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 (net) direct-hydrogen polymer electrolyte membrane fuel cell (PEMFC) system for automotive applications. This past year's (2008-2009) objectives were:

- Estimate the bottom-up manufactured cost of the 2008 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 2008 PEMFC system.
- Participate in an independent peer review of our 2008 cost analysis methodology, assumptions, and resulting cost projections.
- Update the bottom-up manufactured cost for the PEMFC system based on updated stack performance assumptions and system configuration for 2009.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section (3.4.4) of the Hydrogen, Fuel Cells and Infrastructure 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 current high-volume cost estimates based on the 2008 system configuration are shown in Table 1.

Accomplishments

- Updated the bottom-up manufacturing cost for the 2008 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 2009 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 for the technology to be competitive with automotive internal combustion engine power plants, which currently cost about $25-35/kW.

TABLE 1. Progress towards Meeting Cost Targets for PEMFC Systems for Transportation Applications

Component	Cost Units	DOE 2010/2015 Targets	DOE 2008/2009 Targets	TIAX 2008 Status	Comments
System	$\$/kW_e$	45/30	70/60	57	Based on bottom-up manufacturing cost and an assumed 15% markup to the automotive original equipment manufacturer (OEM) for all major balance-of-plant (BOP) components
Stack	$\$/kW_e$	25/15		29	Based on bottom-up manufacturing cost and assumes no markup for all major stack components
Compressor Expander Motor (CEM)	$/unit	400/200		615	Assumes 15% markup to the automotive OEM
Membrane	$\$/m^2$	20/20		16	
Electrocatalyst	$\$/kW_e$	5/3		16	
MEA	$\$/kW_e$	10/5		20	
Bipolar Plates	$\$/kW_e$	5/3		3	

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 PEMFCs for transportation since 1999, analyzing reformate-based systems through 2004, followed by direct-hydrogen systems from 2005 through 2009.

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 as well as BOP components. TIAX has developed a proprietary, bottom-up, technology-based cost model which is used in conjunction with the conventional Boothroyd-Dewhurst Design for Manufacturing and Assembly (DFMA®) software.

The approach starts with a technology assessment of the system configuration and components. 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 Argonne National Laboratory (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 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 2007, the PEMFC system configuration, materials, processes, performance assumptions, and component specifications were updated [1,2]. We developed bottom-up manufacturing cost models for both stack and BOP components [1,2]. During the current reporting period (2008-2009), we updated key stack performance assumptions, i.e. power density and platinum (Pt) loading, with no change to the system layout, cell voltage, or stack operating conditions, i.e. no change to stack efficiency [3-5]. We based our cost assessment on ANL's single-cell modeling which is calibrated using data from an NSTFC-based short stack. We assumed a baseline Pt cost of $1,100/tr.oz., and captured the variability in Pt cost through the lower and upper bounds of the sensitivity analyses.

Table 2 is a summary of stack performance assumptions in 2005, 2007, and 2008.

TABLE 2. Key Stack Performance Assumptions

Parameters	Units	2005 [6]	2007 [1,2]	2008 [3-5]
System net power	kW_e	80	80	80
Stack gross power	kW_e	89.5	86.4	86.9
Stack gross power density	mW/cm^2	600	753	716
Cell voltage (rated power)	V	0.65	0.68	0.685
Pt loading (total)	mg/cm^2	0.75	0.30	0.25
Membrane thickness	μm	50	30	30
Stack temperature	°C	80	90	90
Pressure (rated power)	atm	2.5	2.5	2.5
Stack efficiency (rated power)	% LHV	52%	54%	54%

