# V.A.3 Cost Analyses of Fuel Cell Stack/Systems

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## Objectives

The overall objective is to develop cost analyses for an 80 kW (net) direct-hydrogen polymer electrolyte membrane fuel cell (PEMFC) system for automotive applications. This past year's (2007-2008) objectives were:

- Estimate the bottom-up manufactured cost for a 2007 PEMFC balance-of-plant (BOP), assuming current technology status, and high-volume production (500,000 units/year).
- Analyze the manufactured cost of the BOP for the 2007 PEMFC system with today's technology at different production scales (100, 30,000, 80,000, 130,000 and 500,000 units/year).
- Perform sensitivity analyses on key stack and system parameters, for high-volume production (500,000 units/year) of the 2007 PEMFC system.
- Update the bottom-up manufactured cost for the PEMFC system based on updated stack and system performance assumptions for 2008.

## Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section (3.4.6) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(B) Cost

## Contribution to Achievement of DOE Fuel Cells Milestones

This project will contribute to achievement of the following DOE milestones from the Fuel Cells section (3.4.4) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

**Milestone 71:** Update fuel cell technology cost estimate and compare it to the FY 2007 target of $90/kW for a hydrogen-fueled 80 kW fuel cell power system. (3Q, 2007)

**Milestone 73:** Update fuel cell technology cost estimate and compare it to the FY 2008 target of $70/kW for a hydrogen-fueled 80 kW fuel cell power system. (3Q, 2008)

## 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 2010 and 2015 cost targets and current high-volume cost estimates based on the 2007 system configuration are show in Table 1.

## Accomplishments

- Completed the bottom-up costing of the major BOP components in the 2007 PEMFC system configuration assuming current technology status, and high-volume production (500,000 units/year).
- Analyzed the manufactured cost of the major BOP components in the PEMFC system based on 2007 technology assumptions at different production scales (100, 30,000, 80,000, 130,000 and 500,000 units/year).

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

| Component | Cost Units | DOE 2010/2015 Targets | 2007 Status | 2008 Status (preliminary) | Comments |
|---|---|---|---|---|---|
| System | $/kW$_e$ | 45/30 | 59 | 57 | Based on bottom-up costing and an assumed 15% markup to the automotive original equipment manufacturer (OEM) for all major BOP components |
| Stack | $/kW$_e$ | 25/15 | 31 | 29 | Based on bottom-up costing for all major stack components |
| CEM | $/unit | 400/200 | 615 | | Assumes 15% markup to the automotive OEM |
| Membrane | $/m$^2$ | 20/20 | 16 | | |
| Electrocatalyst | $/kW$_e$ | 5/3 | 18 | | |
| MEA | $/kW$_e$ | 10/5 | 22 | | |
| Bipolar Plates | $/kW$_e$ | 5/3 | 3 | | |

CEM - compressor/expander/motor
MEA - membrane electrode assembly
OEM - original equipment manufacturer

- Performed single-variable and multi-variable (Monte Carlo) sensitivity analyses on key stack and system parameters, for high-volume production (500,000 units/year).

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## Introduction

The DOE seeks to develop a durable fuel cell power system for transportation applications. A rigorous, bottom-up analysis of projected manufactured cost is required to accurately gauge the status and potential of fuel cell technology based on scenarios that 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, starting with a reformate-based system and then direct hydrogen system when the former effort was ended in 2004.

As fuel cell vehicle technology starts to go through field demonstrations, the question of fuel cell system cost at low-volume, during early stages of commercialization, becomes pertinent. At low production volumes, material and processing costs will not benefit from manufacturing economies of scale (EOS), making the overall system much more expensive than at high production volumes. In addition, processing costs can be expected to be a much larger percentage of the manufactured cost at low-volume. Understanding the major cost contributors at low-volume can highlight near-term approaches and processes that might be necessary during the early stages of fuel cell vehicle commercialization.

