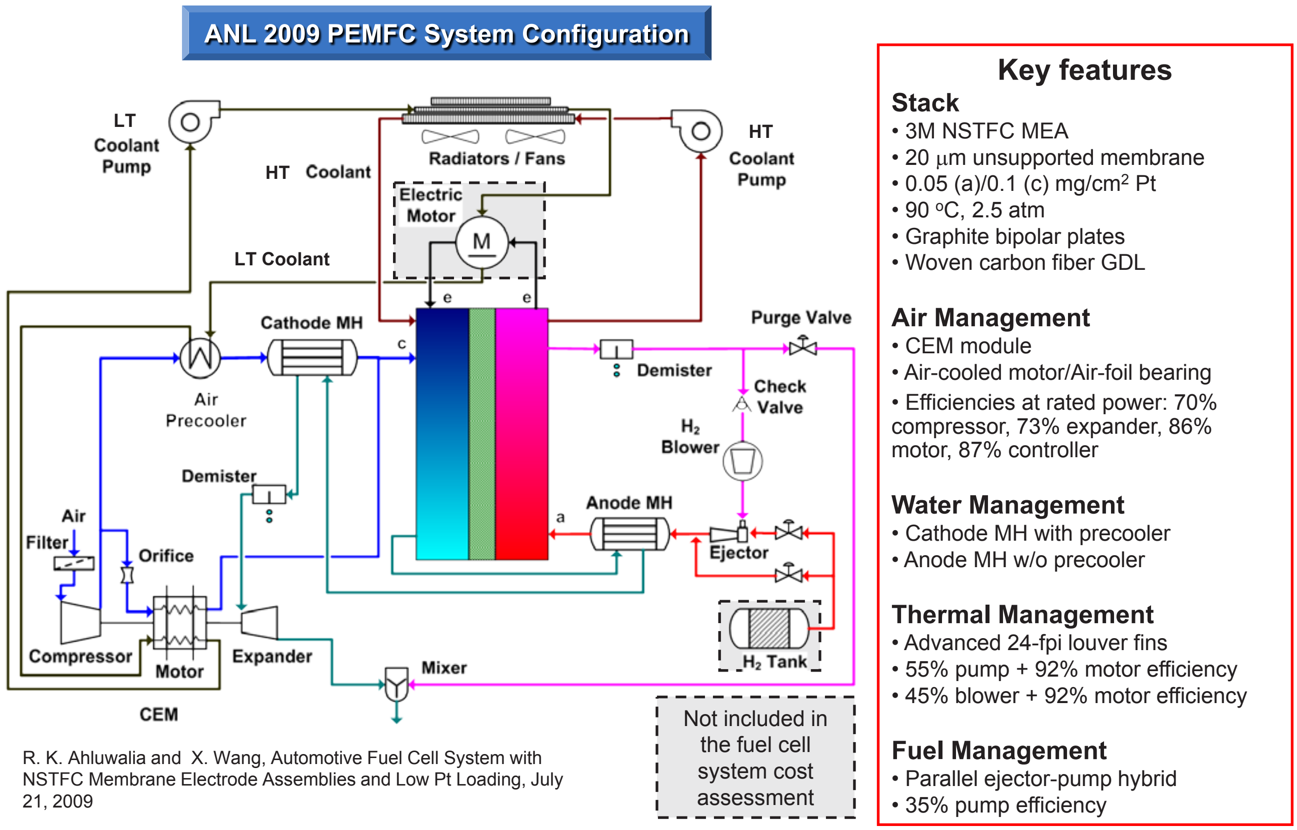


FIGURE 1. ANL 2009 PEMFC System Configuration [1-4]

TABLE 2. 2009 PEMFC Stack Scenarios and Costs [3,4]

