Manufacturing Cost Analysis of 1, 5, 10 and 25 kW Polymer Electrolyte Membrane (PEM) Fuel Cell Systems for Material Handling Applications

Prepared by:
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201

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Executive Summary

Battelle, under a five-year cooperative agreement with the Department of Energy's (DOE's) Fuel Cell Program, is providing an independent assessment of fuel cell manufacturing costs at various volumes and for alternative system designs. This report provides cost estimates for the production of 1, 5, 10, and 25 kW polymer electrolyte membrane (PEM) fuel cell systems designed for material handling applications. This report identifies the manufacturing costs of fuel cells using appropriate manufacturing processes at annual production volumes of 100, 1000, 10,000, and 50,000 units. A conceptual system design was defined by Battelle based on literature review and system integration experience. The conceptual design was refined through discussion with industry partners. This report presents our approach, including the design of the system and primary design assumptions, manufacturing processes modeled using the Boothroyd-Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA®) software, and balance of plant (BOP) component costs obtained via quotes and industry consultation. The main cost drivers were identified and a sensitivity analysis was used to analyze opportunities for cost reduction. The life cycle system costs and benefits were compared to potential material handling applications where the primary incumbent technologies are lead acid battery and propane powered equipment.

System costs are summarized in the following tables for 1-kW to 25-kW complete systems, which include the fuel cell stack, necessary support hardware (e.g. pressure regulators and relief devices, direct current to direct current [DC/DC] converter), hydrogen storage, and appropriate assembly and testing labor.

As shown in the tables below, the costs are dominated by BOP costs for all system capacities and at all volumes considered. Further, the BOP costs do not scale significantly with power output: the BOP for a 5-kW system at 10,000 units per year is only 24% more than the 1-kW system at an equivalent production volume. This characteristic results from threshold costs for many of the components (cost of having a specific component in a system regardless of system capacity). Since a system includes only one instance of most BOP components, the threshold costs dominate at these small sizes. Within the BOP costs, the two highest-cost items are the DC/DC converter (5% to 35% BOP based on system capacity, higher for higher capacity), and batteries (9% to 20% BOP). The major difference from the previous studies in this aspect is a significant reduction in the cost of hydrogen storage with the use of steel tanks, which are 75% cheaper than higher-cost composite tanks. Stack costs (characteristically between 12% and 30% of costs for all systems) are dominated by the cost of the membrane electrode assembly (MEA) (due to catalyst and membrane costs) and bipolar plates (due to plate machine processing time). As system capacity increases, the contribution of the stack cost to the total cost also increases because the BOP cost does not rise as steeply as stack cost. The relatively high cost of the battery may be attributed to the choice to include lithium ion batteries in place of lead acid batteries to achieve higher energy and power density factors for the material handling equipment (MHE) application.

A life cycle cost analysis was performed for manufacturing volumes of 1,000 units/year and 10,000 units/year. Both small (75 trucks) and large fleets (300 trucks) were considered for 2 and 3 shifts. In the individual cases considered, conversion to fuel-cell-powered vehicles showed value with payback periods greater than 1 year and less than 3 years. A sensitivity analysis was also performed to understand the main cost drivers using tornado charts and a Monte Carlo analysis. The cost analysis is particularly sensitive to the assumptions made regarding labor rate, number of shifts per day, the cost of hydrogen, and the cost of battery exchange or recharge. The Monte Carlo results indicated the payback period is around 1 year on average though the payback can be less than a year under favorable conditions (inexpensive H_2 fuel and labor coupled with high electricity costs) and as a high as 4 years under less ideal conditions (expensive H_2 and labor coupled with low electricity costs).

