V.A.6 Economic Analysis of Stationary PEM Fuel Cell Systems

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Objectives

The overarching objectives of the project are to assist the DOE in developing fuel cell systems by analyzing the technical, economic, and market drivers of direct hydrogen polymer electrolyte membrane fuel cell (H-PEMFC) adoption.

In 2010, Battelle's major task focused on developing a manufacturing cost analysis and associated technical targets for a 5 kW backup power fuel cell system operating on direct hydrogen. The cost analysis was performed at three technology levels and production volumes:

- Current Status (2,000 Units)
- 2012 (10,000 Units)
- 2015 (100,000 Units)

Preliminary analysis of the manufacturing costs is presented in this report. Final review and refinement are expected to be complete after the deadline for submission of this report.

Technical Barriers

This analysis considers the impact of many technical barriers in the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan, for Fuel Cells (Stationary/Distributed Generation Systems) including:

(B) Cost

Technical Targets

This project provides cost estimates for the manufacture of a 5 kW direct hydrogen backup power fuel cell system to help DOE establish technical targets for stationary fuel cell systems. The analysis will also provide insight into the key areas that require further research and development within the fuel cell system.

Accomplishments

- Developed baseline design and component specification for 5 kW backup power systems; validated with industry input.
- Analyzed new technologies and manufacturing approaches.
- Developed manufacturing costs and conducted sensitivity analysis.

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Introduction

Backup power is an emerging market for H-PEMFCs with significant potential to assist in maturing technology for other more significant fuel cell markets. A manufacturing cost analysis is performed to identify the projected costs with higher volumes, main drivers for system cost, and impacts of increasing production volumes on costs.

Approach

There are four steps to our approach: research, system and component design, manufacturing cost analysis, and system redesign. Research is conducted continuously and relevant background information is collected from literature (patents and papers) and through interviews with fuel cell system and component manufacturers.

Research provided input to the system design, component design, technologies in use, current state of development, and expected near-term improvements in fuel cell technology. This information was used to determine the preliminary design of the H-PEMFC stack and system for the years of interest (2010, 2012, and 2015). The overall system design was used to design the main components of the system, like the membrane electrode assembly, bipolar plate etc. The system design and configuration was then iterated multiple times based on further input from industry and insights provided by the simultaneous cost analysis. Manufacturing methods were then selected based on the industry practices and considerations for achieving desired durability and costs. These methods were further refined based on feedback from industry and based on cost modeling. Once the system configuration was defined, the system cost was determined. The system cost is comprised of capital equipment, stack production, balance of plant (BOP), and assembly/test costs. Capital equipment and BOP costs are determined using estimates and quotations from vendors of suitable hardware. Whenever possible, multiple vendors were solicited for pricing information to gain confidence in the validity of the costs used in the analysis. The cost of production of the stack and the system assembly and testing was estimated using models developed from the manufacturing process definitions, implemented in the Boothroyd-Dewhurst DFMA™ software.

System Design and Assumptions

An air-cooled system was chosen for the analysis. This is reflective of many commercially available H-PEMFC systems for backup power applications. Compared to a water-cooled system, an air-cooled system offers a reduction in BOP components and advantages in reliability, transport, and durability. An air-cooled system is generally operated at a lower current density than a water-cooled system which in turn requires more membrane active area. Due to equipment limitations, an air-cooled system also is limited on the stack size. The system schematic is shown in Figure 1.

