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

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Objectives

- 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
- 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
- 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 (R&D) efforts.

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

Stack Cost, $/$kW_e$ (net)	2005 Status	Current (2006, 2007)	2010	2015
DOE Target:	$65	-	$25	$15
DTI 2006 Estimate (Year 1):	-	$66	$30	$25
DTI 2007 Estimate (Year 2):	-	$50	$27	$23
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

Accomplishments

- Completed 2006 Status Report (2006, 2010, 2015 technologies).
- Submitted 2006 Status Report for industry review.
- Improved existing conceptual design and component specification of complete fuel cell power systems at three technology levels (2007, 2010, and 2015).
- Completed 2007 Status Update Report (2007, 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 second year of the DTI project and focuses on refinement of the cost estimates and an update to reflect 2007 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 total manufacturing cost of a component or system and then to conduct a comparative cost analysis so as to redesign the system for lowest cost. Normally, a markup rate is used within the DFMA® methodology to reflect the business costs of general and administrative, scrap, 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 2007 status update. Estimates for 2008 will be reported in September.

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, is conducted continuously throughout the project. It encompasses the review of published materials and patents, as well as interviews with key researchers and manufacturers. This allows us to obtain a common ground assessment of the system layout and technologies currently used or anticipated to be used by the fuel cell system community. Once we have collected enough information to move forward, we develop a preliminary system concept and mechanical/piping layout 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 are used to determine heat loads, mass flows, compositions, and pressure levels throughout the systems. The flow diagrams are iteratively modified to obtain a projected optimal configuration and performance.

Armed with the preliminary system concepts and layouts, we next design each of the components that make up the stack system. This involves specifying the detailed geometries of the flow plates, gaskets, membrane electrode assemblies, etc., and determining which materials to use. We then select the most appropriate manufacturing processes to use for each component based primarily on cost, but also consider perceived performance and durability. For cases where it's unclear which method is best, we analyze several, adjusting the component design to suit the manufacturing method. For each component, we define a manufacturing process train, and then apply our costing methodologies to it. Using a comprehensive DFMA®-style approach, we calculate the manufacturing process costs, setup costs, material costs, and assembly costs, and then sum them to determine 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) are included in the cost estimates. Cost of non-stack components such as radiators, pumps, blowers, controllers, sensors, etc. are calculated by a simplified DFMA®-style methodology, or are based on price quotations from vendors.

Results

The cost differences across the three different technology levels (see Figure 1 and Table 2) are driven primarily by expected improvements in stack power density (583 to 1,000 mW/cm^2), total platinum loading (0.35 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 result from increased power density and decreased platinum loading. Balance-of-plant (BOP) cost reductions primarily stem 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 the air, humidification, and coolant systems yield the majority of technology improvement savings.

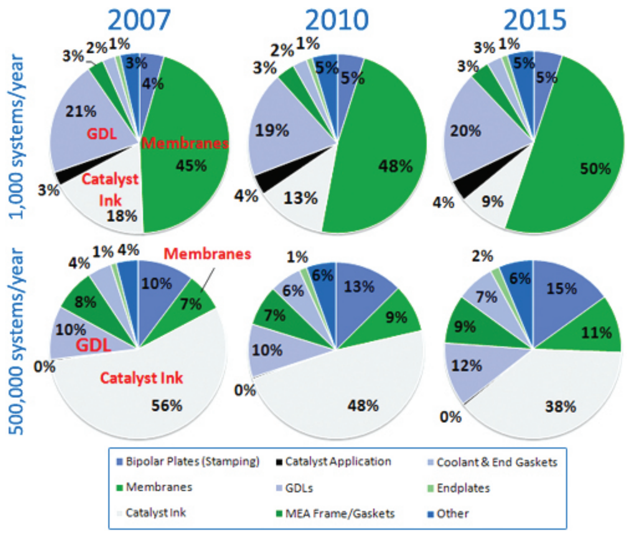

FIGURE 1. Stack Cost Component Distribution

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 membrane electrode assembly 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 refined. 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 2007 update (compared to the 2006 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 2007 estimates of performance, the power density and platinum loading design point was re-optimized to 583 mW/cm^2 at 0.3 mg Pt/cm^2 (2006 status) from the previous 700 mW/cm^2 at 0.65 mg Pt/cm^2 (2007 status). (Design points for 2010 and 2015 remain unchanged.) Decreasing the Pt loading results in a major cost