Cost per Unit Summary for 1-kW MHE PEM Fuel Cell System

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$4,147	$1,046	$531	$402
Stack manufacturing capital cost	$567	$57	$22	$21
BOP	$9,681	$7,619	$6,381	$5,541
System assembly, test, and conditioning	$1,431	$259	$185	$184
Total system cost, pre-markup	$15,826	$8,980	$7,118	$6,149
System cost per net kW, pre-markup	$15,826	$8,980	$7,118	$6,149
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$23,739	$13,471	$10,678	$9,223
System cost per net kW, with markup	$23,739	$13,471	$10,678	$9,223

Cost per Unit Summary for 5-kW MHE PEM Fuel Cell System

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$6,066	$2,015	$1,132	$880
Stack manufacturing capital cost	$567	$71	$30	$30
BOP	$12,411	$9,554	$7,996	$6,941
System assembly, test, and conditioning	$1,429	$257	$183	$183
Total system cost, pre-markup	$20,473	$11,897	$9,341	$8,034
System cost per net kW, pre-markup	$4,095	$2,379	$1,868	$1,607
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$30,709	$17,845	$14,011	$12,051
System cost per net kW, with markup	$6,142	$3,569	$2,802	$2,410

Cost per Unit Summary for 10-kW MHE PEM Fuel Cell System

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$7,986	$3,126	$1,827	$1,490
Stack manufacturing capital cost	$567	$71	$39	$38
BOP	$14,841	$11,628	$9,576	$8,305
System assembly, test, and conditioning	$1,431	$259	$185	$184
Total system cost, pre-markup	$24,825	$15,084	$11,626	$10,018
System cost per net kW, pre-markup	$2,482	$1,508	$1,163	$1,002
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$37,237	$22,626	$17,439	$15,028
System cost per net kW, with markup	$3,724	$2,263	$1,744	$1,503

Cost per Unit Summary for 25-kW MHE PEM Fuel Cell System

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$12,593	$5,683	$3,467	$3,155
Stack manufacturing capital cost	$567	$101	$65	$64
BOP	$20,286	$15,565	$13,121	$11,437
System assembly, test, and conditioning	$1,432	$260	$186	$185
Total system cost, pre-markup	$34,877	$21,609	$16,839	$14,841
System cost per net kW, pre-markup	$1,395	$864	$674	$594
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$52,316	$32,413	$25,259	$22,262
System cost per net kW, with markup	$2,093	$1,297	$1,010	$890

Table of Contents

List of Tables

List of Figures

Page

1. Introduction

Battelle is conducting manufacturing cost assessments of fuel cells for stationary and non-automotive applications to identify the primary cost drivers impacting successful product commercialization. Battelle, under a five-year cooperative agreement with the Department of Energy's (DOE's) Fuel Cell Program, will provide an independent assessment of fuel cell manufacturing costs at varied volumes and alternative system designs. This report provides cost estimates for the manufacture of 1-kW, 5-kW, 10-kW and 25-kW polymer electrolyte membrane (PEM) fuel cells designed for material handling applications. This report identifies the manufacturing costs of fuel cells using high-volume manufacturing processes at annual production volumes of 100, 1000, 10,000, and 50,000 units. The system design and manufacturing volumes were defined using Battelle's fuel cell system integration expertise and refined through discussion with industry partners. The report presents our approach; the design of the system, design assumptions, and manufacturing processes modeled using the Boothroyd-Dewhurst Design for Manufacture and Assembly (DFMA®) software; costs of the system, sub-system, and specific components; the main cost drivers identified through a sensitivity analysis; and a summary of opportunities for cost reduction.

2. Approach

Battelle's cost analysis methodology is a four-step approach (Figure 2-1):

Step 1—Market Assessment
Step 2—System Design
Step 3—Cost Modeling
Step 4—Sensitivity Analysis/Life Cycle Cost Analysis

This approach has been successfully applied to previous cost analyses developed by Battelle.[1,2]

[1] Battelle. 2011. The High Volume Manufacture Cost Analysis of 5-kW Direct Hydrogen Polymer Electrolyte Membrane (PEM) Fuel Cell for Backup Power Applications. Contract No. DE-FC36GO13110.
[2] Battelle. 2006. H. Stone, K. Mahadevan, K. Judd, H. Stein, V. Contini, J. Myers, J. Sanford, J. Amaya, and D. Paul. Economics of Stationary Proton Exchange Membrane Fuel Cells, Interim Report. Contract No. DE-FC36GO13110.