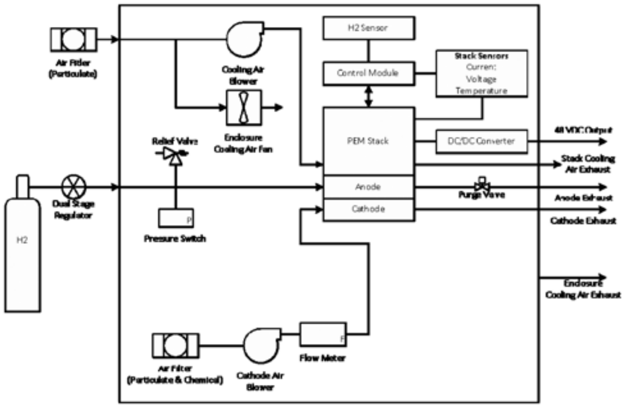


FIGURE 1. 2010 System Schematic

The operational characteristics for the system are listed in Table 1. Stack construction details are summarized in Table 2. Primary changes considered for systems in 2012 and 2015 are an increase in current density, an increase in the membrane utilization, and a decrease in the number of bipolar plates. The increase in current density is expected to come from research advances in membranes and catalysts. The increase in membrane utilization is attributed to improvements in the design and manufacturing capabilities. The reduction in bipolar plates is realized by combining the cathode air and cooling air process streams into a single process air flow and thereby eliminating the need for separate cooling air channels.

TABLE 1. Stack Operational Characteristics for 2010, 2012, and 2015

	2010	2012	2015
Net Power Output	5,000	5,000	5,000
Gross Power Output (W)	7,000	7,000	7,000
Nominal Operating Voltage (VDC)	50	50	50
Stack Temperature (C)	80	80	80
Power Density (W/cm^2)	0.455	0.52	0.65
Current Density (A/cm^2)	0.7	0.8	1.0
Cell Voltage (VDC)	0.65	0.65	0.65
Active Area Per Cell (cm^2)	200	175	140
Overall Membrane Dimensions (cm)	33 x 10	31 x 8.3	25 x 7.1
Overall Membrane Area (cm^2)	330	257	178
Membrane Utilization (Active Area/Total Area)	0.606	0.680	0.789

Battelle approached manufacturing by defining a business model where the fuel cell stack components, stack assembly, system assembly, and test and conditioning are all performed in-house. Doing so means acquiring and operating all necessary machinery as well as buildings and associated infrastructure such as electric distribution, heating and cooling, cleanliness control, lifting and transportation of materials, and storage. System components falling outside the defined core will be purchased or outsourced. As a result, no equipment or facilities are included for production of commercially available off-the-shelf items, such as blowers and pressure regulators, nor are any resources allocated to commercially common processes like metal machining or plastic molding.

Since a transition to high production volumes was anticipated well before the lifetime of the manufacturing equipment, high-volume equipment was identified and used at the outset. The manufacturing processes utilize roll-to-roll style processing (instead of batch processing). This approach results in excess manufacturing capacity initially, but as production volumes increase over time

TABLE 2. Stack Construction Details for 2010, 2012, and 2015

	2010	2012	2015
Number of Cells (#)	77	77	77
Membrane Base Material	PFSA 0.2 mm thick PTFE Reinforced	PFSA 0.2 mm thick PTFE Reinforced	PFSA 0.2 mm thick PTFE Reinforced
Catalyst Loading	Total Loading = 0.4 mg/cm^2 Cathode is 2:1 to 4:1 relative to Anode	Total Loading = 0.35 mg/cm^2	Total Loading = 0.25 mg/cm^2
Catalyst Application	Catalyst ink prepared, rolled on, heat dried	Catalyst ink prepared, rolled on, heat dried	Catalyst ink prepared, rolled on, heat dried
GDL Base Material	Carbon Paper 0.30 mm thick	Carbon Paper 0.30 mm thick	Carbon Paper 0.30 mm thick
GDL Construction	Carbon Paper, PTFE coating for water mgmt, carbon/graphite/PTFE microporous layer	Carbon Paper, PTFE coating for water mgmt, carbon/graphite/PTFE microporous layer	Carbon Paper, PTFE coating for water mgmt, carbon/graphite/PTFE microporous layer
MEA Construction	Catalyst applied to membrane, GDL placed on either side, hot press operation to join	Catalyst applied to membrane, GDL placed on either side, hot press operation to join	Catalyst applied to membrane, GDL placed on either side, hot press operation to join
MEA/Bipolar Plate Seal Material	Viton® FKM 0.3 mm thick	Viton® FKM 0.3 mm thick	Viton® FKM 0.3 mm thick
MEA/Bipolar Plate Seal Construction	Injection Molded	Injection Molded	Injection Molded
Number of Bipolar Plates	155	78	78
Bipolar Plate Material	Composite (Graphite Polymer) 3 mm nominal thickness	Composite (Graphite Polymer) 3 mm nominal thickness	Composite (Graphite Polymer) - or - Metal
Bipolar Plate Details	Anode side has parallel serpentine paths 1 mm wide and 1 mm deep. Cathode has parallel paths 2-3 mm wide and 2 mm deep.	Anode side has parallel serpentine paths 1 mm wide and 1 mm deep. Cathode has parallel paths 2-3 mm wide and 2 mm deep.	Anode side has parallel serpentine paths 1 mm wide and 1 mm deep. Cathode has parallel paths 2-3 mm wide and 2 mm deep.
Bipolar Plate Construction	Compression molded	Compression molded	Compression molded - or – Stamped (metal)
Coolant and End Gaskets	Viton® FKM	Viton® FKM (no coolant gasket)	Viton® FKM (no coolant gasket)
End Plates/Compression System	1″ thick die cast aluminum plates with tie rods	1″ thick die cast aluminum plates with tie rods	1″ thick die cast aluminum plates with tie rods

