# V.A.6 Mass Production Cost Estimation for Direct $H_2$ PEM Fuel Cell Systems for Automotive Applications

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## Objectives

- Identify the lowest cost system design and manufacturing methods for an 80 $kW_{e\ (net)}$ direct-$H_2$ automotive proton exchange membrane (PEM) fuel cell system based on three technology levels:
  - Current status (2006)
  - 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 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, so as to focus future fuel cell research and development (R&D) efforts.

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

| Source | Characteristic | Units | 2005 | 2006 | 2010 | 2015 |
|---|---|---|---|---|---|---|
| DOE Target | Stack Cost | $/kW$_{e\ (net)}$ | $65 | - | $25 | $15 |
| DTI Estimate | Stack Cost | $/kW$_{e\ (net)}$ | - | $66 | $30 | $25 |
| DOE Target | System Cost | $/kW$_{e\ (net)}$ | $125 | - | $45 | $30 |
| DTI Estimate | System Cost | $/kW$_{e\ (net)}$ | - | $108 | $70 | $59 |

## Accomplishments

- Conceptual design and component specification of complete fuel cell power systems at three technology levels (2006, 2010, and 2015).
- Determined comprehensive cost estimates for 15 different scenarios (five production rates across three different technology levels).
- Identified components and systems that warrant further research.

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## Introduction

In previous work for Argonne National Laboratory, DTI performed cost estimation of mass-manufactured fuel cell vehicle power systems. The 50 $kW_{e\ (net)}$ PEM fuel cell systems were examined at four production rates: 500, 10,000, 30,000, and 500,000 systems per year. For this project, we have built on our previous work to extend the analysis to 80 $kW_{e\ (net)}$ PEM fuel cell systems, at five annual production rates (1,000, 30,000, 80,000, 130,000, and 500,000), and at three levels of projected fuel cell and manufacturing technology (2006, 2010, and 2015).

A design for manufacturing and assembly (DFMA®) methodology is employed to obtain the cost estimates. DFMA® is a methodology from Boothroyd Dewhurst Inc. to systematically estimate the total manufacturing cost of a component or system and how it can be redesigned 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. However, per DOE directive for this project, we do not include this traditional markup in the cost estimates. (Scrap costs are included at the component level but not at the system level.) The costs reported in this document are interim values. Consequently, the estimates are subject to changes, with the finalized values to be reported in the project year 1 report.

## 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 (2006), 2010, and 2015 technologies. Excel spreadsheets and HYSYS® models (a chemical engineering modeling environment) 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 design each of the components that make up the system. This involves specifying the detailed geometries of the flow plates, gaskets, membrane electrode assemblies (MEAs), 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.

## Results

The cost differences between the three different technology levels (see Figure 1) are driven primarily by expected improvements in power density (700 to 1,000 $mW/cm^2$), total platinum loading (0.65 to 0.2 $mgPt/cm^2$), operating pressure (2.3 to 1.5 atm), and peak stack temperature (90 to 120°C). Most of these differences manifest themselves in the system bill of materials (BOM), where BOM elements are changed or completely eliminated as technology improves. For example, the current technology system uses water spray injection for the air humidification, the 2010 system uses a polyamide membrane system, and the 2015 has no air humidification system at all. The majority of these BOM differences are found in the balance of plant (BOP) in the form of reduced or eliminated components. Simplifications of the air, humidification, and coolant systems yield the majority of technology improvement savings.

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 90.6 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.

The largest and most important contributor to the system cost is not surprisingly the fuel cell stack. 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. Both of these things provide strong opportunities to reduce the stack cost through use of the DFMA® methodology.

| | Current Technology System | 2010 Technology System | 2015 Technology System |
|---|---|---|---|
| **Power Density (mW/cm²)** | 700 | 1000 | 1000 |
| **Total Pt loading (mg/cm²)** | 0.65 | 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 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. |
| **Hydrogen 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** | Silicon Injection molding of gasket around MEA | Silicon Injection molding of gasket around MEA | Silicon Injection molding of gasket around MEA |
| **Freeze Protection** | Drain water at shutdown | Drain water at shutdown | Drain water at shutdown |
| **Hydrogen Sensors** | 2 H2 Sensors (for FC sys), 1 H2 Sensor (for passenger cabin: not in cost estimate), 1 H2 Sensor (for fuel sys: not in cost estimate | 1 H2 Sensors (for FC sys), 1 H2 Sensor (for passenger cabin: not in cost estimate), 1 H2 Sensor (for fuel sys: not in cost estimate | No H2 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 |

**FIGURE 1.** System Comparison

The most important components of the stack are the bipolar plates and the MEA. The subcomponents of the MEA are the most expensive items, specifically the gas diffusion layer (GDL), the membrane, and the catalyst ink. These three subcomponents are of equal or greater cost than the bipolar plates in almost every cost scenario (see Figure 2).