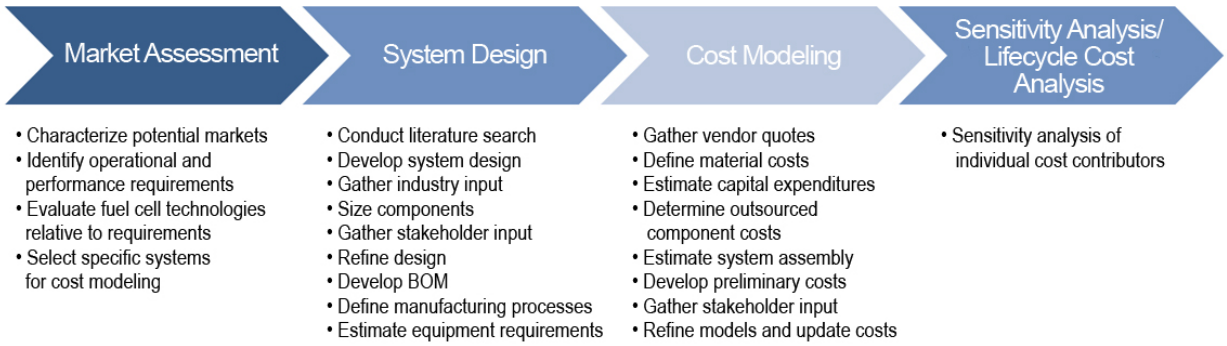


Figure 2-1. Battelle's cost analysis approach

The first step in our methodology, ***Market Assessment***, assured that we selected the right fuel cell type and appropriate production volumes to meet market requirements. In this step, Battelle identified the operational and performance requirements (e.g., hours of operation, frequency, expected lifetime) of the target application and market. Using this information, we defined the user requirements for a fuel cell product. Battelle completed a quick survey of the market through an industry dialogue to estimate the number of units in the market and the expected market growth for fuel cells in material handling applications in the 1-kW to 25-kW range. This information formed the basis for selecting the system design and fuel cell type best suited to meet user requirements and the appropriate production volumes to consider in the modeling exercise.

Step 2 was ***System Design***, a literature review of fuel cell designs for forklift applications, component design and manufacturing processes, and possible improvements in system design and manufacturing. From these results the basic construction and operational parameters for a fuel cell stack and system were defined, as well as potential improvements. The fuel cell design did not focus on an individual manufacturer's designs, but was instead representative of typical designs based on literature and Battelle's engineering expertise. The stack and system design were vetted with industry stakeholders to ensure feasibility of the design, to identify possible improvements, and to determine current and alternate manufacturing approaches. The finalized design and projected improvements were published to form the basis for developing the bill of materials (BOM). Decisions were then made about which components would be manufactured internally and which would be outsourced. For internally manufactured components (including applicable balance of plant (BOP) components), manufacturing processes and production equipment were defined in detail.

In Step 3, ***Cost Modeling***, Battelle gathered vendor quotes for material costs, production equipment, and outsourced components. Where necessary, custom manufacturing process models were defined and parametrically modeled based on knowledge of the machine, energy, and labor requirements for individual steps that comprise the custom process. The sequence of actions required to assemble the components and test the final fuel cell system was developed and analyzed for cost reduction opportunities through component consolidation and process optimization. Manufacturing quality control requirements were based on input from equipment vendors and Battelle's experience with product manufacturing. Outsourced components costs were estimated through vendor quotes. Mathematic functions for scaling factors were developed to estimate the changes to outsourced components and material costs with production volumes when vendor quotes for higher volumes were not available. These estimates were derived using engineering rules of thumb and estimates from other manufacturing processes and considered impacts on system design.

Using the DFMA® software, component costs calculated from both custom and library manufacturing processes and the outsourced components were incorporated into the assembly and test sequence models to determine the final cost of producing the fuel cell systems. The output of the DFMA® models was also used to calculate production station use to determine the number of individual process stations required to support various product demand levels, as input to the manufacturing capital cost model. It was assumed that capital equipment expenditures for production would be amortized over a 20-year period and that the annual amortized cost would be distributed over the production volume for that year. The financial assumptions that were used are consistent with the DOE Hydrogen Analysis (H2A) model. Total stack system costs, including capital expenditures, were then estimated for the baseline system and projected improvements.