PFSA - perfluorinated sulfonic acid; PTFE – polytetrafluoroethylene (Teflon®); GDL – gas diffusion layer; MEA – membrane electrode assembly

the capacity is eventually exceeded. More equipment is bought as those limits are reached, phasing the cost of the manufacturing capital expenditures.

Cost estimates were developed for each piece of machinery in the manufacturing process. Quotes were gathered from vendors when possible, from published pricing information, resale listings, internet searches, and by engineering estimate when necessary. The same price was used across the various manufacturing line itemizations if a machine appears in multiple process lines.

Any capital expenditures are amortized over a 20-year period and the annual amortized cost is distributed over production volume for that year. For example, if total capital financing costs in year 1 are $2,000,000 with a production volume of 10,000 units, each unit's price will reflect $200 of capital cost. This approach results in capital costs representing a diminishing portion of the fuel cell system cost with increasing production volume. In all three of the forecast years, manufacturing capital costs are a minority contributor to the overall cost of a fuel cell system.

The cost of production was estimated using models developed from the manufacturing process definitions, implemented in the Boothroyd-Dewhurst DFMA™ software. Standard models for processes or machinery existing in the software were used whenever possible. A custom model was programmed, using fundamental mechanical principles and published machinery specifications or data gathered from vendors, when a standard model was not available. Basic cost assumptions are detailed in Table 3.

TABLE 3. Production Process Assumptions

Parameter	Value
MEA Manufacturing Process	Roll-to-roll
Process line speeds: Catalyst application GDL fabrication MEA hot pressing	 10 m/min 5 m/min 0.5 m/min
Roll length	1,000 ft
Membrane roll width	1 m
Carbon cloth width	1 m
Overall plant efficiency	85%
Inspection steps included in processing	None
Labor cost	$45/hr
Machine cost	$25/hr
Energy cost	$0.07/kW-h
Setup operations per roll	1
Operators on membrane line	3
Operators on all other lines	1

Assumptions were developed from previously published information, discussions with vendors, using standard values defined in the software, and by engineering estimates.

Scrap rates for the stack manufacturing processes vary and in some cases represent a tangible portion of the process's cost. As with the manufacturing process definition itself, much of this information is considered proprietary in industry. The values used for the Battelle analysis are representative of ranges documented in previously published information. When such data was not available, engineering estimates were made based on Battelle's manufacturing knowledge. Table 4 delineates the scrap rates, which were held constant over all the forecasted years. These rates capture not only scrap resulting from initial production of material, but also excess material consumed during stack rework as part of test and conditioning.

The remainder of the fuel cell system components, including BOP and structure (frame) and enclosure, are purchased or outsourced. The assembly, integration, testing, and conditioning of all these items are done in-house. Stack assembly and test costs are included in the stack estimate while the cost of system assembly and test is included at that level.