## 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, activities-based cost model which is used in conjunction with the conventional Boothroyd-Dewhurst Design for Manufacturing (DFM) 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 document the bill of materials (BOM) based on the system performance modeling provided by Argonne National Laboratory (ANL), determine material costs at the assumed production volume, develop process flow charts, 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 developer and stakeholder feedback on the key performance assumptions, process parameters, and material cost assumptions; we calibrate our model using this feedback.

For the EOS analysis, we used a bottom-up approach to determine the impact of production volume on the manufactured cost of each major BOP component. We developed three production scenarios – pilot plant, semi-scaled and full-scaled – to represent a phased advance from proof-of-concept to mature manufacturing process. For each of the scenarios, we included the impact of volume on material price, process type, process parameters, choice of equipment and level of automation (i.e. equipment capital cost) for the major BOP components. For each major BOP component, we then developed cost vs. volume curves over the entire range of production volumes for the three scenarios. An integrated BOP cost curve was compiled from these three curves comprising the lowest cost scenario at that production volume. The production volume estimates requested by DOE (100, 30,000, 80,000, 130,000 and 500,000 units/year) were placed on this integrated curve.

## Results

Throughout this document, we report a "factory cost," which is a bottom-up estimate of the high-volume manufactured 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 are assumed to be purchased and therefore implicitly include supplier markup.

In the previous reporting period, we reported on the 2007 PEMFC stack cost projection [1,2]. Key performance assumptions (power density, platinum loading) were updated by ANL based on modeling and data from a nano-structured thin film catalyst-based stack. Overall, the 2007 assumptions lowered the stack cost by 45% to $31/kW [1,2] and the system cost by 39% to $59/kW [1,2] over the 2006 estimates [3].

We worked with DOE and ANL to define the 2007 system configuration and component specifications [1,2,4]. ANL developed the system layout so that it meets the DOE 2010 target of 50% system efficiency at rated power, and comes close (57%) to achieving the DOE 2010 target of 60% system efficiency at 25% of rated power [4].

During this reporting period, we focused on performing bottom-up costing for the major BOP sub-systems for thermal, water, air and fuel management. Thermal management includes a heat exchanger, a radiator fan and a high-temperature coolant pump. Water management (relative humidity control) has two parts – an enthalpy wheel for the air stream, and a membrane humidifier for the fuel stream. Air management comprises a CEM module. Fuel management consists of a hydrogen recirculation blower and hydrogen ejectors. We used experience-based estimates for the minor BOP components such as radiator fan, coolant pump, enthalpy wheel motor, hydrogen ejectors, sensors, controls, valves and regulators, all of which are assumed to be purchased components.

The thermal management system cost was based on a Modine all-aluminum tube-fin automobile radiator design. We developed a manufacturing process flow chart and BOM for the heat exchanger based on Modine patents (U.S. Patent 5,350,012 and U.S. Patent 7,032,656) and in-house experience. The 2007 price of the thermal management system is estimated to be $220, wherein the factory cost of the radiator is $56/unit, of which 40% is material cost. The radiator fan and coolant pump were assumed to be purchased components.

The membrane humidifier (for fuel stream humidification) manufacturing process was based on discussions with PermaPure on their FC200-780-7PP Series™ humidifiers. We used U.S. Patents 5,486,328, 5,515,672, and 5,569,429 to develop manufacturing process flow charts and BOM for the membrane humidifier. The material cost represents approximately 44% of the $58 membrane humidifier manufactured cost. The enthalpy wheel humidifier (for air stream humidification) BOM was deduced from Emprise patents, white papers and personal communications. The motor is the largest contributor, followed by the cordierite core, to the $160 cost of the enthalpy wheel humidifier.