For all three technology levels, the stack consists of 93 active cells, each containing an MEA and two

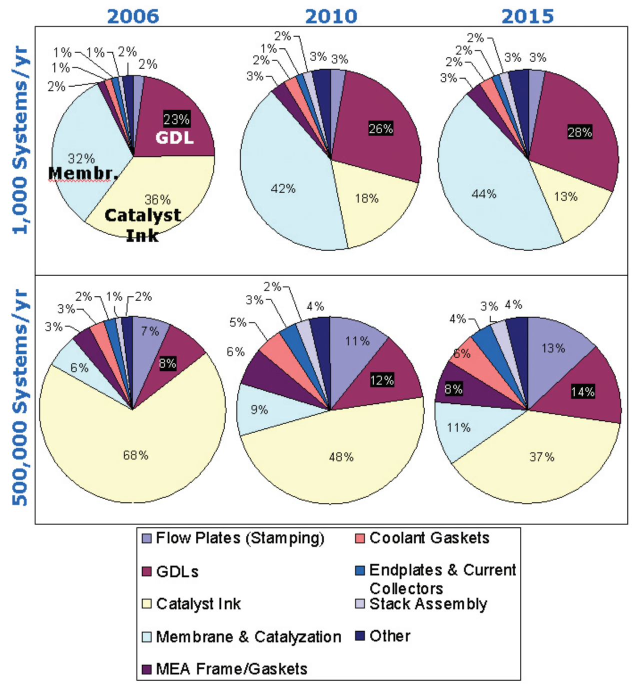


**FIGURE 2.** Stack Cost Component Distribution

bipolar plates. The active-to-cooling cell ratio is one, and four stacks were used in each system to achieve the required power with an approximately ~200 volt system voltage. Consequently the total number of plates in a stack is 188: 93 cells times two plates per cell + two coolant-only plates. With four stacks/system, there are almost 400 MEAs and 800 bipolar plates per system, so even at the lowest production rate, there are hundreds of thousands of repeat parts required. This means that high volume production methods for the repeat parts may be optimally employed even at relatively low system production rates.

To date, we have examined two different designs for the bipolar plate: injection-molded carbon powder/polymer and stamped stainless steel. Assuming equivalent performance, the stamped metal plates appear to be the most promising, with costs ranging from \$4.30/$kW_{gross}$ (current technology, 1,000 systems/year) to \$2.93/$kW_{gross}$ (2015 technology, 500,000 systems/year), compared to \$6.08/$kW_{gross}$ and \$3.83/$kW_{gross}$ for the injection molded version.

The PEM membrane is widely acknowledged as one of the more costly stack components and needs to be reduced in cost to achieve a cost competitive fuel cell system. We modeled our membrane as DuPont Nafion® ionomer occluding the pores of a 95% porous expanded polytetrafluoroethylene (ePTFE) substrate. This approach is similar to Gore PEMSelect® products as we understood it through reading product literature and patents, as well as discussions with Gore engineers. While alternate approaches such as homogenous cast or extruded membranes have the potential for lower cost by obviating the ePTFE substrate, we have selected the Gore-like approach since it achieves excellent mechanical properties and thus is inherently better suited for roll-to-roll processing than homogeneous ionomer films of the same thickness. Mechanical strength is an important characteristic in roll-to-roll processing, which in our judgment offers the best opportunity for very fast (and thus lowest cost) membrane formation. Membrane cost decreases dramatically with increased production due to better amortization of capital equipment, and ranges from $56/kW$_{gross}$ (current technology, 1,000 systems/year) to $3/kW$_{gross}$ (2015 technology, 500,000 systems/year).

The catalyst ink is a slurry of platinum, Vulcan XC-72 carbon, and 5% wt ionomer solution, with an aqueous methanol solution for a solvent. After dispersing the platinum onto the carbon powder, and ultrasonically mixing the ink, it is simultaneously applied to both sides of the membrane. Platinum cost dominates catalyst ink cost, which in turn is a major factor in the stack cost (see Figure 2), climbing as high as 68% of the stack cost in the 500,000 systems/year scenario with current technology.

Each catalyst-coated membrane (CCM) is sandwiched between two layers of GDL in the MEA, which are then hot-pressed together, and insertion molded into a sealing frame/gasket. Our GDL is a dual-layer design in which a microporous layer is applied onto a macroporous carbon substrate. The macroporous layer cost is currently derived from price estimates from SGL Carbon rather than from first principles DFMA® analysis. The cost is very high at low production ($114/m$^2$), but drops much lower ($12/m$^2$) for the 500,000 systems/year production level. The materials and application costs for the microporous layer are much cheaper in comparison, and the overall GDL cost ranges from $42.98/kW$_{gross}$ (current technology, 1,000 systems/year) down to $3.27/kW$_{gross}$ (2015 technology, 500,000 systems/year).