Results

The system cost breakdown and total system costs are shown in Table 5. According to the Battelle analysis, in 2010 with an annual production volume of 2,000 units, cost of a 5 kW H-PEMFC system is $6,986 or $1,379 per kW. This cost declines by 26% to $5,084 or $1,017 per kW in 2012, and by 39% to $4,221 or $844 per kW in 2015. Approximately 60% of the reduction to $844/kW in 2015 is achieved through reduction in costs of the stack components, particularly the bipolar plates and the MEA. The remaining 40% is equally split between reductions in the BOP component cost and the lower assessment of capital costs on a per unit basis. The modest decrease in BOP costs is due to many of them already being produced in high quantities with limited margin for cost reduction. Approximately 50% of the source for reduction in cost for both the 2012 and 2015 cases is due to technology advances while the other half is due to increased production volume.

TABLE 4. Scrap Rates for Production

Scrap/Reject Rates	
Catalyst application	30%
GDL fabrication	30%
MEA hot pressing	5%
Slit to width	0.5%
Slit and cut	0.5%
Compression molding - Pre-form	0.5%
Compression molding - Mold	1%
Compression molding - Post bake	1%
Die casting – End plate	0.5%
Die casting - Thread tapping	0.5%
Testing and conditioning	5%

In general, materials represent the most significant cost of fuel cell stack production, evident in Figure 2. In the case of the bipolar plates; production cost is split more uniformly across all three of tooling, processing, and raw materials. The cost production breakdown is similar for 2012 and 2015.

At initial and low volume production, much of the capacity of the manufacturing equipment goes unused. In some cases, the entire year's worth of production can be run in a few calendar days. However, by business model definition, the equipment purchase at the beginning is justified by the rapidly increasing production quantities over the five year period of study. Despite much of the machinery's production capacity potentially going unused in the first few years, the unused capacity represents, by way of capital costs allocated to each unit, a small portion of the system cost.

Considering line utilization is useful for identifying process bottlenecks. Battelle defined line utilization as a percentage calculated as the number of machine hours necessary to produce the annual quantity divided by the total number of annual machine hours available.

TABLE 5. System Cost and Breakdown for 2010, 2012, and 2015

	2010 Cost per Stack	2010 Cost Each	2012 Cost per Stack	2012 Cost Each	2015 Cost per Stack	2015 Cost Each
Bipolar plates	$862	$5.56	$367	$4.70	$320	$4.10
MEA	$1,513	$19.64	$981	$12.73	$498	$6.46
Cathode side gasket	$49	$0.64	$49	$0.63	$47	$0.61
Anode side gasket	$52	$0.68	$51	$0.66	$49	$0.64
Cooling gasket	$49	$0.64	-	-	-	-
End gaskets	$1	$0.64	$1	$0.63	$1	$0.61
Tie rods and hardware	$40	$5.00	$40	$5.00	$40	$5.00
End plates	$28	$14.11	$27	$13.55	$22	$11.02
Stack assembly	$41	$40.89	$41	$40.89	$41	$40.89
Stack Subtotal	$2,635		$1,557		$1,018	
BOP Cooling	$333		$305		$278	
BOP Cathode	$502		$441		$396	
BOP Anode	$225		$218		$206	
BOP Sensors	$217		$200		$188	
BOP ECU	$380		$380		$380	
BOP DC/DC Converter	$1,250		$1,125		$1,000	
BOP Frame	$207		$144		$144	
BOP Misc. Components (Fittings, Tubing, Wiring, Connectors, etc.)	$289		$276		268	
BOP Subtotal	$3,403		$3,089		$2,860	
Stack Subtotal	$2,635		$1,557		$1,018	
BOP Subtotal	$3,403		$3,089		$2,860	
Capital Cost	$540		$120		$25	
System Assembly, Test, and Conditioning	$318		$318		$318	
System Total	$6,896		$5,084		$4,221	
$/kW	$1,379		$1,017		$844.20	