The ***Sensitivity Analysis*** (Step 4) was then performed to determine which design parameters or assumptions have the most effect upon the stack and system cost. Single factor sensitivity analysis was performed and helped determine the impact of individual parameters on system costs. Based on these results, Battelle provided insights into design optimization to reduce the total fuel cell system cost and total cost of ownership.

A preliminary Life Cycle Cost Analysis was developed for the systems evaluated in this portion of the overall project. Life cycle analyses are necessarily tied to specific applications. For this study, we considered material handling applications of 1 kW to 25 kW of total power requirements.

3. Market Analysis

Battelle performed a market analysis to support the selection of the system and fuel cell type for the cost analysis. For this study, Battelle focused on fuel cell systems for material handling applications. Battelle reviewed various types of material handling equipment (MHE) to gain a general understanding of the characteristics and equipment types available in the market.

3.1 Market Requirements and Desired Features

In FY12[3] and FY13[4], Battelle conducted studies to assess the potential for fuel cell technology to be adopted in material handling applications. Battelle sought to identify those applications in which fuel cell systems could meet or exceed the performance of currently deployed equipment. Aspects of performance that were considered included power, responsiveness, efficiency, operability, and air and noise emissions.

At present, MHE applications that require a mobile power source, high operational time, and locally low emissions and/or noise (e.g., indoors) are predominantly battery powered. For these applications, fuel cells can significantly out-perform the currently deployed technology by providing essentially continuous

[3] Battelle. 2012. Task 2: Market and Application Requirements to Support Fuel Cell Design: Material Handling Equipment. Report to the U.S. Department of Energy. DOE Contract No. DE-EE0005250/001.
[4] Battelle. 2013. Manufacturing Cost Analysis of 1-kW and 5-kW Direct Hydrogen Polymer Electrolyte Membrane (PEM) Fuel Cell for Material Handling Applications. Report to the U.S. Department of Energy. DOE Contract No. DE-EE0005250.

or near continuous power, thus eliminating recharging or battery exchange. These advantages are likely to remain regardless of advances in battery technology.

Three types of MHE were identified as having a high potential for fuel cell technology: auto guided vehicles (AGVs), forklifts, and industrial/cargo trucks. Table 3-1 summarizes general system operating requirements for these equipment types. Having the capability for near continuous operation is a common requirement across all three equipment types, although the daily operational requirement for any specific application varies. Users generally expect equipment to last at least 10 to 15 years with heavy use. A fast start-up time is common. For systems powered by battery or internal combustion (IC) engine, the nominal motor power listed below is essentially the peak power.

Table 3-1. System Operating Requirements for MHE with High Potential for Fuel Cell Technology

Equipment Type	Maximum Duty Cycle	Equipment Lifetime	Power Module Lifetime	Nominal Power
AGVs - Industrial	Near continuous, 24/7	12-15 years	battery: 6-8 years	1-30 kW
AGVs - Commercial	4 hours of 8-hour shift	20 years	battery: 6-8 years	<1 kW
Forklifts - Class I & II	Near continuous, 24/7	12-15 years	battery: 3-5 years fuel cell: 2 years[5]	5-20 kW
Forklifts - Class III	Near continuous, 24/7	12-15 years	battery: 3-5 years fuel cell: 2 years	3-5 kW

