V.A.2 Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell System for Automotive Applications

Brian D. James (Primary Contact), Jeffrey A. Kalinoski
Directed Technologies, Inc. (DTI)
3601 Wilson Blvd., Suite 650
Arlington, VA 22201
Phone: (703) 243-3383; Fax: (703) 243-2724
E-mail: brian_james@directedtechnologies.com

DOE Technology Development Manager: Jason Marcinkoski
Phone: (202) 586-7466; Fax: (202) 586-9811
E-mail: Jason.Marcinkoski@ee.doe.gov

DOE Project Officer: Gregory Kleen
Phone: (303) 275-4875; Fax: (303) 275-4788
E-mail: Greg.Kleen@go.doe.gov

Technical Advisor: Walt Podolski
Phone: (630) 252-7558; Fax: (630) 972-4430
E-mail: podolski@cmt.anl.gov

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Objectives

1. Identify the lowest cost system design and manufacturing methods for an 80 kW_e direct-H_2 automotive proton exchange membrane (PEM) fuel cell system based on three technology levels:
   - Current status
   - 2010 projected performance
   - 2015 projected performance
2. Determine costs for these three technology level systems at five production rates:
   - 1,000 vehicles per year
   - 30,000 vehicles per year
   - 80,000 vehicles per year
   - 130,000 vehicles per year
   - 500,000 vehicles per year
3. Analyze, quantify and document the impact of fuel cell system performance on cost.
   - Use cost results to guide future component development

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 will provide realistic, defensible fuel cell power systems cost estimates for comparison with the DOE technical targets. Insights gained from these estimates will help to adjust and further validate the DOE targets. Furthermore, our analysis will shed light on the areas in need of the most improvement and thereby provide guidance for future fuel cell research and development efforts.

TABLE 1. DOE Targets/DTI Estimates (at 500,000 Systems/Year Manufacturing Rate)

Stack Cost, $/$kW_{e\ (net)}$	2005 Status	Current (2006/2007/2008)	2010	2015
DOE Target:	$65	-	$25	$15
DTI 2006 Estimate (Year 1):	-	$66	$30	$25
DTI 2007 Estimate (Year 2):	-	$50	$27	$23
DTI 2008 Estimate (Year 3):	-	$38	$29	$25
System Cost, $/$kW_{e\ (net)}$				
DOE Target:	$125	-	$45	$30
DTI 2006 Estimate (Year 1):	-	$108	$70	$59
DTI 2007 Estimate (Year 2):		$94	$66	$53
DTI 2008 Estimate (Year 3):	-	$72	$65	$51

Accomplishments

- Improved existing conceptual design and component specification of complete fuel cell power systems at three technology levels (2008, 2010, and 2015).
- Completed 2008 Status Update Report (2008, 2010, 2015 technologies).

- Performed detailed sensitivity analysis using tornado charts and Monte Carlo techniques.
- Analyzed new technologies and manufacturing alternatives.
- Identified components and systems that warrant further research.

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Introduction

In this project, DTI has built on previous analyses to estimate the cost of 80 $kW_{e\ (net)}$ PEM fuel cell vehicular power systems at five annual production rates (1,000, 30,000, 80,000, 130,000, and 500,000 systems per year) and three levels of projected fuel cell and manufacturing technology (current, 2010, and 2015). During the first year of the project, we investigated the technology and prepared the cost models to reflect 2006, 2010, and 2015 estimates of PEM technology. This annual report covers the third year of the DTI project and focuses on refinement of the cost estimates and an update to reflect 2008 advances in technology.

A Design for Manufacturing and Assembly (DFMA®) methodology is employed to obtain the cost estimates. DFMA® is a methodology created by Boothroyd Dewhurst Inc. to systematically estimate the manufacturing and assembly costs of a component or system. By analyzing variations in component design and manufacturing methods, one can conduct a comparative cost analysis and determine the pathway to achieving the lowest system cost. Normally, a markup rate is used within the DFMA® methodology to reflect the business costs of general and administrative, scrap, research and development (R&D), and profit and is applied to all levels contributing to the effort (original equipment manufacturer, Tier 1, Tier 2, etc.). However, per DOE directive for this project, a markup is only applied to lower-tier supplied materials and components, not to materials or operations conducted by the highest-tier fuel cell assembler. (Scrap costs are included at the component level but not at the system level.)