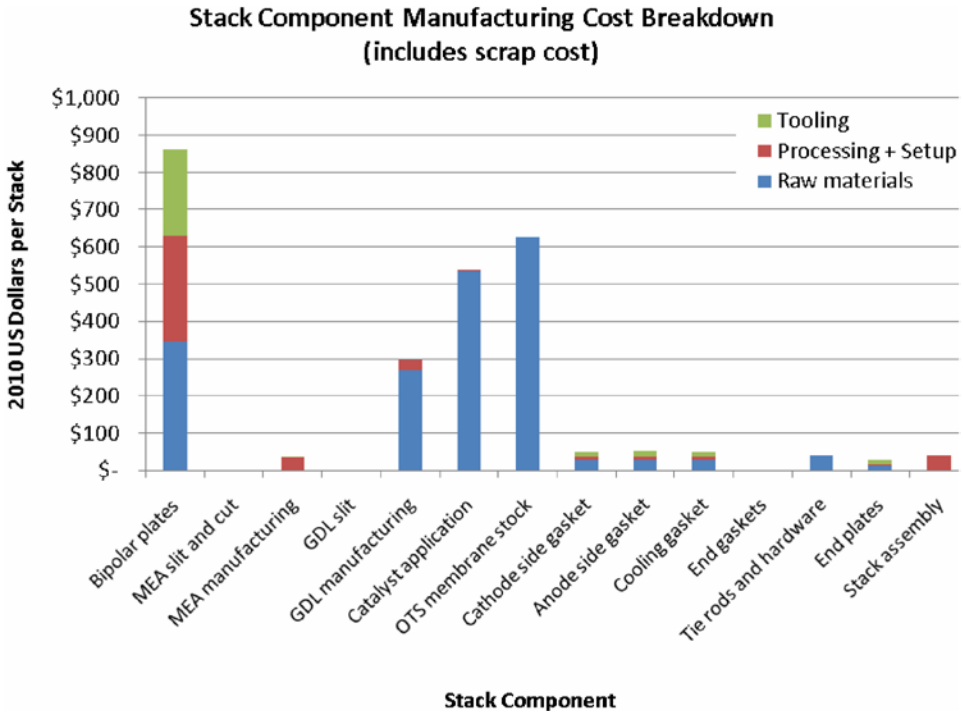
ECU – electronic control unit; DC – direct current

The annual machine hours available are the number of machines times 24 hours (3, 8-hour shifts) in a day. The results of this are tabulated in Table 6.

The bottlenecks in production are identified by these tables and include the bipolar plate forming, stack assembly, and test and conditioning. Despite having limitations to productivity, the system cost impact of these bottlenecks is mostly low since raw material costs are the predominant expense in stack production. Of the group, eliminating the bipolar plate forming bottleneck will have the most impact on stack cost. The elimination of the bipolar plate bottleneck can be achieved by emerging technologies, like flat/unformed sheet metal or foils. Industry expects test and conditioning time to decrease significantly over the next five years, providing a modest opportunity for cost reduction.

Conclusions and Future Directions

System costs and stack costs are expected to decline to $847 per kW and $203 per kW, respectively with annual volumes of 100,000 units. Major contributors to the system cost are the bipolar plates, MEA, and the DC/DC converter. The main drivers to MEA cost are the raw materials, most specifically catalyst. Additional research in alternative material-based bipolar plates and lower-catalyst MEAs could reduce these costs. The lack of a suitable off-the-shelf DC/DC converter is a significant obstacle. Further work to understand the



OTS – off the shelf

FIGURE 2. 2010 Fuel Cell Stack Components Cost Breakdown

TABLE 6. Year 2010 (2,000 Units) Manufacturing Process Utilization

	2,000 Units		10,000 Units		100,000 Units	
Process Description	**Quantity**	**Utilization (%)**	**Quantity**	**Utilization (%)**	**Quantity**	**Utilization (%)**
Catalyst application	1	0.8	1	3.3	1	22.8
GDL fabrication	1	1.7	1	6.6	1	45.6
MEA hot press	1	17.6	1	68.8	2	79.1
Bipolar plate forming	1	68.4	2	57.0	12	95.1
Stack assembly	1	9.9	3	100.0	30	100.0
Test and conditioning	2	83.3	9	92.6	84	99.2

application requirements and the drivers for DC/DC converter cost is recommended.

Next steps on the project are to complete a sensitivity analysis of the cost drivers likely to most impact the cost of the system and incorporate the feedback from industry and the peer reviewers and publish final results.

FY 2010 Publications/Presentations

1. Mahadevan, K, V. Contini, M. Goshe, F. Eubanks, J. Price, and F. Griesemer . 2010. Economic Analysis of Stationary Fuel Cell Systems. DOE Annual Peer Review. Washington, D.C.