Key Cost Assumptions		2009 PEMFC Stack Scenarios[1] [3,4]					
		S1	S2	S3	S4	S5	S6
System net power	kW_e	80					
Stack gross power [3]	kW_e	91.5	92.1	92.3	91.6	91.8	92.1
Cell voltage (rated power) [3]	V	0.729	0.690	0.659	0.736	0.693	0.661
Stack gross power density [3]	mW/cm^2	479	658	789	451	701	886
Pt loading (total) [3]	mg/cm^2	0.25			0.15		
Stack Pt content	g/kW_{gross}	0.52	0.38	0.32	0.33	0.21	0.17
System Pt content	g/kW_{net}	0.60	0.44	0.37	0.38	0.25	0.20
Stack efficiency (rated power) [3]	% LHV	57.4	54.5	52.1	57.4	54.6	52.1
System efficiency (rated power) [3]	% LHV	50.0	47.3	45.0	50.0	47.3	45.0
System voltage (rated power)	V	300					
System active area	m^2	19.1	14.0	11.7	20.3	13.1	10.4
Stack cost[2,3]	$\$/kW_{net}$	40.2	30.0	25.9	33.2	22.3	18.7

[1] All 2009 scenarios assume a Pt cost of $1,100/tr.oz., NSTFC-based MEA, 20 µm PFSA membrane, and stack operating conditions of 90°C and 2.5 atm.
[2] Assumes a vertically integrated stack manufacturing process by the OEM-based on bottom-up, high-volume manufacturing cost and assumes no markup for all major stack components.
[3] High-volume manufactured cost based on an 80 kW_e net power PEMFC system; does not represent how costs would scale with power (kW_e).
LHV = lower heating value

TABLE 3. High-Volume OEM Cost[1] of the 2009 BOP Subsystems [4]

BOP Subsystem	Component	Technology / Cost Basis	Factory Cost[2], $	OEM Cost[1], $
Water Management	Cathode planar membrane humidifier (for air)	ANL	96	111
	Anode planar membrane humidifier (for H_2)	ANL	52	59
Thermal Management	HT automotive tube-fin radiator	Modine	83	95
	LT automotive tube-fin radiator	Modine	13	15
	Air precooler	Bell Intercooler	-	43
	HT/LT radiator fan	McMaster-Carr	-	75
	HT coolant pump	McMaster-Carr	-	150
	LT/Air precooler coolant pump	Aweco	-	30
	Other (two temperature sensors)	-	-	5
Fuel Management	H_2 blower	Parker Hannifin	219	252
	H_2 ejectors	-	-	40
	H_2 demister	Parker Hannifin	-	61
	Solenoid valves	McMaster-Carr	-	46
	Purge valve	DFMA	13	15
	Check valve	DFMA	9	10
Air Management	Compressor Expander Motor (CEM)	Honeywell	687	790
	Air demister	Parker Hannifin	-	156
	Air/H_2 mixer	McMaster-Carr	-	27
	Flow orifice	McMaster-Carr	-	5
	Air filter	-	-	4
TOTAL		**-**	**1,815**	**1,991**

[1] Based on bottom-up high-volume manufacturing cost and an assumed 15% markup to the automotive OEM for all major BOP components.
[2] Assumes a vertically integrated stack manufacturing process by the OEM-based on bottom-up, high-volume manufacturing cost and assumes no markup for all major stack components.