The costs reported in this document reflect the values from the 2008 status update.

Approach

There are four main steps to our approach: research, system modeling, component design, and application of DFMA®-style redesign and costing techniques. The first step, research, has been conducted continuously throughout the project. It encompasses the review of published materials and patents, as well as interviews with key researchers and manufacturers. This provides a common ground assessment of the system layout and technologies currently used or anticipated to be used by the fuel cell system community. After enough information was collected to move forward, a preliminary system concept and mechanical/piping layout were developed to meet the technical requirements for each of the three different systems to be examined: current, 2010, and 2015 technologies. Excel spreadsheet-based performance models were used to determine heat loads, mass flows, compositions, and pressure levels throughout the systems. The flow diagrams were then iteratively modified to obtain a projected optimal configuration and performance.

Armed with the preliminary system concepts and layouts, we designed each of the main components that make up the system. This involved specifying the detailed geometries of the flow plates, gaskets, membrane electrode assemblies (MEAs), etc., and determining which materials to use. The most appropriate manufacturing processes to use for each component were then selected based primarily on cost, but with consideration of the performance and durability parameters. Several different cases were analyzed when it was unclear which approach was best, and the component designs were adjusted to suit the manufacturing method. For each component, we defined a manufacturing process train, and then applied our costing methodologies to it. Using a comprehensive DFMA®-style approach, we calculated the manufacturing process costs, setup costs, material costs, and assembly costs, and then summed them to determine the total costs for the stack and the system. Amortization of the machinery capital costs and expendable tooling, as well as labor costs (including indirect labor costs for fringe benefits) were included in the cost estimates. The costs of some non-stack components such as radiators, pumps, blowers, controllers, sensors, etc. were calculated by a simplified DFMA®-style methodology, or were based on price quotations from vendors.

Results

The cost differences across the three different technology levels (see Table 2 and Figure 1) were driven primarily by expected improvements in stack power density (715 to 1,000 mW/cm^2), total platinum loading (0.25 to 0.2 $mgPt/cm^2$), operating pressure (2.3 to 1.5 atm), and peak stack temperature (90 to 120°C). Stack cost reductions primarily resulted from increased power density and decreased platinum loading. Balance-of-plant (BOP) cost reductions stemmed primarily from system simplifications (i.e. reduced or eliminate components). For example, the current technology system uses water spray injection for the air humidification, the 2010 system uses a polyamide membrane humidification system, and the 2015 has no air humidification system at all. Simplifications of

TABLE 2. System Comparison

	2008 Technology System	2010 Technology System	2015 Technology System
Power Density (mW/cm²)	715	1000	1000
Total Pt loading (mgPt/cm²)	0.25	0.3	0.2
Operating Pressure (atm)	2.3	2	1.5
Peak Stack Temp. (°C)	70-90	99	120
Membrane Material	Nafion on ePTFE	Advanced High-Temperature Membrane	Advanced High-Temperature Membrane
Radiator/Cooling System	Aluminum Radiator, Water/Glycol coolant, DI filter	Smaller 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
Air Compression	Twin Lobe Compressor, Twin Lobe 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
Catalyst Application	Double-sided vertical die-slot coating of membrane	Double-sided vertical die-slot coating of membrane	Double-sided vertical die-slot coating of membrane
Air Humidification	Water spray injection	Polyamide Membrane	None
H_2 Humidification	None	None	None
Exhaust Water Recovery	SS Condenser (Liquid/Gas HX)	SS Condenser (Liquid/Gas HX)	None
MEA Containment	Injection molded LIM Hydrocarbon MEA	Injection molded LIM Hydrocarbon MEA	Injection molded LIM Hydrocarbon MEA
Coolant & End Gaskets	Laser Welding/Screen Printed Resin	Laser Welding/Screen Printed Resin	Laser Welding/Screen Printed Resin
Freeze Protection	Drain water at shutdown	Drain water at shutdown	Drain water at shutdown
H_2 Sensors	2 H_2 sensors *(for FC sys),* 1 H_2 sensor *(for passenger cabin; not in cost estimate),* 1 H_2 sensor *(for fuel sys; not in cost estimate)*	1 H_2 sensor *(for FC sys),* 1 H_2 sensor *(for passenger cabin; not in cost estimate),* 1 H_2 sensor *(for fuel sys; not in cost estimate)*	No H_2 sensors
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
Stack/System Conditioning	5 hours of power conditioning	4 hours of power conditioning	3 hours of power conditioning