At 500,000 systems per year, the total cost for the stacks, including assembly and stack conditioning, come to $66/kW$_{net}$, $30/kW$_{net}$, and $25/kW$_{net}$, for the current, 2010, and 2015 systems respectively (see Figure 3). These should be compared to the DOE targets of $65/kW$_{net}$, 25/kW$_{net}$, and $15kW$_{net}$. For the current technology, we undercut the DOE cost by ~$4/kW, but come in notably higher for the other two, especially the 2015 target.

When accounting for the BOP items, the system costs roughly double the stacks-only cost (see Figure 4). Our current system cost estimate is again below the DOE target, but our 2010 and 2015 estimates are significantly higher than the DOE targets.

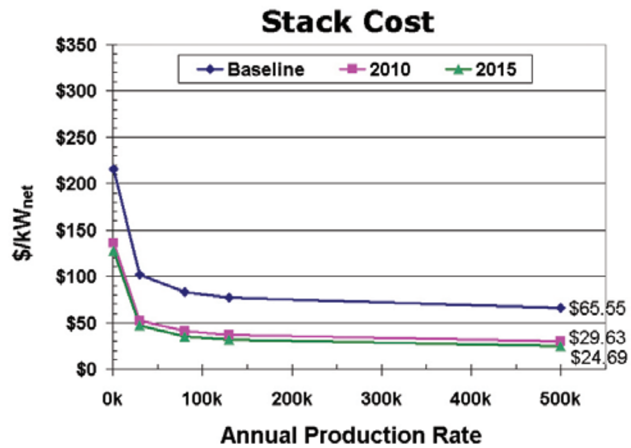


**FIGURE 3.** Stack Cost in $/kW$_{e (net)}$

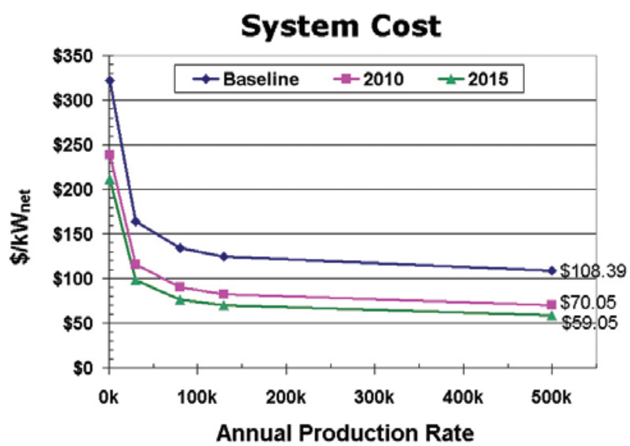


**FIGURE 4.** System Cost in $/kW$_{e (net)}$

## Conclusions and Future Directions

Key conclusions from the first year of the project include:

- Cost estimates indicate that current technology (2006) fuel cell systems are almost able to achieve the 2005 DOE cost target of $65/kW for the stack, and can easily achieve the $125/kW target for the entire system (at 500,000 systems per year).
- However, projections for the 2010 and 2015 technology systems are estimated at approximately $10/kW to $40/kW higher than DOE targeted values.
- Substantial cost reductions (factors of three to five) are achieved by increasing manufacturing volume from 1,000 to 500,000 systems per year production rate.
- The membrane, GDL and the catalyst layers are identified as the primary cost centers of the stack.

Consequently, further R&D should be focused on these areas to bring about stack cost reduction.

- 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 $H_2$ sensor subsystems. R&D is needed to ensure that these projected advances are achieved.

While our projected costs for the current system are slightly better than the DOE targets, the 2010 and 2015 costs are not. Consequently, future work will concentrate on refining the analysis to ensure accuracy and on exploring ways that future cost reductions may be realized. Since they are the biggest contributors to stack cost, the membrane, GDL, and catalyst will be particularly scrutinized. Additionally, we will examine:

- New membrane technologies
- Varying catalyst alloys
- A ground-up analysis of the GDL macroporous layer
- Coatings for stamped bipolar plates
- Alternative catalyst application methods
- Updating the “current” technology system to reflect 2007 technology

## FY 2007 Publications/Presentations

**1.** December 5th, 2006 - Arlington, VA: Status Presentation to NREL team examining fuel cell manufacturing.

**2.** March 19th, 2007 - San Antonio, TX: NHA Conference Poster Presentation.

**3.** April 18th, 2007 - Southfield, MI: Fuel Cell Tech Team Presentation at USCAR.

**4.** May 18th, 2007 - Crystal City, VA: DOE $H_2$ Program Review Presentation.