V.A.2 Mass-Production Cost Estimation for Automotive Fuel Cell Systems

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

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

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

Technical Advisor: Mark Ruth
Phone: (303) 384-6874
E-mail: Mark.Ruth@nrel.gov

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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 (now two) technology levels:
  - Current status
  - 2010 projected performance (replaced by "current status" for 2010 update)
  - 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 Fuel Cell 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 in $/$kW_{e\,(net)}$ (at 500,000 Systems/Year Manufacturing Rate)

<table>
<tr><th></th><th></th><th>2005 Status</th><th>Current (2006-2010)</th><th>2010</th><th>2015</th></tr>
<tr><td rowspan="6">Stack Cost</td><td>DOE Target</td><td>$65</td><td>-</td><td>$25</td><td>$15</td></tr>
<tr><td>DTI 2006 Estimate (Year 1)</td><td>-</td><td>$66</td><td>$30</td><td>$25</td></tr>
<tr><td>DTI 2007 Estimate (Year 2)</td><td>-</td><td>$50</td><td>$27</td><td>$23</td></tr>
<tr><td>DTI 2008 Estimate (Year 3)</td><td>-</td><td>$38</td><td>$29</td><td>$25</td></tr>
<tr><td>DTI 2009 Estimate (Year 4)</td><td>-</td><td>$26</td><td>$24</td><td>$22</td></tr>
<tr><td>DTI 2010 Estimate (Year 5)</td><td>-</td><td colspan="2">$25</td><td>$21</td></tr>
<tr><td rowspan="6">System Cost</td><td>DOE Target</td><td>$125</td><td>-</td><td>$45</td><td>$30</td></tr>
<tr><td>DTI 2006 Estimate (Year 1)</td><td>-</td><td>$108</td><td>$70</td><td>$59</td></tr>
<tr><td>DTI 2007 Estimate (Year 2)</td><td>-</td><td>$94</td><td>$66</td><td>$53</td></tr>
<tr><td>DTI 2008 Estimate (Year 3)</td><td>-</td><td>$72</td><td>$65</td><td>$51</td></tr>
<tr><td>DTI 2009 Estimate (Year 4)</td><td>-</td><td>$61</td><td>$56</td><td>$51</td></tr>
<tr><td>DTI 2010 Estimate (Year 5)</td><td>-</td><td colspan="2">$51</td><td>$39</td></tr>
</table>

Accomplishments

- DTI 2009 Cost Estimate:
  - Improved existing conceptual design and component specification of complete fuel cell power systems at three technology levels (2009, 2010, and 2015).
  - Determined final 2009 cost status.
  - Completed 2009 Status Update Report (2009, 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.
- DTI 2010 Cost Estimate:
  - Improved existing conceptual design and component specification of complete fuel cell power systems at two technology levels (2010 and 2015).
  - Determined final 2010 cost status.

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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 state-of-the-art PEM fuel cell technology and prepared system cost models to reflect 2006, 2010, and 2015 estimates. Each ensuing year, the cost model was updated to reflect advances in technology and the evolving cost analysis. During the most recent reporting period, an adjustment in funding led to a compression of the project timeline, and the 2010 update was completed earlier than originally scheduled. As such, this annual progress report covers the fourth year and part of the fifth year of the DTI project, reflecting updates and advances in technology from both 2009 and 2010. Since the current year is 2010, the "current" technology and the 2010 projected technology have merged, leaving only two technology levels to examine: the current status (2010) and the 2015 projection.