We used the Boothroyd-Dewhurst DFM Concurrent Costing package to estimate costs for the CEM. The overall compressor/expander design was referenced from Honeywell/DOE project presentations from 2000 to 2005 and U.S. Patent 5,605,045. The major sub-assemblies (e.g. variable nozzle vanes, motor, air bearing) were referenced from U.S. Patents and other public materials. The CEM motor stator and rotor assembly were referenced from Honeywell/DOE 2005 program review and U.S. Patent 5,605,045. The journal air bearing assemblies were referenced from Honeywell/DOE project presentations and U.S. Patent 2006/0153704. The turbine variable nozzle vanes and control assembly were referenced from U.S. Patent 6,269,642 and a Garrett/Honeywell DOE report, DE-FC05-00OR22809. The manufactured cost of the CEM (including motor and motor controller) is projected to be $535 per unit. The motor assembly and motor controller are estimated to cost $412, representing 77% of the CEM manufactured cost. The 5.5 kW inverter is projected to dominate the CEM motor controller cost.

The hydrogen blower costing was based on published information and patents on the Parker Hannifin Model 55™ Univane rotary compressor. The rotor and single vane structure are referenced from U.S. Patent 5,374,172. We used the Boothroyd-Dewhurst DFM Concurrent Costing package to estimate costs for the $H_2$ blower. The manufactured cost of the $H_2$ blower is projected to be $193 per unit. The rotor/vane assembly, blower housing and DC motor are the top three cost drivers for the $H_2$ blower.

Table 2 is a summary of the factory and OEM cost of the BOP sub-systems of the PEMFC system; the high-volume factory cost for the BOP components is projected

**TABLE 2.** Cost Summary for BOP Components

| BOP Sub-System | Component | Technology Basis | Factory Cost, $ (without supplier markup) | OEM Cost, $ (with 15% supplier markup) |
|---|---|---|---|---|
| Water Management | Enthalpy wheel air-humidifier | Emprise | 160 | 184 |
| | Membrane $H_2$-humidifier | PermaPure | 58 | 66 |
| | Other | - | 10 | 10 |
| Thermal Management | Automotive tube-fin radiator | Modine | 57 | 65 |
| | Radiator fan | - | 35 | 35 |
| | Coolant pump | - | 120 | 120 |
| | Other | - | 5 | 5 |
| Air Management | Compressor-Expander-Motor (CEM) | Honeywell | 535 | 615 |
| | Other | - | 97 | 97 |
| Fuel Management | $H_2$ blower | Parker Hannifin | 193 | 222 |
| | $H_2$ ejectors | - | 40 | 40 |
| | Other | - | 41 | 41 |
| Total | | | 1,351 | 1,500 |

to be ~$1,350. The CEM factory cost of ~$7/kW is the largest contributor to the overall BOP cost.

Figure 1 shows the breakdown of the overall factory and OEM cost for the stack and the BOP sub-systems. Both stack and BOP component costs are significantly reduced from the 2005 cost assessment. With the much reduced stack cost of $31/kW in 2007, BOP components make up a much larger fraction of the PEMFC system cost. BOP component costs represent ~46% of the PEMFC system cost in 2007, as compared to ~38% in 2005. As seen in Table 3, the 2007 projected PEMFC stack and system costs are ~25-30% higher than the DOE 2010 cost targets.

While our focus is on cost, we also independently evaluated power density and specific power for the stack and system. Figure 2 shows our weight and volume estimates for the PEMFC stack and BOP sub-systems. We see that the 2007 PEMFC configuration meets or exceeds DOE 2010 targets for stack and system power density and system specific power; it falls short of the DOE 2010 target for stack specific

| PEMFC System Cost [1] ($/kW) | 2005 OEM Cost | 2007 Factory Cost [1] | 2007 OEM Cost [1,2] |
|---|---|---|---|
| **Stack** | **67** | **31** | **31** |
| Water Management | 8 | 2.8 | 3.3 |
| Thermal Management | 4 | 2.7 | 2.8 |
| Air Management | 14 | 7.9 | 8.9 |
| Fuel Management | 4 | 3.4 | 3.8 |
| Miscellaneous | 7 | 3.1 | 3.1 |
| Assembly | 4 | 5.5 | 5.5 |
| **Total** | **108** | **57** | **59** |

