

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

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Fiscal Year (FY) 2011 Objectives

- Prepare a written report documenting the results and assumptions used in the 2010 80 kW automotive fuel cell system cost analysis.
- Continue cost analysis of automotive fuel cell systems and update the cost estimates for 2011 technology advances.
- Examine the robustness and technological maturity of the capital equipment projected to be used in fabrication of automotive fuel cell power systems, so as to determine where further research and development is required.
- Determine the optimal operating pressure, air stoichiometry and catalyst loading to achieve minimal system cost.
- Thoroughly examine both currently used and developing quality control (QC) measures for each step of the stack manufacturing process to assess cost impact and high rate production feasibility.
- Explore the trade-off between system efficiency and fuel cost in order to optimize the system for lifecycle cost (LCC).

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)

	DOE 2010 Target	DTI 2010 Estimate	DTI 2011 Interim Estimate
Stack Cost	\$25	\$25	\$22
System Cost	\$45	\$51	\$48

Accomplishments

- Document 2010 Cost of Automotive Fuel Cell Systems:
 - Prepared a reference report on the cost of automotive fuel cell systems utilizing 2010 technology.
- Assessment of Capital Equipment and Research and Development (R&D) Needs:
 - Tabulated the major capital equipment needed for the manufacturing of all stack and most major balance-of-plant (BOP) components.
 - Evaluated each process and rated them for both cost assumption risk and process risk.
 - Used this ranking system to identify which components are in need of the most R&D in order to achieve risk reduction.
- Optimization of Operating Conditions to Minimize System Cost:
 - Collaborated with Rajesh Ahluwalia at Argonne National Laboratory (ANL) to develop a simplified five-variable stack polarization curve based on ANL's existing models and 2009 polarization data from 3M.
 - Used this simplified polarization curve to independently vary pressure, catalyst loading, temperature and air stoichiometry to select the

optimal combination of parameters for lowest overall system cost.

- Assessment of Fuel Cell Manufacturing QC Systems:
 - Investigated potential QC systems for each step of the stack production.
 - Determined the optimal QC systems to be used both in the 2010 system and 2015 system.
 - Added the appropriate costs and changed the appropriate process parameters for each QC system.
- LCC Assessment of Automotive Fuel Cell Systems:
 - Collaborated with Rajesh Ahluwalia of ANL to conduct basic LCC analysis to determine the optimal tradeoff between system efficiency and fuel cost.
- Preliminary 2011 Cost Assessment:
 - Integrated the above studies with the 2010 cost estimate to prepare a preliminary 2011 automotive fuel cell system cost assessment.
 - Improved existing conceptual design and component specification of complete fuel cell power systems at two technology levels (2011, and 2015).



Introduction

The project seeks to estimate the material and manufacturing costs of complete 80 kW_{net} direct-hydrogen proton exchange membrane (PEM) fuel cell systems suitable for powering light-duty automobiles. The project examines five annual production rates (1,000, 30,000, 80,000, 130,000, and 500,000 systems per year) and three projected technology levels (2010, 2011, and 2015). The project builds upon work previously conducted by DTI for the DOE under a multi-year effort entitled “Mass-Production Cost Estimation for Automotive Fuel Cell Systems”, which focused on annual updates of system cost. Unlike that past effort, the current project is structured as a series of analytic studies, which when taken together, work to strengthen and update the cost analysis to reflect 2011 technology.

Approach

The project consists of a series of semi-independent analyses based on the cost estimation work previously conducted by DTI for 2010 technology automotive fuel cell systems. The approach to each task will be described individually below.

Documentation of the 2010 Cost Estimates: A comprehensive written report was prepared to document the system configuration, designs dimensions, manufacturing and assembly assumptions, and cost results made for the 2010 cost estimates.

Capital Equipment and R&D Needs: Each manufacturing process associated with the stack and some

of the BOP components was evaluated both for the cost assumption risk and process risk. Cost assumption risk gauges risk that uncertainty or errors in assumed capital cost or material cost used in the analysis may lead to significant increases in overall system cost. Process risk gauges the risk that uncertainty or errors in defining the manufacturing and assembly process (including process parameters such as cycle times) may lead to an end product that doesn't meet minimum performance standards or otherwise forces system changes that lead to system cost increase. Both risk scales range from 1 to 3. When these ratings are summed, they yield a combined score which may be used to rank the overall risk of that process or component. Components with a combined score of 4 or more are components that warrant R&D attention.