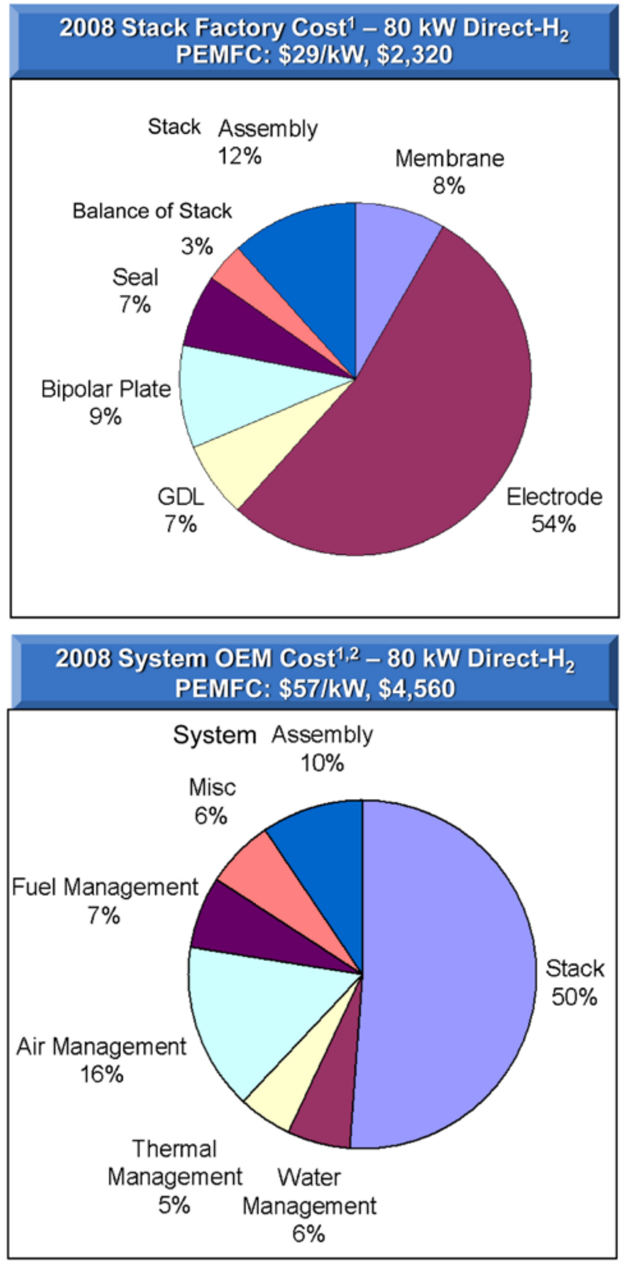
LHV – lower heating value

Overall, the 2008 assumptions lowered the stack cost by ~57% to $29/kW [3-5] and the system cost by ~47% to $57/kW [3-5] over the 2005 estimates [6] due to a significant reduction in Pt loading with increase in power density and the use of bottom-up methodology for estimating high-volume cost of BOP components. The lower Pt loading is attributed to novel catalyst and support structure (i.e. NSTFC on organic whisker support). Material costs dominate the high-volume factory cost of the PEMFC stack components. Pt material cost alone makes up ~90% of the electrode cost, while the electrodes represent ~54% of the $29/kW stack cost. Therefore, Pt cost accounts for ~48% of the total stack cost.

Because there were no changes to the assumed BOP subsystems in 2008, their high-volume factory cost of $1,350 (OEM cost of $1,500) is unchanged from 2007 [1,2]. The projected compressor expander motor factory cost of $535 or ~$7/kW is the largest contributor to the combined BOP and assembly cost of $28/kW [3-5].

Figure 1 shows the breakdown of the 2008 PEMFC stack and system cost by component and subsystem, respectively. Both stack and BOP component costs are significantly reduced from the 2005 cost assessment [6]. With the much reduced stack cost of $29/kW in 2008, BOP and assembly together represent ~50% of the PEMFC system cost in 2008, compared to ~38% in 2005 [3-5].

We performed single- and multi-variable sensitivity analyses to examine the impact of major stack and BOP parameters on the high-volume 2008 PEMFC system