[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

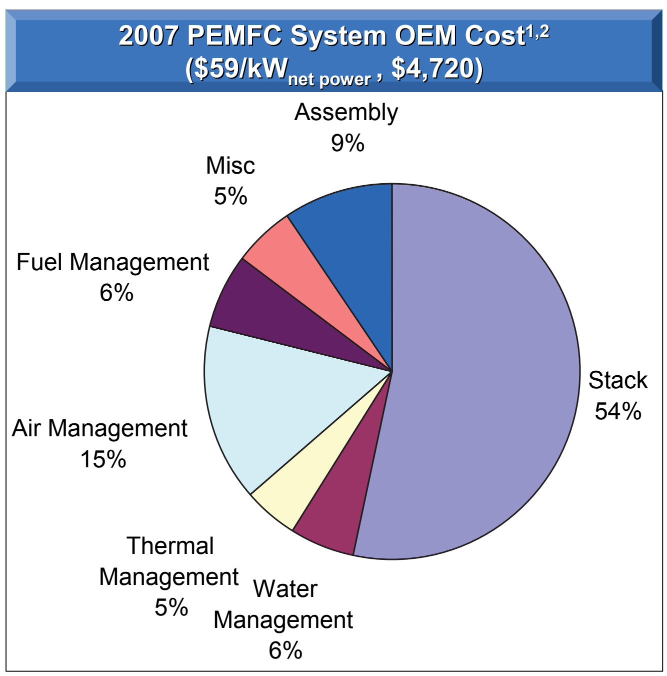



**FIGURE 1.** 2007 PEMFC System OEM Cost

**TABLE 3.** Comparison of Stack and System Cost to DOE 2010 Targets

| PEMFC Sub-System | Factory Cost, $/kW (without supplier markup) | OEM Cost, $/kW (with 15% supplier markup) | DOE 2010 Cost Target, $/kW |
|---|---|---|---|
| Stack | 31 | | 25 |
| Balance-of-Plant | 26 | 28 | 20 |
| Water management (enthalpy wheel, membrane humidifier) | 2.8 | 3.3 | |
| Thermal management (radiator, fan pump) | 2.7 | 2.8 | |
| Air management (CEM, motor controller | 7.9 | 8.9 | 5 |
| Fuel management ($H_2$ blower, $H_2$ ejectors | 3.4 | 3.8 | |
| Miscellaneous and assembly | 8.6 | | |
| Total System | 57 | 59 | 45 |

power. It is important to note that these estimates do not include a packing factor, which would lower the volumetric power density.

We performed single and multi-variable sensitivity analyses to examine the impact of the major stack and BOP parameters on the high-volume PEMFC system cost. As seen in Figure 3, platinum (Pt) loading, power density and Pt cost are the top three drivers of the PEMFC system OEM cost. 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 analysis. Figure 4 shows that among the BOP components, the CEM has the greatest impact on the PEMFC system OEM cost. The results of a multi-variable (Monte Carlo) analysis are shown in Figure 5; the high-volume PEMFC system OEM cost ranges between $45/kW and $97/kW ($\pm 2\sigma$).

We also analyzed the manufactured cost of the 2007 PEMFC BOP at DOE specified production volumes for three manufacturing scenarios - pilot plant, semi-scaled and full-scaled production. As seen in Figure 6, we found that at low production volumes (~100 units/year), the pilot plant yields the lowest BOP cost of ~$339/kW, while at high production volumes (≥80,000 units/year), the full-scaled scenario yields the lowest BOP cost of ~$26/kW.