Operating Condition Optimization: In order to represent stack polarization performance within the cost model, ANL exercised their stack performance model over a range of expected operating conditions to create a numerical database of projected polarization curves. A regression analysis was then conducted on the approximately 600 data points to derive a simplified second-order polynomial equation representing 3M's 2009 current density as a function of five independent variables: cell voltage, catalyst loading, pressure, temperature, and air stoichiometry. This enabled the fuel cell cost model to determine system cost for all combination of these variables. Pressure was varied from 1.5 atm to 3 atm. Air stoichiometry was varied from 1.5 to 2.5. Temperature was varied from 75°C to 95°C. Cathode catalyst loading was varied from 0.10 mgPt/cm² to 0.20 mgPt/cm². (Anode catalyst loading was held constant at 0.05 mgPt/cm².) In addition to the manual optimization, a Monte Carlo analysis was conducted using the @Risk plug-in for Excel. Ten thousand iterations of the DTI fuel cell system cost model were run varying the four stack parameters over the ranges previously states. (Cell voltage was held constant at 0.676 V.) The results were then sorted by resulting system cost. The iteration with the lowest system cost was used to identify the optimal stack parameters.

QC: In order to ensure that adequate QC systems were included in the automotive fuel cell system cost estimates, a comprehensive reassessment of stack manufacturing and assembly QC systems was conducted. The reassessment began with the QC systems utilized in the 2010 system cost estimates and combined it with the PEM-focused QC work being conducted at Ballard, BASF, NREL, the National Institute of Standards and Technology, and Precitec Inc.. Competing QC systems from these organizations were conceptually applied to each step of the stack manufacturing process. The systems were extrapolated to high production rates and assessed on the basis of practicality and cost. In some cases, more advanced QC processes, still in the testing phase, were hypothesized for the 2015 system.

LCC: A simplified LCC analysis was conducted to explore the tradeoff between the initial purchase price of the fuel cell power system and the fuel cost over the lifetime of

the vehicle. By assessing this tradeoff, the system efficiency and operating conditions that lead to the lowest overall lifecycle cost may be identified. The methodology employed consists of three main steps: 1) determination of the stack operating parameters (total catalyst loading, temperature, pressure, air stoichiometry) that lead to minimum system cost at stack efficiencies from 48.8% to 57% (which corresponds to cell voltages of 0.6 to 0.7 volts per cell), 2) determine the relationship between system efficiency and vehicle fuel consumption (miles per gallon gasoline equivalent) for a specified set of vehicle assumptions (vehicle mass, frontal area, rolling resistance, drive cycle, etc.) through use of the ANL PSAT model, 3) determine lifecycle system costs by assessing the net present value of vehicle initial cost and annual operating expenses.

Results

- Results for the capital cost tabulation and risk assessment can be found in Table 2. The highest combined risk scores were for the membrane production process and the nano-structured thin filament (NSTF) catalyst coating process with risk scores of 5.5 and 6, respectively. (NSTF risk is high primarily due to lack of demonstrated performance using high rate production techniques.) In the BOP, the only component with a combined risk score above 4 is the membrane humidifier with a score of 6 (also due to lack of demonstration using high rate production techniques).
- Table 3 displays the optimized parameters that lead to lowest system cost as determined via DTI's parametric analysis of the parameters and verified by Monte Carlo analysis. A sequence of four different scenarios is shown in Table 3: the pre-optimization values used in the DTI 2010 cost analysis, the previous case but with minor system adjustments to the assumptions, the previous case with the new simplified polarization equation from ANL, and finally the post-optimization values using the ANL polarization equation. The resulting system cost is observed to decrease from \$51.38/kW_{net} to \$47.81/kW_{net}. In order to achieve such a cost reduction, stack temperature was increased to its upper limit of 95°C, air stoichiometry was reduced to its lower limit of 1.5, stack pressure was increased to the upper limit of 3 atm, and total catalyst loading was increased to 0.186 mgPt/cm².
- As shown in Table 4, despite the high capital cost of much of the QC equipment, at the highest production level, the cost impact of the added QC is very low, only \$0.32/kW_{net}. The addition of these systems, however, seeks six-sigma-level quality of the finished products to protect against malfunctions in the manufacturing that would incur costs far exceeding that of the QC equipment.
- The LCC analysis shown in Figure 1 reveals that there is an optimum/minimal lifecycle cost occurring at roughly 44% system efficiency, which translates to