A Design for Manufacturing and Assembly (DFMA®) methodology is employed to obtain the fuel cell system 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 allow a redesign to achieve the lowest system cost. Typically, a markup factor is applied to the materials and direct manufacturing/assembly costs to reflect the business costs of general and administrative, scrap, research and development (R&D), and profit and is applied to all manufacturing entities 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 2010 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 the different technology levels. 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. When it was unclear which approach was best, several different methods were analyzed, 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 between the two different technology levels (see Table 2) are driven primarily by expected improvements in stack power density (833 to 1,000 mW/cm^2), operating pressure (1.69 to 1.5 atm), and peak stack temperature (90 to 99°C). Of these, increased power density is most responsible for stack cost reduction. Balance-of-plant (BOP) cost reductions stem primarily from system simplifications (i.e. reduced or eliminate components). For example, the current technology system uses a Nafion® membrane air humidification system with an air precooler, and the 2015 has no humidification system at all. Simplifications of the air, humidification and coolant systems yield the majority of technology improvement savings.

The stack cost decreases with advancing technology level due to both power density improvement and reduction of the parasitic electrical loads. 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) result in a reduction of cell active area and a corresponding decrease in material cost.

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 in previous years of the project has been focused on the stack, since it provided the most potential for cost improvement. Since the 2008 status update however, the focus has shifted towards the BOP. With the exception of the nanostructured thin-film (NSTF) catalyst application process, the changes to the stack analysis are mostly adjustments of operating parameters rather than the addition of new components or changes in design. Also, the number of stacks per system is cut from two to one based on suggestions from industry and the United States Council for Automotive Research Fuel Cell Technical Team (FCTT).

TABLE 2. System Comparison

	2010	2015
Power Density (mW/cm^2)	833	1,000
Total Pt loading (mgPt/cm^2)	0.15	0.15
Gross Power (kW$_{gross}$)	87.91	87.27
Operating Pressure (atm)	1.69	1.5
Peak Stack Temp. (°C)	90	99
Membrane Material	Nafion on ePTFE	Advanced High-Temperature Membrane
Radiator/ Cooling System	Aluminum Radiator, Water/Glycol coolant, DI filter, Air Precooler	Smaller Aluminum Radiator, Water/Glycol coolant, DI filter, No Air Precooler
Bipolar Plates	Stamped SS 316L with Coating	Stamped SS 316L with Coating
Air Compression	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
Catalyst Application	Nanostructured Thin Film (NSTF)	Nanostructured Thin Film (NSTF)
Air Humidification	Polyamide Membrane	None
H_2 Humidification	None	None
Exhaust Water Recovery	None	None
MEA Containment	Injection molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E	Injection molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E
Coolant & End Gaskets	Laser Welding/ Screen-Printed Adhesive Resin	Laser Welding/ Screen-Printed Adhesive Resin
Freeze Protection	Drain water at shutdown	Drain water at shutdown
H_2 Sensors	2 for FC system 1 for passenger cabin *(not in cost estimate)* 1 for fuel sys *(not in cost estimate)*	None
End Plates/ Compression System	Composite molded end plates with compression bands	Composite molded end plates with compression bands
Stack Conditioning (hrs)	5	3

The NSTF catalyst application process is a major technological improvement on the previous VertiCoater die-slot application method, and facilitates large improvements in power density and catalyst loading while simultaneously improving durability. The previously-modeled VertiCoater method had the advantage of being one of the least-costly application techniques judged adequate for high production rates and reasonably high MEA performance. However, it became increasingly clear that further increases in power density with simultaneously lower Pt loading were probably not possible with this technique. Consequently, the switch was made to the NSTF method, which has shown remarkable recent improvements in power density and durability at low Pt loadings. Developed at 3M, the NSTF deposition process begins with the sublimation of a layer of crystalline finger-like projections, or "whiskers", that create a high surface area substrate on which the active catalysts may be deposited. Next, vapor deposition methods are utilized to deposit a very thin layer of a ternary catalyst alloy coating onto the whiskers in a very precise and even manner. The resulting catalyst-coated whiskers can then be hot pressed into the fuel cell membrane to form a porous mat electrode intimately bonded to the membrane. 3M has recently demonstrated significant improvements in the durability and the power-density-to-catalyst-loading ratio that surpass the 2010 DOE performance targets.