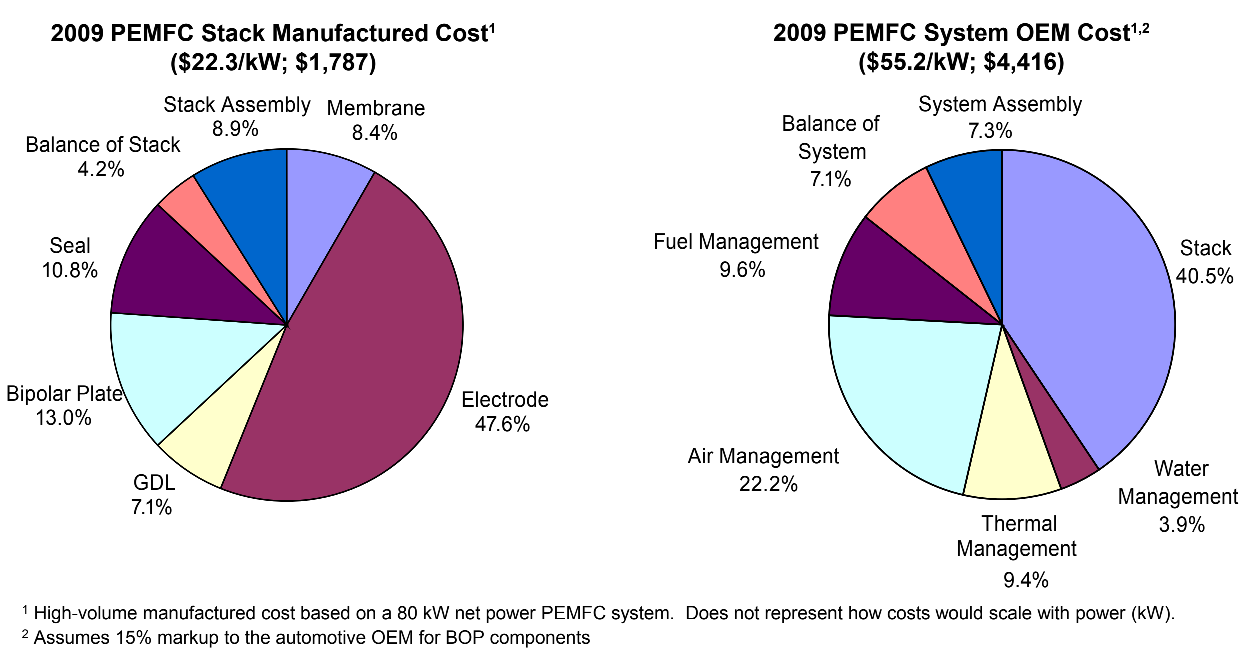


FIGURE 2. TIAX 2009 PEMFC Stack and System Cost [4]

balance of system, and system assembly costs together represent ~60% of the PEMFC system cost in 2009, compared to ~38% in 2005. The projected high-volume OEM cost of the CEM at $790/unit (~$10/kW$_e$) is the largest contributor to the combined BOP and assembly cost of $33/kW$_e$ in 2009.

We performed single- and multi-variable sensitivity analyses to examine the impact of major stack and BOP parameters on the high-volume 2009 PEMFC system cost. As seen in Figure 3, Pt loading, power density and Pt cost are the top three drivers of the PEMFC system OEM cost. The results of a multi-variable (Monte Carlo) analysis are shown in Figure 4; the high-volume 2009 PEMFC system OEM cost ranges between $45/kW$_e$ and $97/kW$_e$ ($\pm 2\sigma$), with the mean of the distribution being $71/kW$_e$.

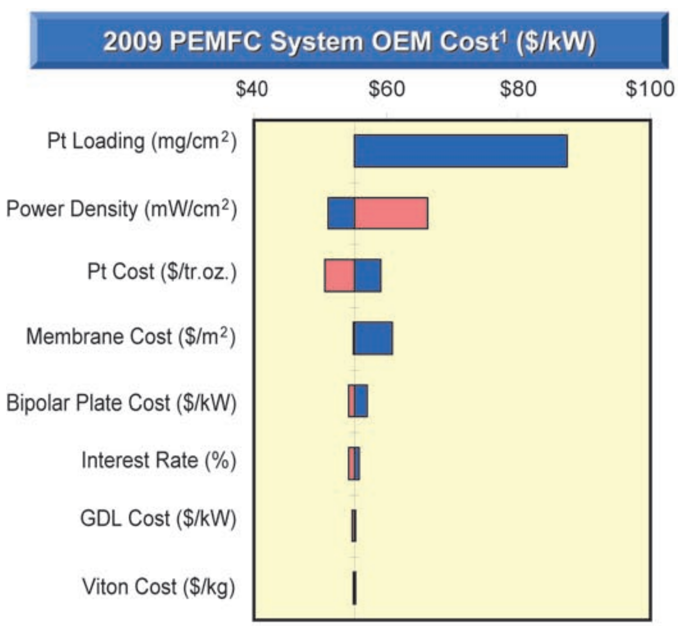
We are currently working on updating our cost projections to the ANL 2010 PEMFC system configuration, stack performance assumptions, and stack and BOP component specifications. Figure 5 shows a *preliminary* layout of the 2010 PEMFC system [4,5]. The key features are: NSTFC MEA with 20 µm reinforced PFSA membrane, thermal nitrided metal bipolar plates, non-woven carbon paper gas diffusion layer (GDL), pleated planar membrane humidifier for cathode air humidification, and no anode fuel humidifier.