TABLE 2. Manufacturing Process Risk Assessment

Stack Component Manufacturing			
Step/Component	Process Risk	Cost Assumption Risk	Total Score
Bipolar Plate Stamping	1	1	2
Bipolar Plate Coating	1.67	2	3.67
Membrane Production	2.5	3	5.5
NSTF Coating	3	3	6
Microporous GDL	2	2	4
M & E Hot Pressing	2	2	4
M & E Cutting & Slitting	1	1	2
MEA Frame/Gaskets	2	2	4
Coolant Gaskets (Laser Welding)	2	1	3
End Gaskets (Screen Printing)	2	1	3
End Plates	1	1	2
Current Collectors	1	1	2
Compression Bands	1	2	3
Stack Assembly	1	2	3
Stack Conditioning	2	2	4
BOP Component Manufacturing			
Step/Component	Process Risk	Cost Assumption Risk	Total Score
Membrane Air Humidifier	2	3	5
Belly Pan	1	1	2
Ejectors	2	1	3
Stack Housing	1	1	2
Air Precooler	1	1	2
Demister	1	1	2
CEM	2	2	4

GDL - gas diffusion layer; MEA - membrane electrode assembly; M&E - membrane & electrode; CEM - compressor-expander-motor

0.61 volts/cell. However, the optimization curve is very flat and shows only a minor cost change (~\$70) over the range of system efficiencies examined (43% to 51%). Decreases in fuel cost due to increased efficiency are almost totally offset by the subsequent increase in power plant purchase price. Sensitivity analysis shows the optimization curve to be surprising flat over all expected parameter ranges.

Conclusions and Future Directions

Key conclusions from the past year of the project include:

- Membrane fabrication and NSTF catalyst application are the stack components, and the membrane air

TABLE 3. Key Parameters and Cost Results for Different Sets of Parameters

		Base Case (2010 Status)	Base Case w/ Updates	Base Case w/ Updates & ANL Curve Fit	Optimized Case
Annual Production Rate	systems/year	500,000	500,000	500,000	500,000
Stack Efficiency @ Rated Power	%	55%	55%	55%	55%
Cell Voltage @ Rated Power	V/cell	0.676	0.676	0.676	0.676
Oxygen Stoichiometric Ratio		2.5	2.5	2.5	1.5
Peak Stack Operating Pressure	atm	1.69	1.69	1.69	3
Peak Stack Operating Temperature	°C	90	90	90	95
Total Platinum-Group Catalyst Loading	mgPt/cm ²	0.15	0.15	0.15	0.186
MEA Areal Power Density @ Rated Power	mW/cm ²	833	833	732	1,110
Power Density Equation Selected		Standard	Standard	ANL Curve Fit	ANL Curve Fit
System Cost	\$/kW_{net}	\$51.38	\$51.92	\$54.72	\$47.81

TABLE 4. QC Systems and their Associated Cost Impact

		Total Cost Increase from QC Equipment				
Technology Level		2011				
Systems/year		1,000	30,000	80,000	130,000	500,000
QC Cost (\$/kW _{net})	Membrane QC	\$5.14	\$0.17	\$0.06	\$0.04	\$0.01
	NSTF Catalyst Deposition QC	\$1.24	\$0.04	\$0.03	\$0.04	\$0.03
	MEA QC	\$4.76	\$0.16	\$0.06	\$0.04	\$0.02
	Bipolar Plates QC	\$0.35	\$0.03	\$0.03	\$0.03	\$0.03
	MEA Frame Gasket QC	\$1.17	\$0.19	\$0.18	\$0.18	\$0.18
	GDL QC	\$0.61	\$0.02	\$0.02	\$0.02	\$0.02
	End Plate QC	\$0.21	\$0.01	\$0.00	\$0.00	\$0.00
	Laser Welding BPP QC	\$0.35	\$0.03	\$0.03	\$0.03	\$0.03
Total (\$/kW_{net})	\$13.81	\$0.66	\$0.43	\$0.38	\$0.32	