the air, humidification, and coolant systems yielded the majority of technology improvement savings.

The stack cost decreases with advancing technology level due to both power density improvement and gross power reduction. Major cost reductions are not currently projected as a result of manufacturing method change or material selection. Rather, future improvements in stack power density (as a result of expected improved MEA performance) results in the cells shrinking geometrically and thereby incurring less material cost. Additionally, gross power requirements (ranging from 90.3 to 87.1 kW_e) are directly driven by the aforementioned BOP component selection (specifically, the differing air compression approaches), and lead to further cell size and cost reduction.

Unsurprisingly, the stack cost is the largest and most important contributor to the system cost. While most of the BOP components are based on modifications of proven, existing technology, the stack designs are comparatively immature. The impact of this is twofold: the stack has the most room for technological improvement and the component production methods are less defined. Therefore, most of our analysis is focused on the stack, since it provides the most potential for cost improvement.

One of the key changes for the 2008 update (compared to the 2007 estimate) is in selection of the power density and platinum loading levels. High power density generally correlates with high Pt loading thus a careful optimization must be conducted to achieve the lowest cost design point. Based on 2008 estimates of performance, the power density and platinum loading design point was re-optimized to 715 mW/cm^2 at 0.25 mg Pt/cm^2 (2008 status) from the previous 583 mW/cm^2 at 0.3 mg Pt/cm^2 (2007 status). (Design points for 2010 and 2015 remain unchanged.) Decreasing the platinum loading resulted in a major cost reduction ($9.81/kW) and increasing the power density resulted in another significant cost decrease ($7.17/kW). The net effect of these two changes is a $16.98/kW cost reduction, which represents the majority of the $18.51 drop in system cost from 2007 status levels.

Though no other change had as much impact as those two, a variety of other important changes helped to further reduce the system cost, and many of them did so for all three technology levels. By switching to laser-welded coolant gaskets and screen-printed end gaskets, another $4.06/kW was saved. Halving the number of system controllers (from two to one) cut $2.50/kW from the cost, and adjusting the labor rate from $60/hr to $45/hr dropped it another $1.24/kW. However there were also a few changes which increased cost, such as