Table 4 is a summary of the stack performance assumptions and resultant high-volume manufactured cost of the 2010 PEMFC stack cost for six different scenarios modeled by ANL [4,5]. Our *preliminary* estimates show that the high-volume 2010 PEMFC stack cost for six scenarios ranges between $17/kW$_e$ and $33/kW$_e$ [4]. These initial estimates will be finalized by the next reporting period.

Table 5 is a summary of the high-volume system OEM cost of the 2010 PEMFC system for six different scenarios modeled by ANL [4,5]. The *preliminary* 2010 PEMFC system OEM cost is estimated to range from $49/kW$_e$ to $65/kW$_e$ [4]. These initial estimates will be finalized by the next reporting period.

Conclusions and Future Directions

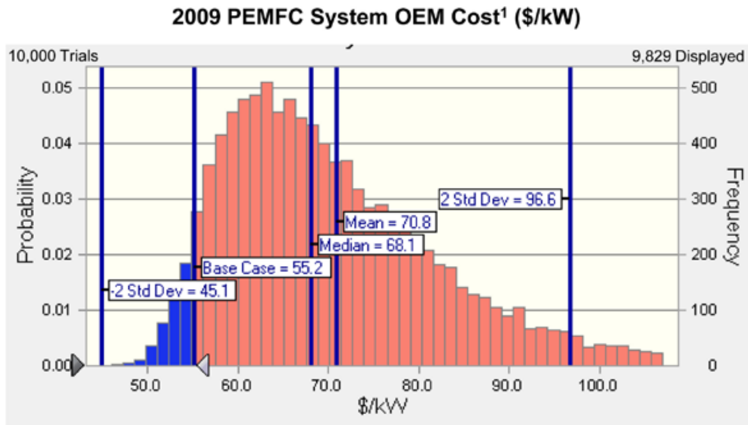
- The 2009 PEMFC stack cost was estimated to range between $19/kW$_e$ and $40/kW$_e$ over six different scenarios.
- The PEMFC stack and system costs were estimated to be $22/kW$_e$ and $55/kW$_e$, respectively for the 2009 baseline scenario.
- BOP, balance of system and system assembly costs together represented ~60% of the projected PEMFC system cost, for the 2009 baseline scenario.



#	Variables	Min	Max	Base	Comments
1	Pt Loading (mg/cm^2)	0.15	0.75	0.15	Minimum: 2009 status; Maximum: TIAX 2005 report[2]
2	Power Density (mW/cm^2)	350	1000	701	Minimum: industry feedback; Maximum: DOE 2015 target[3].
3	Pt Cost ($/tr.oz.)	450	1675	1100	Minimum: ~ 108-year min. in 2007 $[4]; Maximum: 12-month maximum LME price[5]
4	Membrane Cost ($/m^2)	10	50	11.4	Minimum:GM[6] study; Maximum: DuPont[7] projection from 2002
5	Bipolar Plate Cost ($/kW)	1.8	5.0	2.9	Minimum: Based on component single variable sensitivity analysis; Maximum: DOE 2010 target[3]
6	Interest Rate (%)	8%	20%	15%	Based on industry feedback
7	GDL Cost ($/kW)	1.3	1.9	1.6	Minimum: 80% of the baseline; Maximum: 120% of the baseline
8	Viton Cost ($/kg)	39	58	48	Based on industry feedback

1. High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Assumes a % markup to automotive OEM for BOP components.
2. Carlson, E.J. et al., "Cost Analysis of PEM Fuel Cell Systems for Transportation", Sep 30, 2005, NREL/SR-560-39104
3. http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf
4. www.platinum.matthey.com
5. www.metalprices.com
6. Mathias, M., "Can available membranes and catalysts meet automotive polymer electrolyte fuel cell requirements?", Am. Chem. Soc. Preprints, Div. Fuel Chem., 49(2), 471, 2004
7. Curtin, D.E., "High volume, low cost manufacturing process for Nafion membranes", 2002 Fuel Cell Seminar, Palm Springs, Nov 2002