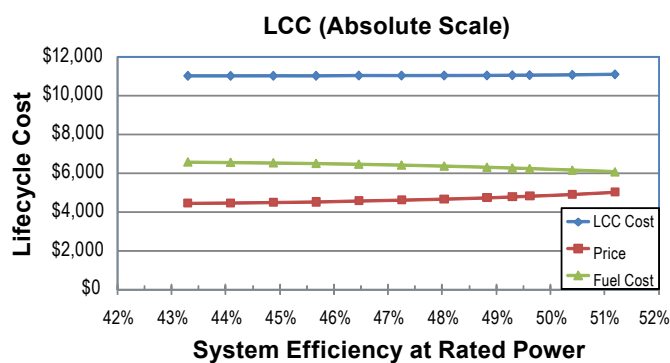
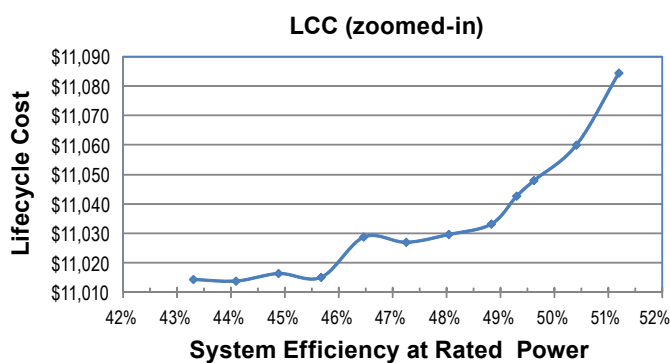


FIGURE 1. Lifecycle Cost Results

humidifier is the BOP component, that carry the highest cost risk. These components have a significant impact on the overall system cost and therefore warrant an R&D focus.

- The system cost is quite sensitive to the oxygen stoichiometric ratio; doubling this value adds roughly \$8/kW_{net} and is a direct consequence of increased compressor size and a larger system gross power.

- Air pressure has a relatively large impact on system cost; the minimum costs at the extremes of the range of validity shift the cost by $\$8/\text{kW}_{\text{net}}$. Above this range, the costs are expected to decrease further and bottom out around 4 atm; although performance at pressures greater than 3 atm are outside the range of validity of the ANL polarization curve fits and thus have greater uncertainty.
- Stack temperature has a limited impact on system cost: the system cost difference between 75°C and 95°C peak temperature operation being only $\$3/\text{kW}$.
- The impact of changing the catalyst loading is comparatively minimal. The maximum cost change between systems optimized across this range of loadings is about $\$2/\text{kW}_{\text{net}}$.
- With the exception of the catalyst loading, all the parameters leading to the minimum system cost are at one of the limits of their ranges of validity. This suggests that these ranges of validity ought to be examined to see if they can be expanded, so as to lower costs further.
- Increases in discount rate minimize net present value of the fuel costs, thus favoring lower efficiency systems that have lower initial capital investments.
- Conversely, increases in H_2 cost increase the lifecycle fuel costs, favoring higher efficiency. Increasing vehicle lifetime favors higher efficiency systems, since longer lifetime increases the relative impact of fuel cost.
- Finally, power system markup increases favor higher efficiency systems that have a lower power system capital cost, and thus a decreased impact due to the higher markup.

FY 2011 Publications/Presentations

1. August 18th, 2010 - Detroit, MI: Presentation to Fuel Cell Tech Team.
2. May 12th, 2011 – Washington, DC: Presentation to DOE H_2 Program Review.
3. June 16th, 2011 – Germany: Presentation at 12th Ulm Electrochemical Talks, Presented by DOE (Jason Marcinkoski).
4. “Manufacturing Process Assumptions Used in Fuel Cell System Cost”, Journal of Power Sources, doi:10.1016/j.jpowsour.2011.02.035 (Marcinkoski J, James BD, Kalinoski JA, Podolski W, Benjamin T, Kopasz J.).
5. “Performance and Cost of Automotive Fuel Cell Systems with Ultra-Low Platinum Loadings”, Journal of Power Sources, doi:10.1016/j.jpowsour.2011.01.059 (Ahluwalia R, Wang X, Kwon J; Rousseau A, Kalinoski JA, James BD, Marcinkoski J.).
6. Automotive fuel cell system cost analysis: Results of task 4.1.1 – 4.1.5. DTI Report to DOE, December 2010.
7. Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications: 2010 Update, DTI Report to DOE, September 2010.