| PEMFC Sub-System | Volume[1] (L) | Weight (kg) | DOE 2010 Target |
|---|---|---|---|
| **Stack** | **40** | **47** | |
| Power density[2] ($W_e$/L) | 2,000 | | 2,000 |
| Specific power[2] ($W_e$/kg) | 1,702 | | 2,000 |
| **Balance of Plant** | **78** | **63** | |
| Water management (enthalpy wheel, membrane humidifier) | 14 | 10 | |
| Thermal management (radiator, fan, pump) | 25 | 5 | |
| Air management (CEM, motor controller) | 15 | 20 | |
| Fuel management ($H_2$ blower, $H_2$ ejectors) | 5 | 7 | |
| Miscellaneous and assembly | 19 | 21 | |
| **Total System** | **118** | **110** | |
| Power density[2] ($W_e$/L) | 678 | | 650 |
| Specific power[2] ($W_e$/kg) | 727 | | 650 |

[1] Does not include packing factor, which would lower volumetric power density.
[2] Based on stack net power output of 80 kW, and **not** on the gross power output of 86.5 kW

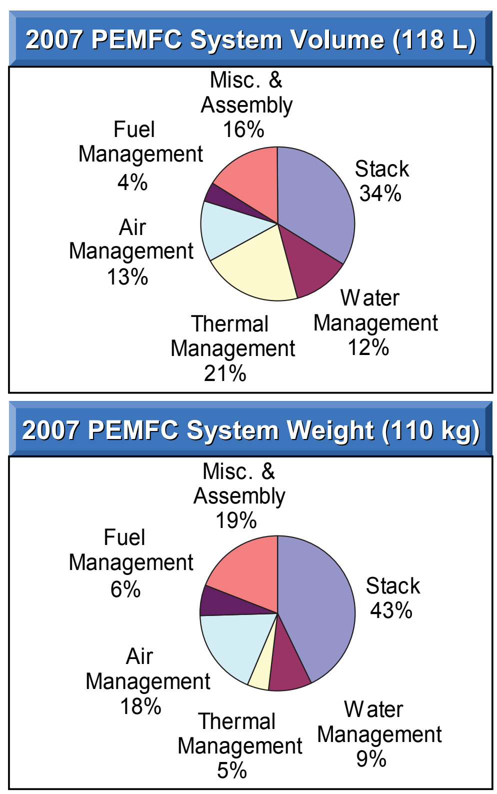
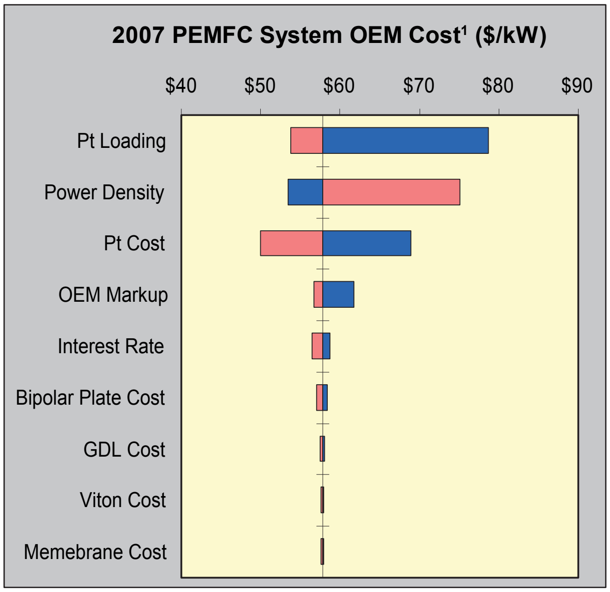