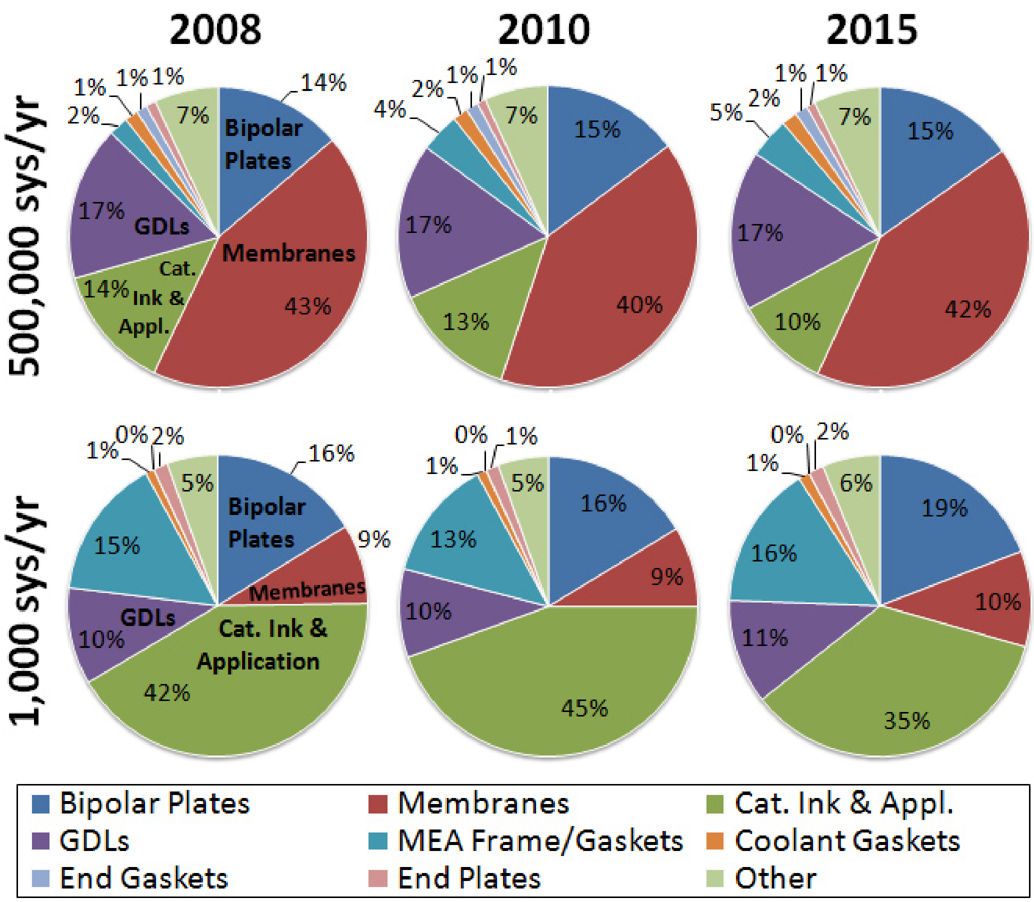

FIGURE 1. Stack Cost Component Distribution

updating material and machinery prices ($1.92/kW), and the addition of a coating on the stamped metal bipolar plates ($1.77/kW). Because the 2010 and 2015 systems did not benefit from the same improvements in power density and catalyst loading as the current technology did, stack cost projections actually went up for those two systems. Fortunately cost savings from the BOP components were able to compensate for these increases, so the overall system costs went down for all three systems (as compared to the 2007 analysis).

Numerous other minor assumption changes were made, the result of which yields a small cumulative net savings: while their net effect is comparatively small, the improvements improve the analysis appreciably and lead to greater confidence in the cost estimates.

At 500,000 systems per year, the total cost for the stacks, including assembly and stack conditioning, comes to $\$38/kW_{net}$, $\$29/kW_{net}$, and $\$25/kW_{net}$, for the 2008, 2010, and 2015 technology year cost projections, respectively (see Figure 2). These should be compared to the 2010 and 2015 DOE stack targets of $\$25/kW_{net}$, and $\$15kW_{net}$. When accounting for the BOP items, the system costs are roughly double that of the stacks alone and sum to $\$75/kW_{net}$, $\$62/kW_{net}$, and $\$51/kW_{net}$

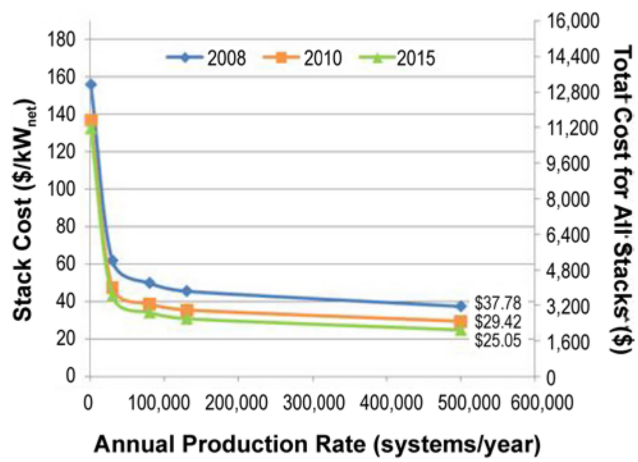

FIGURE 2. Stack Cost in $\$/kW_{e\ (net)}$

for 2008, 2010, and 2015, respectively, all at 500,000 systems per year (see Figure 3).