Class I, II, and III forklifts are a demonstrated market for polymer electrolyte membrane (PEM) fuel cell technologies. PEM systems with power outputs ranging from 2 to 15 kW have been incorporated into hybrid power modules capable of delivering peak powers up to 50 kW for short durations. Major companies have begun incorporating this technology into their material handling applications and replacing the existing battery operated fleet with fuel cell powered forklifts. PEM MHE suppliers have grown their production and installation volumes by an order of magnitude as many companies are stepping in to reap the benefits of switching to fuel cells. Significant efforts have been put into research and development of this technology through fruitful three-way partnerships among fuel cell developers, lift truck manufacturers, and end-users. Such partnerships between a stakeholder and manufacturers involve staff and experts from all parties working on data analysis and logistics of a PEM MHE program in the stakeholder’s warehouses. Endeavors like the one described above paved the way for personalized installation programs for other end users, which led to the commercialization of fuel cells in MHE applications while reducing their manufacturing costs and increasing the market for fuel cell MHE. Figure 3-1 shows the trends in fuel cell forklift deployment in the US. The blue bars represent PEM fuel cell forklifts while the orange bars correspond to direct methanol fuel cell (DMFC) forklifts, which are beyond the scope of this study.

[5] http://www.plugpower.com/Solutions/FAQ.aspx

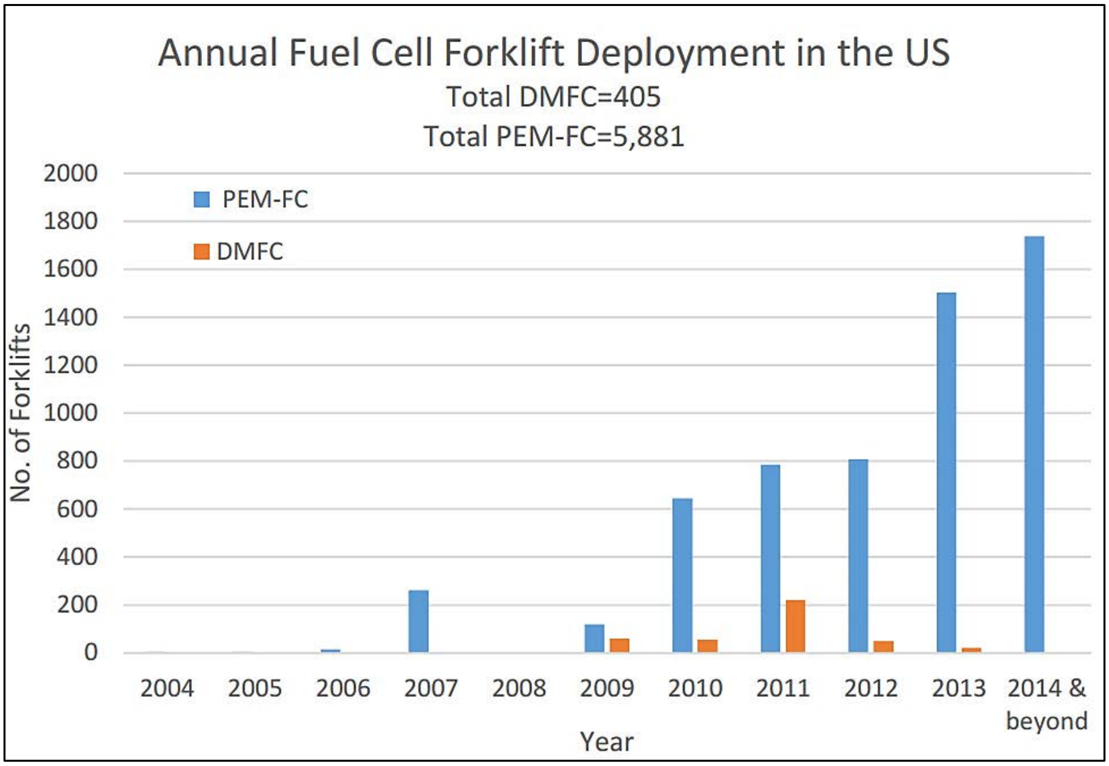


Figure 3-1. Fuel cell forklift deployment in the US[6]

There are the two types of programs that facilitate the conversion to an MHE fleet based on business needs of the end user, namely "greenfield" and "brownfield" projects. Greenfield projects include building new warehouses, purchasing new fuel cell operated equipment, and creating a hydrogen based infrastructure from scratch. This is highly beneficial to end users because companies can save thousands of square feet of space as well as electrical expenses that are otherwise required for battery operated MHE operation. This process, however, includes other infrastructure costs such as fenced-in concrete pads for hydrogen fueling and electric hook ups for remote monitoring of the equipment. But these costs are minimal as the hydrogen is usually outsourced from a commercial gas provider.