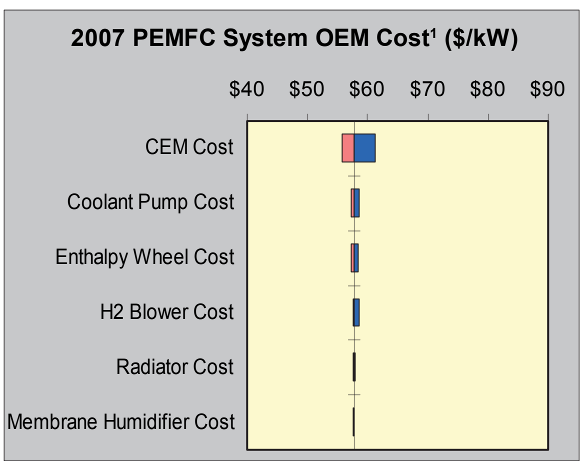

**FIGURE 2.** 2007 PEMFC System Weight and Volume




| # | Variables | Minimum | Maximum | Base | Comments |
|---|---|---|---|---|---|
| 1 | Pt Loading (mg/cm$^2$) | 0.2 | 0.75 | 0.3 | Minimum: DOE 2015 target[2]; Maximum: TIAX 2005 study[3] |
| 2 | Power Density (mW/cm$^2$) | 350 | 1000 | 753 | Minimum: industry feedback; Maximum: DOE 2015 target[2]. |
| 3 | Pt Cost ($/tr.oz.) | 450 | 2000 | 1100 | Minimum: historical average[4]; Maximum: current LME price[5] |
| 4 | OEM Markup | 5% | 20% | 15% | Based on industry feedback |
| 5 | Interest Rate | 8% | 20% | 15% | Based on industry feedback |
| 6 | Bipolar Plate Cost ($/kW) | 1.8 | 3.4 | 2.6 | Based on component single variable sensitivity analysis |
| 7 | GDL Cost ($/kW) | 1.7 | 2.2 | 1.9 | Based on component single variable sensitivity analysis |
| 8 | Viton Cost ($/kg) | 39 | 58 | 48 | Based on industry feedback |
| 9 | Membrane Cost ($/m$^2$) | 10 | 50 | 16 | Minimum: GM study[6]; Maximum: DuPont projection[7] |

[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] 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 3.** Stack Single-Variable Sensitivity Analysis

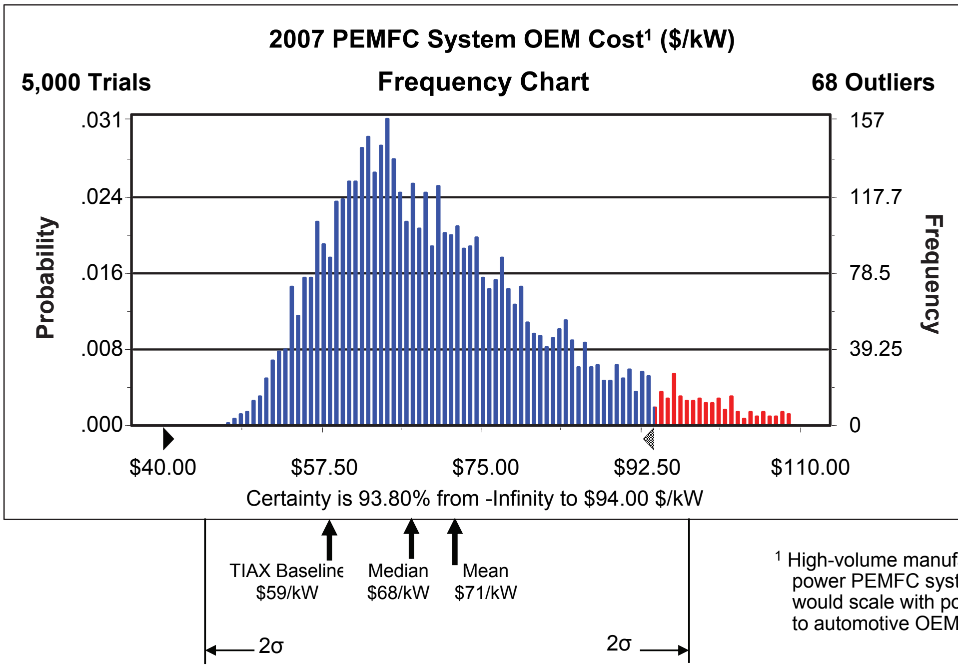



[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Assumes a % markup to automotive OEM for BOP components.