TABLE 2. System Comparison

	2007 Technology System	2010 Technology System	2015 Technology System
Power Density	583	1000	1000
Total Pt loading	0.35	0.3	0.2
Operating Pressure	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 Stainless Steel (uncoated) or Injection Molded Carbon/Polymer	Stamped Stainless Steel (uncoated) or Injection Molded Carbon/Polymer	Stamped Stainless Steel (uncoated) or Injection Molded Carbon/Polymer
Air Compression	Twin Lobe Compressor, Twin Lobe Expander	Centifugal Compressor, Radial Inflow Expander	Centifugal 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
Hot Pressing	Hot pressing of MEA	Hot pressing of MEA	Hot pressing of MEA
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	MEA Frame with Hot Pressing	MEA Frame with Hot Pressing	MEA Frame with Hot Pressing
Gaskets	Silicone injection molding of gasket around MEA	Silicone injection molding of gasket around MEA	Silicone injection molding of gasket around MEA
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 endplates with compression bands	Composite molded endplates with compression bands	Composite molded endplates with compression bands
Stack/System Conditioning	5 hours of power conditioning - from UTC's US Patent #7,078,118	4 hours of power conditioning - from UTC's US Patent #7,078,118	3 hours of power conditioning - from UTC's US Patent #7,078,118

reduction (-\$19.56/kW) but decreasing the power density results in a significant cost increase (\$8.58/kW). The net effect of these two changes is a \$10.98/kW cost reduction, which represents the majority of the \$16.04 drop in system cost from 2006 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 doubling the number of cells per stack and halving the number of stacks from four to two, we were able to save a lot on elements such as the endplates and current collectors. Improved material cost estimates also played a role in the savings, particularly for the ionomer and the macroporous gas diffusion layer material. Lowering the oxygen stoichiometry from 2.0 to 1.8 also yielded savings: by reducing the load on the air compressor and making the system more efficient, it allowed the entire stack to be smaller, which saves on material costs. Numerous other minor assumption changes were made and result is 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 \$50/kW_{net}, \$27/kW_{net}, and \$23/kW_{net}, for the 2007, 2010, and 2015 systems, respectively (see Figure 2). These should be compared to the 2010 and 2015 DOE targets of 25/kW_{net}, and \$15/kW_{net}. When accounting for the BOP items, the system costs are roughly double that of the stacks alone (see Figure 3).

Note that platinum cost is held constant at \$1,100 per troy ounce to allow direct comparison with previous (2006) estimates. System cost is highly dependent on this assumption, especially for the current technology system, which has a relatively high Pt loading and low power density. If current platinum prices were used (~\$2,050 per troy ounce), the stack costs would leap by \$23, \$11, and \$7 per kW_{net} for the three different technology levels, respectively. Sensitivity analysis tornado charts for the 2007 and 2015 system cost are shown in Figure 4.

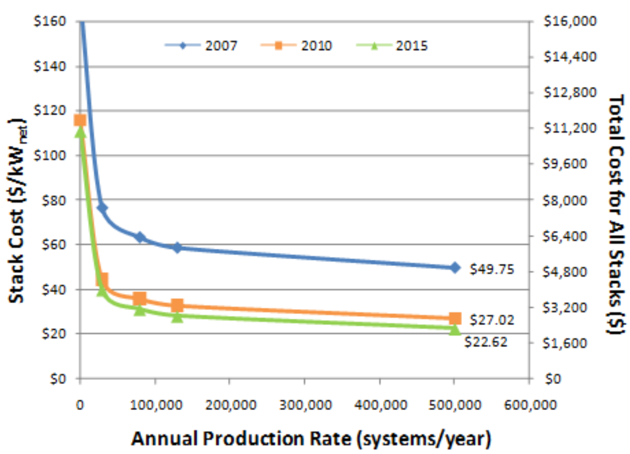

FIGURE 2. Stack Cost in $\$/kW_{e\ (net)}$

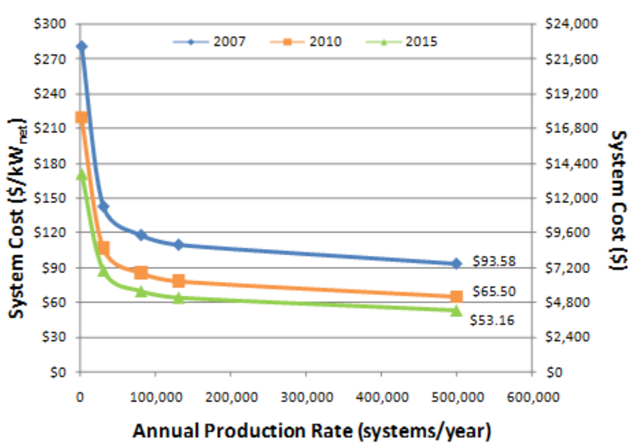

FIGURE 3. System Cost in $\$/kW_{e\ (net)}$

Conclusions and Future Directions

Key conclusions from the second year of the project include:

- All cost estimates were recomputed to reflect 2007 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 2006 status estimate and the 2007 status estimate.
- 2010 and 2015 stack cost estimates (at 500,000 systems/year) are predicted to be \$7-8/kW higher than DOE targets.
- 2010 and 2015 system cost estimates (at 500,000 systems/year) are predicted to be approximately \$22/kW higher than DOE targets.
- Large technical breakthroughs will be required in order to satisfy the 2010 and 2015 goals.
- Catalyst cost (especially the 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 estimates from last year, it's clear that technology is improving and these improvements will continue to yield substantial cost reductions. Still, there is a substantial predicted shortfall in meeting 2010 targets: \$2/kW on the stack and \$21/kW for the system. The shortfall for 2015 grows to \$8/kW and \$23/kW for the stack and system, respectively. Clearly a major R&D or system configuration advance is needed to close these gaps.