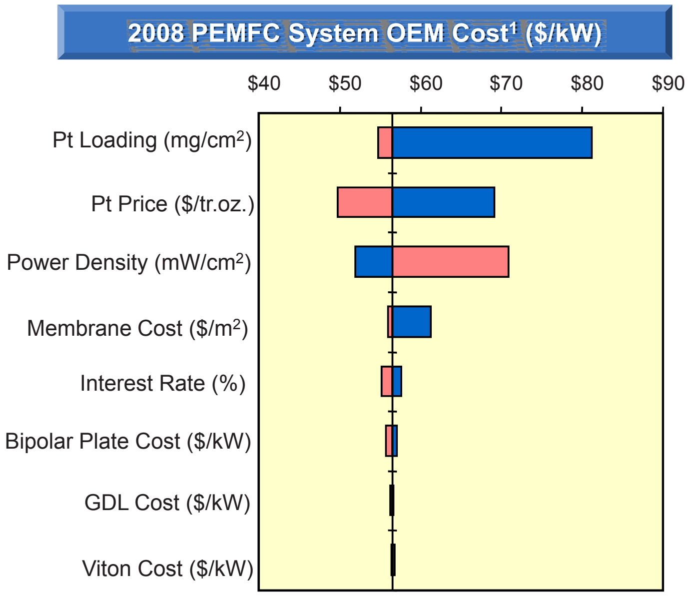


[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

[2] Assumes 15% markup to the automotive OEM for BOP components.

FIGURE 1. 2008 PEMFC Stack and System Cost [5]

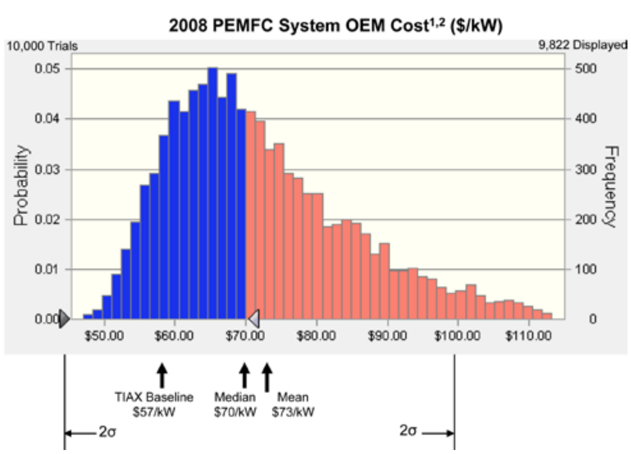
cost. As seen in Figure 2, Pt loading, power density, and Pt cost are the top three drivers of the PEMFC system OEM cost. The results of a multi-variable (Monte Carlo) analysis are shown in Figure 3; the high-volume 2008 PEMFC system OEM cost ranges between $45/kW and $101/kW (± 2σ), with the mean of the distribution being $73/kW [5].



#	Variables	Min.	Max.	Base	Comments
1	Pt Loading (mg/cm²)	0.2	0.75	0.25	Minimum: DOE 2015 target[2]; Maximum: TIAX 2005 report[3]
2	Pt Cost ($/tr.oz.)	450	2250	1100	Minimum: ~ 108-year min. in 2007 $[4]; Maximum: 12-month maximum LME price[5]
3	Power Density (mW/cm²)	350	1000	716	Minimum: industry feedback; Maximum: DOE 2015 target[2].
4	Membrane Cost ($/m²)	10	50	16	Minimum:GM[6] study; Maximum: DuPont[7] projection from 2002
5	Interest Rate	8%	20%	15%	Based on industry feedback
6	Bipolar Plate Cost ($/kW)	1.8	3.4	2.7	Based on component single variable sensitivity analysis
7	GDL Cost ($/kW)	1.7	2.2	2.0	Based on component single variable sensitivity analysis
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 only for BOP components.
2. http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf
3. Carlson, E.J. et al., "Cost Analysis of PEM Fuel Cell Systems for Transportation", Sep 30, 2005, NREL/SR-560-39104
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 2. 2008 Stack Single-Variable Sensitivity Analysis [5]



Cost[1,2]	$/kW
Mean	73
Median	70
Std. Dev.	14
TIAX Baseline	57

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
[2] Assumes 15% markup to the automotive OEM for BOP components.