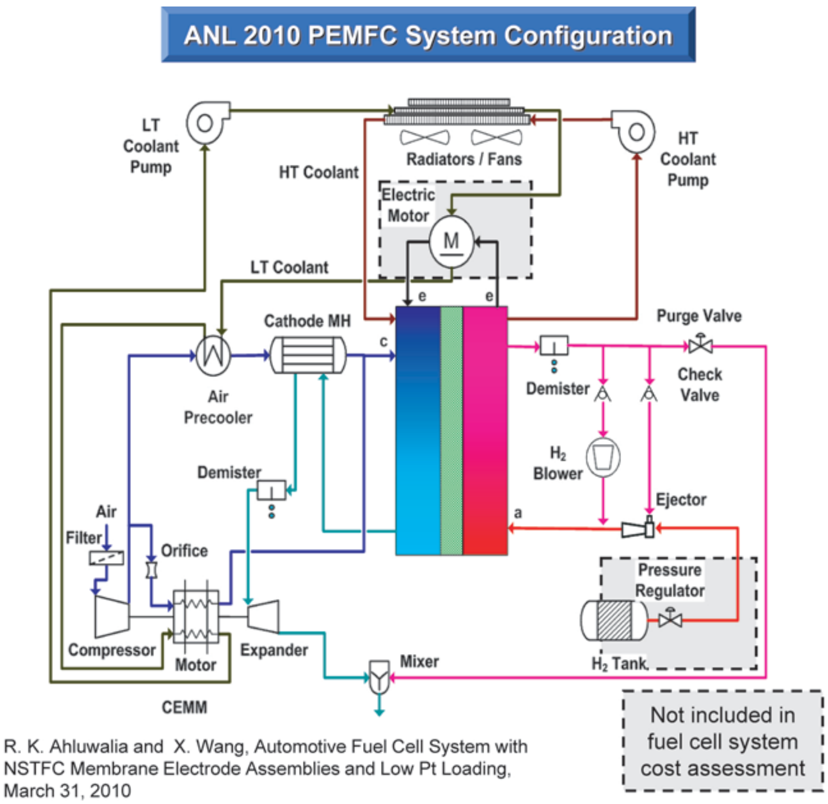
FIGURE 3. 2009 Stack Single-Variable Sensitivity Analysis [4]



Cost[1]	$/kW
Mean	71
Median	68
Std. Dev.	13
TIAX Baseline	55

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Assumes a % markup to automotive OEM for BOP components.

FIGURE 4. 2009 System Multi-Variable (Monte-Carlo) Analysis [4]



Key features

Stack
- 3M NSTFC MEA
- 20 µm reinforced membrane
- 0.05 (a)/0.1 (c) mg/cm² Pt
- Metal bipolar plates
- Non-woven carbon paper GDL

Air Management
- CEM module
- Air-cooled motor/Air-foil bearing

Water Management
- Cathode MH with precooler

Thermal Management
- Advanced 40-fpi microchannel fins

Fuel Management
- Parallel ejector-pump hybrid

FIGURE 5. ANL 2010 PEMFC System Configuration [5]

- The projected high-volume OEM cost of the CEM at $790/unit (~$10/kW$_e$) is the largest contributor to the combined BOP and assembly cost of $33/kW$_e$ in 2009.
- Platinum loading, power density, platinum cost, membrane cost and CEM cost are the top five drivers of the PEMFC system cost in 2009.
- Monte Carlo analysis shows that the 2009 PEMFC system OEM cost ranges between $45/kW$_e$ and $97/kW$_e$ (± 2σ), with a mean cost of $71/kW$_e$.
- *Preliminary* estimates for the manufactured cost of the 2010 PEMFC stack range between $17/kW$_e$ and $33/kW$_e$, while *preliminary* estimates for the OEM cost of the 2010 PEMFC system range from $49/kW$_e$ to $65/kW$_e$ over six different scenarios.

TABLE 4. *Preliminary* 2010 PEMFC Stack Scenarios and Costs [4,5]