| # | Variables | Minimum | Maximum | Base | Comments |
|---|---|---|---|---|---|
| 1 | CEM Cost ($/unit) | 368 | 808 | 535 | Based on component single variable sensitivity analysis |
| 2 | Coolant Pump Cost ($/unit) | 80 | 200 | 120 | Based on industry feedback |
| 3 | Enthalpy Wheel Cost ($/unit) | 123 | 217 | 160 | Based on component single variable sensitivity analysis |
| 4 | H2 Blower Cost ($/unit) | 178 | 259 | 193 | Based on component single variable sensitivity analysis |
| 5 | Radiator Cost ($/unit) | 46 | 71 | 56 | Based on component single variable sensitivity analysis |
| 6 | Membrane Humidifier Cost ($/unit) | 46 | 62 | 58 | Based on component single variable sensitivity analysis |

**FIGURE 4.** BOP Single-Variable Sensitivity Analysis

We have a preliminary estimate of the 2008 PEMFC cost based on initial input from ANL's updated system modeling; the system configuration is unchanged from 2007. Assuming a gross stack power density of 716 mW/cm$^2$, total Pt loading of 0.25 mg/cm$^2$, cell voltage of 0.68 V, net system parasitics of 7 kW, and Pt cost of $1,100/tr.oz., we estimate the stack cost is ~$29/kW, of which the electrodes represent ~54%. Using the 2007 estimate for the BOP cost, the 2008 PEMFC OEM cost is projected to be ~$57/kW. These preliminary estimates will be updated.




| Cost[1] | $/kW |
|---|---|
| *Mean* | 71 |
| *Median* | 68 |
| *Std. Dev.* | 13 |
| *TIAX Baseline* | 59 |

[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 5.** 2007 PEMFC System Monte Carlo Analysis