Note that platinum cost is held constant at $1,100 per troy ounce to allow direct comparison with previous estimates. System cost is highly dependent on this

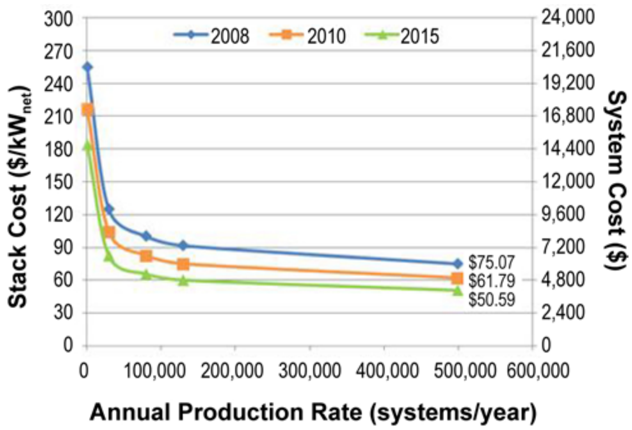

FIGURE 3. System Cost in $/kW$_{e\,(net)}$

assumption, especially for the current technology system, which has a relatively high Pt loading and low power density. In recent months, the platinum prices have returned to roughly $1,150 per troy ounce, which validates the $1,100 used. However, if prices were to return to their 2008 peak of $2,280 per troy ounce, the stack costs would leap by $16, $13, and $9 per kW$_{net}$ for the three different technology levels, respectively. Sensitivity analysis tornado charts for the 2008 and 2015 system cost are shown in Figure 4.