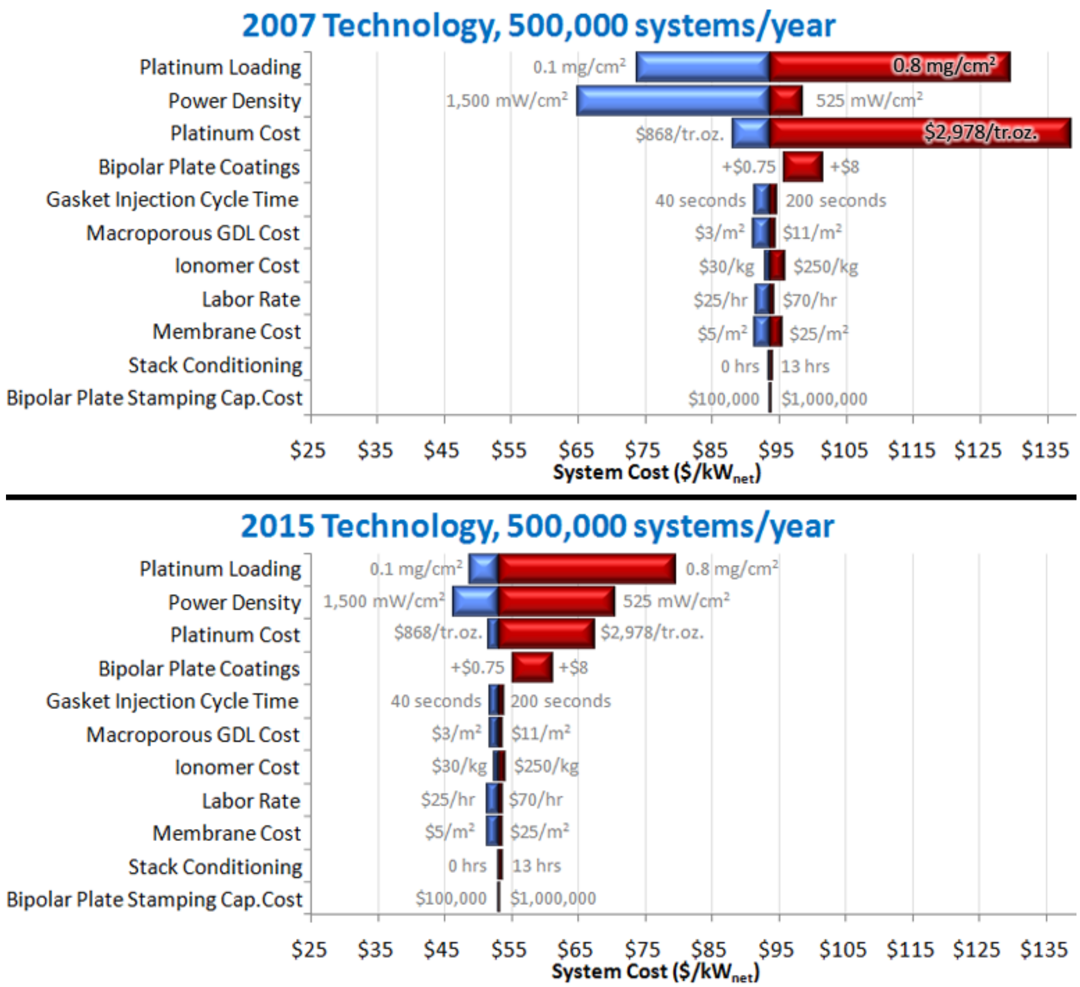

FIGURE 4. System Cost Sensitivity Analysis

Because of the comparative immaturity of the stack technology compared to the BOP components, our work to date has been focused mainly on the stack estimates. However, the BOP represents a large fraction of total system cost, and for the 2010 estimate, it accounts for $19 of the $21 distance from the DOE target. This suggests that there may be significant savings to be found in BOP improvements. Consequently, the focus of next year's work will be on BOP cost estimates and innovative approaches to BOP cost reduction.

Additionally, we will address the following topics:

- Updating the 2007 technology system to reflect 2008 technology.
- Optimization of the power density-catalyst loading design point.
- Consideration of alternative catalyst alloys.
- Coatings for stamped bipolar plates.
- Alternative catalyst application methods.
- Additional sensitivity analysis.

FY 2008 Publications/Presentations

1. November 28th, 2007 – Washington, D.C.: Status Presentation at DOE Headquarters.

2. May 16th, 2008 - Southfield, MI: Fuel Cell Tech Team Presentation at USCAR.

3. June 10th, 2008 - Crystal City, VA: DOE H_2 Program Review Presentation.