Key Cost Assumptions		2010 PEMFC Stack Scenarios[1,2] [4,5]					
		S1-1	S1-2	S1-3	S2-1	S2-2	S2-3
System net power	kW_e	80					
Stack gross power [5]	kW_e	90	91	92	86	87	88
Cell voltage (rated power) [5]	V	0.721	0.650	0.590	0.685	0.622	0.563
Stack gross power density [5]	mW/cm^2	573	1059	1411	561	930	1201
Pt loading (total) [5]	mg/cm^2	0.15					
Stack Pt content	g/kW_{gross}	0.26	0.14	0.11	0.27	0.16	0.12
System Pt content	g/kW_{net}	0.29	0.16	0.12	0.29	0.18	0.14
Stack efficiency (rated power) [5]	% LHV	57	52	47	54	49	45
System efficiency (rated power) [5]	% LHV	50	45	40	50	45	40
System voltage (rated power)	V	300					
System active area	m^2	15.7	8.6	6.5	15.3	9.4	7.3
Stack cost[3,4]	$\$/kW_{net}$	33.0	20.7	17.4	32.4	22.3	19.0

[1] All 2010 scenarios assume a Pt cost of $1,100/tr.oz., NSTFC-based MEA, and 20 μm reinforced PFSA membrane.
[2] S1: 2.5 atm, 85°C and S2: 1.5 atm, 75°C
[3] Assumes a vertically integrated stack manufacturing process by the OEM-based on bottom-up, high-volume manufacturing cost and assumes no markup for all major stack components.
[4] High-volume manufactured cost based on an 80 kW_e net power PEMFC system; does not represent how costs would scale with power (kW_e).

TABLE 5. TIAX 2010 PEMFC System Cost Scenarios [4]

PEMFC System Cost[1] ($/kW)	2009 OEM Cost[4, 5]	2010 Stack Scenarios[1, 2, 3]					
		S1-1	S1-2	S1-3	S2-1	S2-2	S2-3
Stack[4]	22.3	33.0	20.7	17.4	32.4	22.3	19.0
Water Management[5, 6, 7]	2.1	1.4	1.4	1.4	1.4	1.4	1.4
Thermal Management[5, 7]	5.2	5.2	5.2	5.2	5.2	5.2	5.2
Fuel Management[5, 7]	5.3	5.3	5.3	5.3	5.3	5.3	5.3
Air Management[5, 7, 8]	12.3	12.2	12.4	12.9	9.9	10.4	10.6
Balance of System[5, 7]	4.0	4.0	4.0	4.0	4.0	4.0	4.0
System Assembly	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Total System[4, 5, 6, 7]	55.2	65.0	52.9	50.0	62.2	52.4	49.4

[1] All scenarios assume a Pt cost of $1,100/tr.oz., NSTFC-based MEA, and 20 μm reinforced PFSA membrane.
[2] S1: 2.5 atm, 85 °C; S2: 1.5 atm, 75 °C
[3] Based on stack and system modeling results by ANL for 2010 PEMFC system: R. K. Ahluwalia and X. Wang, March 31, 2010.
[4] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
[5] Assumes 15% markup to the automotive OEM for BOP components
[6] Water Management in 2010 preliminarily assumes cathode planar membrane humidifier and no anode humidifier
[7] Using 2009 cost numbers for BOP subsystems' preliminary cost; all BOP costs pending ANL input, are planned to be updated in 2010
[8] CEM motor controller cost varies based on preliminary modeling by ANL, of CEM parasitic power, for different scenarios

These initial estimates will be finalized by the next reporting period.

Our next steps are outlined below:

- Finalize baseline scenario for 2010 PEMFC system and develop BOP cost estimates.
- Finalize reinforced membrane, non-woven GDL and metal bipolar plate (thermal nitrided and Au-precoated) cost estimates for baseline scenario for 2010 PEMFC stack.
- Develop bottom-up cost projection for stack conditioning.
- Perform single-variable and Monte Carlo sensitivity analyses on stack and system costs.

FY 2010 Publications/Presentations

1. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, J. Sinha, Y. Yang, DOE Annual Merit Review, Washington DC, June 9, 2010.

References

1. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, J. Sinha, S. Lasher, Y. Yang, DOE Annual Merit Review, Arlington VA, May 21, 2009.

2. *Cost Analyses of Fuel Cell Stacks/Systems*, J. Sinha, S. Lasher and Y. Yang, DOE Hydrogen Program Annual Report, V.A.3, 2009.

3. *Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading*, R.K. Ahluwalia and X. Wang, ANL internal document, July 21, 2009.

4. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, J. Sinha, Y. Yang, DOE Annual Merit Review, Washington DC, June 9, 2010.

5. *Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading*, R.K. Ahluwalia and X. Wang, ANL internal document, March 31, 2010.