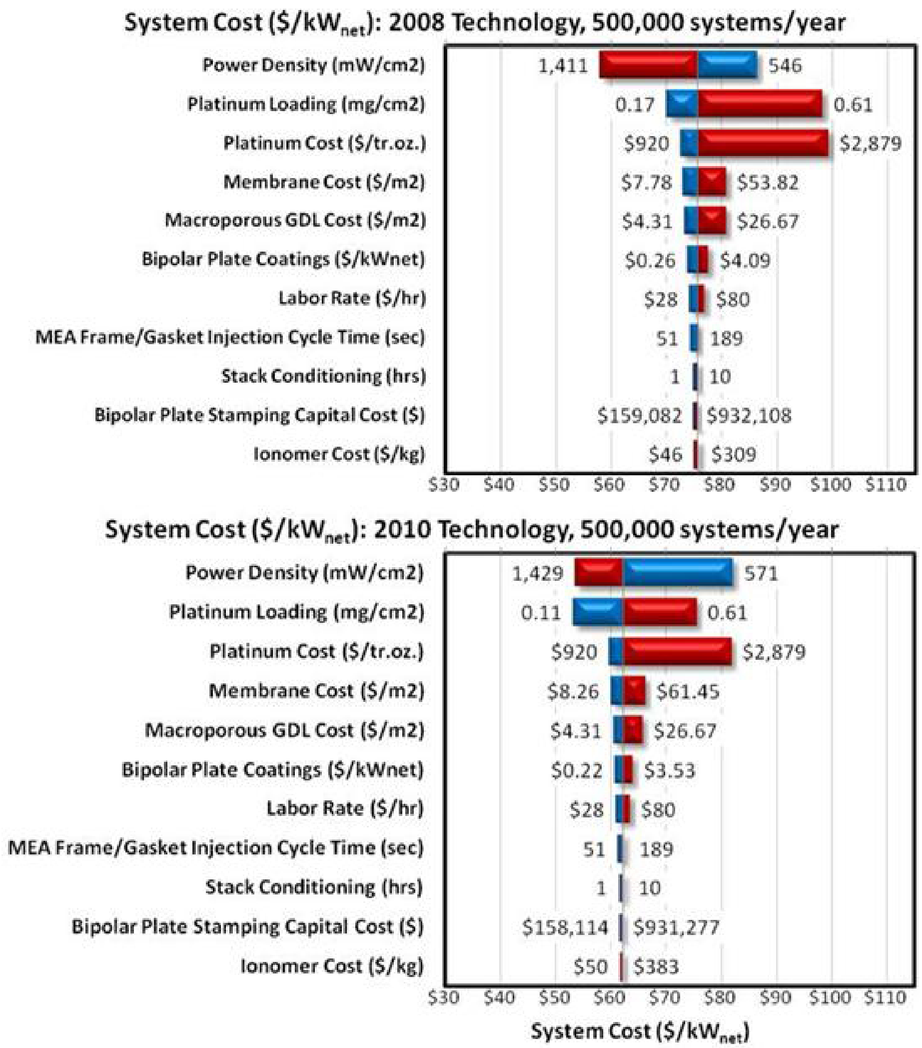

FIGURE 4. System Cost Sensitivity Analysis

Conclusions and Future Directions

Key conclusions from the second year of the project include:

- All cost estimates were recomputed to reflect 2008 technology advances and an overall improvement in modeling methods.
- This cost estimate update results in across-the-board cost reductions with the largest savings occurring between the 2007 status estimate and the 2008 status estimate.
- 2010 and 2015 stack cost estimates (at 500,000 systems/year) are predicted to be $4/kW and $10/kW higher than DOE targets, respectively.
- 2010 and 2015 system cost estimates (at 500,000 systems/year) are predicted to be $17/kW and $21/kW higher than DOE target, respectively.
- Significant technical breakthroughs will be required in order to achieve the 2010 and 2015 DOE system cost targets.
- Catalyst cost (especially platinum) is the largest single cost contributor, so any efforts to reduce the amount used will yield large savings.
- Substantial cost reductions (factors of 3-5) are achieved by increasing manufacturing volume from 1,000 to 500,000 systems per year production rate.
- BOP components are comparable to stack costs. Consequently, R&D to reduce, simplify, or eliminate BOP components is needed to achieve a significant overall system cost reduction.
- Most of the BOP cost reduction that is expected to occur as technology level advances occurs from simplification of the air compressor, humidification, and hydrogen sensor subsystems. R&D is needed to ensure that these projected advances are achieved.

When compared to the DOE's 2005 status values and our 2006 and 2007 estimates from the previous two years, it's clear that the significant technology advances of the last several years have resulted in substantial cost reductions. Still, there is a substantial predicted overage in meeting 2010 targets: $4/kW on the stack and $17/kW for the system. The expected overage for 2015 grows to $10/kW and $21/kW for the stack and system respectively. Further R&D or system configuration advances are needed to close these gaps.

On such potential advance is the development of the nano-structured thin-film catalyst application technology, developed by 3M. They have recently demonstrated a platinum catalyst loading and areal power density pairing of 815 mW/cm^2 and 0.15 mg/cm^2, which surpasses the DOE's 2010 targets and could help to dramatically lower the fuel cell system cost. In the 2009 analysis, DTI will examine this technology and integrate it as an option in our cost analysis.

Additionally, DTI will address the following topics:

- Updating the 2008 technology system to reflect 2009 technology.
- A detailed bottom-up DFMA® analysis of Honeywell turbochargers.
- Optimization of the power density-catalyst loading design point.
- Alternative catalyst alloys.
- Examination of low-pressure fuel cell systems.
- Additional sensitivity analysis.

FY 2009 Publications/Presentations

1. September 18th, 2008 – Washington, D.C.: Status Presentation at DOE Headquarters.

2. September 24th, 2008 - [Videoconference]: Presentation to Fuel Cell Tech Team.

3. December 4th, 2008 – [Videoconference]: Presentation to Independent Review Panel.

4. May 21st, 2009 - Crystal City, VA: DOE H_2 Program Review Presentation.

5. July 15th, 2009 - Hartford, CT: HTAC Open Meeting.