When compared to the previous method of catalyst application considered (die-slot application based on the Coatema VertiCoater), the total NSTF catalyst system and application is only slightly more expensive for a given power density and catalyst loading. However, the NSTF method facilitates a lower catalyst loading and improved power density that cannot be otherwise achieved. Consequently, taking power density and catalyst loading into consideration, a net savings of $10.28/kW$_{net}$ is obtained by switching from a die-slot catalyst application to the NSTF catalyst system.

A central theme of the past year's work has been the integration of performance-parameter-based scaling into the cost model. Although the previous cost model included performance parameters, we have enhanced the level of detail and interaction to better reflect the actual performance. Integration between all of the components (in both the stack and the BOP) has been greatly increased, such that geometries and costs now scale dynamically based on a variety of parameters (e.g. operating pressure, air mass flow, and cooling and power requirements).

In past years of the analysis, the power density and catalyst loading values used in the model were specified by the DOE and the FCTT, and reflected the average performance of several different technologies. Now that the NSTF process has been implemented in the model, the power density and catalyst loading values are based on experimental data polarization curves that correspond to NSTF MEAs under specified operating conditions. Interpolation between polarization curves is used to determine power density at the model-specified operating pressure.

Almost all of the BOP components were re-examined in greater detail, with extra emphasis on those with the largest contribution to cost. The system schematics were refined, and components were added and subtracted. Detailed analyses were conducted of the wiring and piping/tubing requirements, with consideration for flow rates, cooling and power requirements, and the physical distances between components.

The most substantial cost analysis improvement relates to the new compressor/expander motor (CEM) analysis, for which an all-new cost estimate was conducted in collaboration with Honeywell. It is a bottom-up cost analysis based directly on the blueprints from an existing Honeywell design, utilizing a combination of DFMA® methodology and price quotes from established Honeywell vendors. Current and future CEM designs were analyzed, and a detailed model was developed to scale the size, cost, and power draw of the CEM based on rotational speed, air mass flow, pressure ratio, and the inclusion or exclusion of an expander. For current technology, the CEM cost shrinks from $8.51/kW$_{net}$ in 2008 to $8.07/kW$_{net}$ in 2010. For 2015 technology, it increases from $5.37/kW$_{net}$ to $6.31/kW$_{net}$.

Numerous other small changes were made to the fuel cell system cost model, the result of which yields a small cumulative net savings. While their net effect is comparatively small, the improvements enhance 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 $25/kW$_{net}$, and $21/kW$_{net}$, for the 2010 and 2015 technology year cost projections respectively (see Figure 1). These should be compared to the 2010 and 2015 DOE stack 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 and sum to $51/kW$_{net}$ and $39/kW$_{net}$ for 2010 and 2015, respectively (see Figure 2).

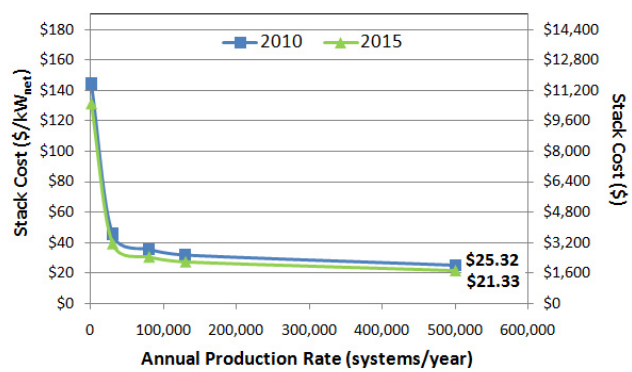

FIGURE 1. Stack Cost in $/kW$_{e\ (net)}$

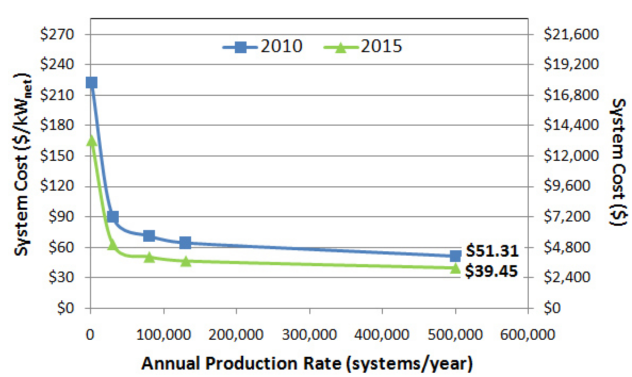

FIGURE 2. System Cost in $/kW$_{e\ (net)}$

Conclusions and Future Directions

Key conclusions from the past year of the project include:

- 2010 stack cost estimate (at 500,000 systems/year) meets the DOE target of $25/kW$_{net}$, and 2015 cost is predicted to be $6/kW higher than DOE target for 2015.
- The 2010 and 2015 system cost estimates (at 500,000 systems/year) are $6/kW and $9/kW higher than DOE targets, respectively.
- Significant technical breakthroughs will be required in order to achieve the 2015 DOE system cost targets.
- NSTF catalyst application method represents current state-of-the-art, shows great promise.
- Switch from die-slot catalyst coating to the NSTF method yielded savings of $10.28/kW$_{net}$, due primarily to enhanced power density made possible by NSTF MEA.
- Though not as dominating as in previous years, catalyst cost (especially Pt) remains largest single stack cost contributor.
- Pt catalyst reduction remains a potential pathway to appreciable cost savings.
- Although detailed new CEM cost analysis resulted in only minor cost changes, new estimate is much more robust, scales with system performance parameters.
- 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 component costs are comparable to stack costs, so R&D to reduce, simplify, or eliminate BOP components is needed for significant overall system cost reduction.

When compared to the DOE's 2005 status values and our estimates from the previous four years, it's clear that the significant technology advances of the last several years have resulted in substantial cost reductions (see Figure 3). Still, there is a substantial predicted overage in meeting 2015 targets: $6/kW on the stack and $9/kW for the total system. Further R&D or system configuration advances are needed to close these gaps.

During the coming year, DTI will address the following topics:

- Documentation of the 2010 update in the Year 5 annual report update.
- Updating of the 2010 technology system to reflect 2011 technology.
- Identification of capital equipment and R&D needs.
- Optimization study of stack operating pressure.
- Lifecycle cost analysis.

FY 2010 Publications/Presentations

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

2. **August 12th, 2009** - Detroit, MI: Presentation to Fuel Cell Tech Team

3. **October 26th, 2009** – Washington, DC: Presentation to National Academy of Sciences

4. **November 18th, 2009** – Palm Springs, CA: Presentation to Fuel Cell Seminar

5. **June 9th, 2010** – Washington, DC: DOE H_2 Program Review Presentation

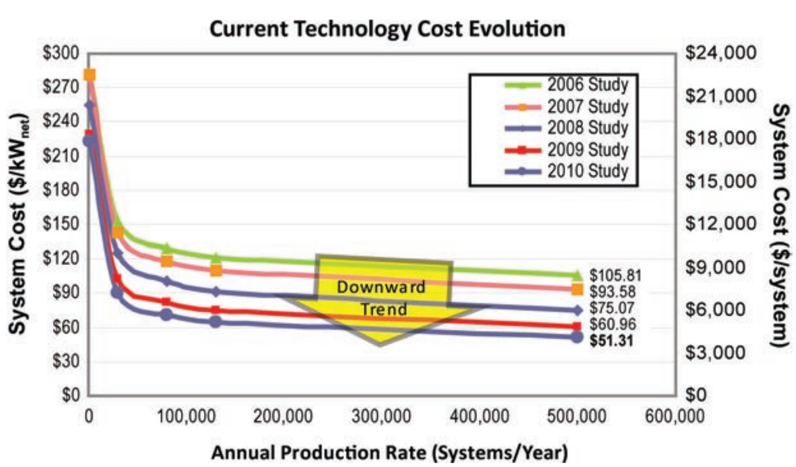

FIGURE 3. Annual Progress in Cost Reduction