FIGURE 3. 2008 System Multi-Variable (Monte-Carlo) Analysis [5]

We are currently working with DOE and ANL to define the 2009 system configuration, update stack performance assumptions, system parasitics and BOP component specifications. Figure 4 shows a preliminary layout of the 2009 PEMFC system [5,7,8]. The key changes proposed over the 2008 configuration [3,4] are: the enthalpy wheel humidifier (EWH) will be replaced by a planar membrane humidifier (MH) with precooler for cathode air humidification; tubular MH for anode hydrogen humidification will be replaced by a planar MH; and the low-temperature (LT) radiator, LT coolant pump for air precooler, and needle metering valve for CEM will be included in the scope of the 2009 PEMFC system [5,7,8].

Our preliminary estimates show that the high-volume 2009 PEMFC stack cost for three scenarios ranges between $24/kW to $33/kW [5], based on initial results from ANL's stack and system modeling [7,8]. Table 3 outlines the key assumptions and cost of the three stack scenarios modeled in 2009 [5]. All scenarios assume a Pt cost of $1,100/tr.oz., NSTFC-based MEA, 30 µm PFSA membrane, and stack operating conditions of 90°C and 2.5 atm.

Using the 2008 estimate of $28/kW for the BOP and assembly cost [3,4], the preliminary 2009 PEMFC system OEM cost is estimated to range between $52/kW to $61/kW. These initial estimates will be finalized by the next reporting period.

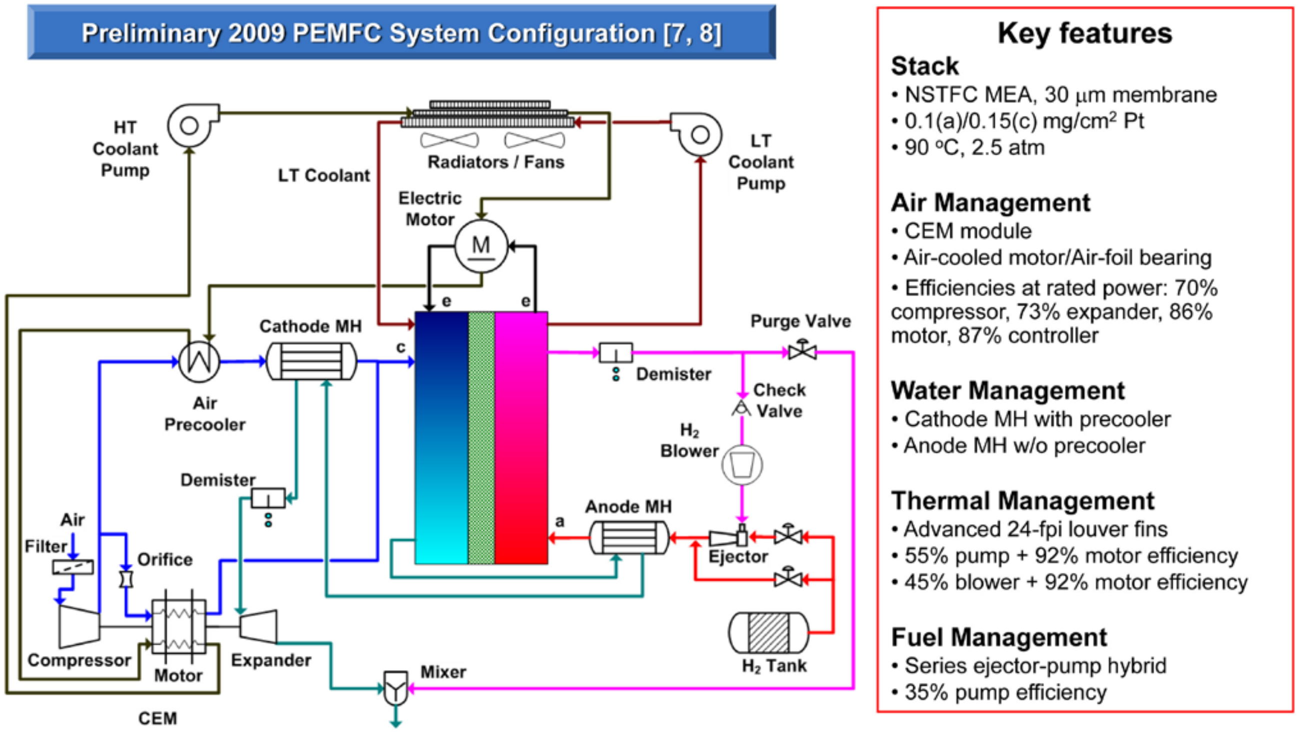


FIGURE 4. Preliminary 2009 PEMFC System Configuration [7,8]