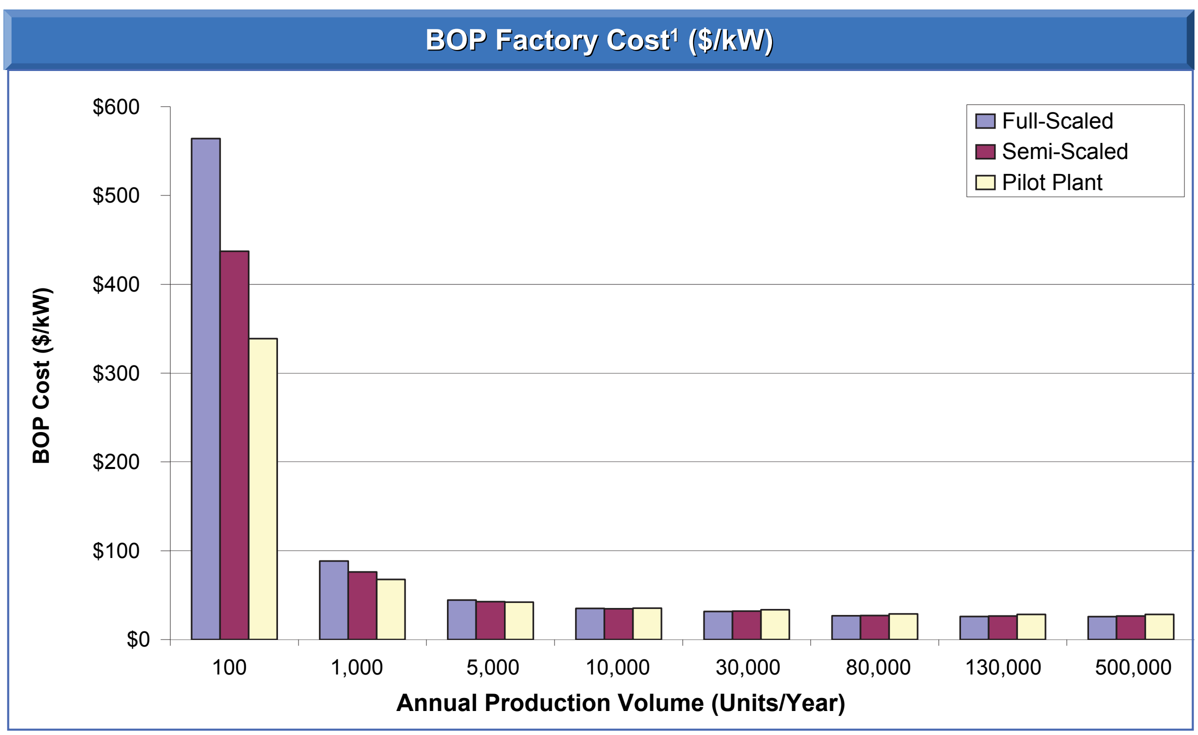



**FIGURE 6.** EOS Analysis on 2007 BOP Cost

## Conclusions and Future Directions

- The projected 2007 PEMFC system cost of $59/kW is 39% lower than the 2006 system cost [3] and 45% lower than the 2005 system cost [5] primarily due to the decrease in the stack cost, and due to the lower bottom-up cost estimate for the BOP.
- Both stack and BOP component costs are significantly reduced from the 2005 cost assessment. With the much reduced stack cost of $31/kW in 2007, BOP components make up a much larger fraction of the PEMFC system cost. BOP component costs represent ~46% of the PEMFC system cost in 2007, as compared to ~38% in 2005.
- The CEM factory cost (without supplier markup) of approximately $7/kW is the largest contributor to the overall BOP cost.
- The results of a multi-variable (Monte Carlo) analysis show that the high-volume PEMFC system OEM cost ranges between $45/kW and $97/kW ($\pm 2\sigma$).
- At low production volumes (~100 units/year), the pilot plant yields the lowest BOP cost of ~$339/kW, while at high production volumes (≥80,000 units/year), the full-scaled scenario yields the lowest BOP cost of ~$26/kW.
- A preliminary estimate for the 2008 PEMFC stack cost is ~$29/kW, of which the electrodes represent ~54%. Using the 2007 estimate for the BOP cost, the 2008 PEMFC OEM cost is projected to be ~$57/kW.

Our next steps are outlined below:

- Prepare a comprehensive report on the 2007 bottom-up costing of the PEMFC stack and BOP, at high-volume production (500,000 units/year).
- Seek feedback from key developers, vendors and the Fuel Cell Tech Team on performance assumptions and cost analysis and incorporate any modifications.
- Finalize performance assumptions and update cost results for 2008 based on input from ANL, and on-going development and testing of state-of-the-art PEM fuel cell stacks and systems.

## FY 2008 Publications/Presentations

1. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, J. Sinha et al., Presentation to Dr. JoAnn Milliken and the DOE HFCIT Team at DOE HQ, Washington D.C., November 28, 2007.
2. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, J. Sinha et al., FreedomCAR Fuel Cell Tech Team presentation, Detroit MI, May 16, 2008.
3. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, S. Lasher, J. Sinha, Y. Yang, S. Sriramulu, DOE Annual Merit Review, Washington, D.C., June 10, 2008.

## References

1. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, S. Lasher, J. Sinha, Y. Yang, S. Sriramulu, DOE Annual Merit Review, Washington, D.C., May 18, 2007.
2. *Cost Analyses of Fuel Cell Stack/Systems*, S. Lasher, J. Sinha, Y. Yang, DOE Hydrogen Program Annual Report, V.A.5, 2007.
3. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, E.J. Carlson et al., poster session at DOE Hydrogen Program Annual Merit Review, Washington, D.C., May 2006.
4. *Fuel Cell Systems Analysis*, R.K. Ahluwalia, X. Wang and R. Kumar, DOE Hydrogen Program Annual Merit Review, Arlington, VA, May 2007.
5. *Cost Analysis of PEM Fuel Cell Systems for Transportation*, E.J. Carlson, P. Kopf, J. Sinha, S. Sriramulu, Y. Yang, NREL Report - NREL/SR-560-39104, September 30, 2005.