TABLE 3. Preliminary 2009 PEMFC Stack Scenarios

Parameters	Units	2009 Stack Scenarios [5]		
		S1	S2	S3
System net power	kW_e	80		
Stack gross power	kW_e	91.6	92.0	92.5
Cell voltage (rated power)	V	0.721	0.685	0.655
Stack gross power density	mW/cm^2	640	837	966
Pt loading (total)	mg/cm^2	0.25		
Stack efficiency (rated power)	% LHV	57.4%	54.5%	52.1%
System efficiency (rated power)	% LHV	50.0%	47.3%	45.0%
System voltage (rated power)	V	300		
System Active area	m^2	14.3	11.0	9.6
Stack cost	**$\$/kW_{net}$**	**33**	**26**	**24**

Conclusions and Future Directions

- Both stack and BOP component costs are significantly reduced from the 2005 cost assessment. The 2008 PEMFC stack cost of $29/kW is ~57% lower than the 2005 stack cost [6] due to a significant reduction in Pt loading with increase in power density. The lower Pt loading is attributed to novel catalyst and support structure (i.e. NSTFC on organic whisker support). The 2008 PEMFC system cost of $57/kW is ~47% lower than the 2005 system cost [6] due to the use of bottom-up methodology for estimating high-volume cost of BOP components.
- With the much reduced stack cost of $29/kW in 2008, BOP and assembly together represent ~50% of the PEMFC system cost in 2008, compared to ~38% in 2005 [6].
- The CEM factory cost (without supplier markup) of approximately $7/kW is the largest contributor to the overall BOP cost [3-5].
- Platinum loading, power density, platinum cost, membrane cost and CEM cost are the top five drivers of the PEMFC system cost [5].
- The 2008 stack and system costs of $29/kW and $57/kW are ~15-30% higher than the DOE 2010 targets of $25/kW and $45/kW, respectively [3-5].
- Preliminary estimates for the high-volume 2009 PEMFC stack cost range between $24/kW and $33/kW for different stack scenarios. These initial estimates will be finalized by the next reporting period [5].

Our next steps are outlined below:

- Complete a comprehensive report on the 2008 PEMFC cost analysis (high-volume, bottom-up stack and BOP cost).
- Seek feedback from key developers, vendors and the Fuel Cell Tech Team on performance assumptions and cost analysis and incorporate any modifications.
- Finalize 2009 PEMFC system layout and performance assumptions. Update cost results for 2009 based on input from ANL, on-going development and testing of state-of-the-art PEMFC stacks and systems.

FY 2009 Publications/Presentations

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.

References

1. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, S. Lasher, J. Sinha, Y. Yang and S. Sriramulu, DOE Annual Merit Review, Washington, D.C., May 18, 2007.

2. *Cost Analyses of Fuel Cell Stacks/Systems*, S. Lasher, J. Sinha and Y. Yang, DOE Hydrogen Program Annual Report, V.A.5, 2007.

3. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, J. Sinha, S. Lasher, Y. Yang and P. Kopf, DOE Annual Merit Review, Washington, D.C., June 10, 2008.

4. *Cost Analyses of Fuel Cell Stacks/Systems*, J. Sinha, S. Lasher and Y. Yang, DOE Hydrogen Program Annual Report, V.A.3, 2008.

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

6. *Cost Analysis of PEM Fuel Cell Systems for Transportation*, E.J. Carlson, P. Kopf, J. Sinha, S. Sriramulu and Y. Yang, NREL Report - NREL/SR-560-39104, September 30, 2005.

7. *Status of Automotive Fuel Cell Systems*, R.K. Ahluwalia and X. Wang, internal communications, March 3 & May 10, 2009.

8. *Fuel Cell Systems Analysis*, R.K. Ahluwalia, X. Wang, K. Tajiri and R. Kumar, DOE Annual Merit Review, Arlington, VA, May 21, 2009.