Brownfield projects involve adopting hydrogen based infrastructure in an existing facility where battery operated MHE is in operation. A major value proposition for these projects is an increase in productivity and elimination of costs and downtime associated with battery recharging. Reduced consumable costs and emissions in addition to reliable and continuous operability of hydrogen fuel cell MHE have helped build a stronger case for brownfield projects.

Governmental economic incentives also facilitate the adoption of fuel cell technologies, primarily the Emergency Economic Stabilization Act (EESA) of 2008 and the American Recovery and Reinvestment

[6] See "Industry Deployed Fuel Cell Powered Lift Trucks" DOE Hydrogen and Fuel Cells Program Record at https://www.hydrogen.energy.gov/pdfs/17003_industry_deployed_fc_powered_lift_trucks.pdf for 2017 update.
See "Fuel Cell MHE Systems Deployed" as result of ARRA of 2009: https://www.nrel.gov/docs/fy14osti/62130.pdf

Act (ARRA) of 2009, as well as state-specific incentives. The EESA ended in 2016 and the ARRA ended in 2010[7]. Even in the absence of incentives, a compelling economic argument can be made for fuel cell powered MHE with high daily usage requirements.[8] In this context, conversations with one end-user suggest that fuel cell incorporation initiatives barely break even or are economically viable in the pilot stage, thus the incentives encourage the continuation of such programs. Therefore, companies venturing into fuel cell MHE program should consider seeking out manufacturers that are compatible with their business needs and are willing to work through the initial hurdles of their MHE programs. One example, Plug Power Inc., has established on-site programs to power, fuel, and service its customers. These programs also eliminate the need for end users to incur any overhead costs for training existing employees on maintenance aspects while integrating fuel cells into their material handling operations.

With the success of fuel-cell-powered forklifts (and, to some extent, AGVs), coupled with a significant reduction in manufacturing costs (indicated at almost 70% in the past five years in private conversations between suppliers and Battelle), manufacturers are now investigating the potential application of fuel cell technologies for other MHE such as cargo tractors, delivery/pickup trucks, and range extenders. For these relatively new potential markets, pilot studies and collaborative programs are under way to evaluate their feasibility.

3.2 Technology Selection

Having identified potential markets and general application requirements, Battelle identified fuel cell technologies best suited to meet those needs. In typical material handling applications, the full nominal power is required only for brief periods of lifting or for overcoming stationary inertia. A battery or IC engine power module must be able to supply this power level entirely on its own. A fuel cell power module, however, can be hybridized with batteries or supercapacitors to meet the infrequent peak power demands. National Renewable Energy Laboratory (NREL)'s composite data product CDPARRA-MHE-17 shows that for about 80% of the time in a fleet of hybridized fuel cell powered forklifts, the fuel cell system is operating at less than 50% of its rated capacity.[9] A review of the capabilities and accepted performance of deployed systems indicates that a fuel cell system rated at 25% to 50% of the nominal required power could be incorporated into a hybrid system that would meet the application requirements. The exact ratio depends upon the specific application requirements and typical drive cycles. Battelle's market research completed in this task indicates that existing Class I, II, and III equipment powered by fuel cells falls within these bounds. The Class I forklifts are defined as Electric Motor Rider Trucks. The Class II forklifts are Electric Motor Narrow Aisle Trucks. The Class III forklifts are Electric Motor Hand Trucks or Hand/Rider Trucks.

Battelle started with the entire range of system sizes and technologies specified by the DOE's Fuel Cell Technologies Office (FCTO) in funding opportunity announcement, DOE FOA-0000420. Based on our

[7]U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Fuel Cell Technologies Office, "Financial Incentives for Hydrogen and Fuel Cell Projects": https://energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects
[8] U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Fuel Cell Technologies Office (April 2013): https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/market_transformation.pdf
[9] ARRA Material Handling Equipment Composite Data Products Data through Quarter 4 of 2013 Technical Report NREL/TP-5400-62130 (June 2014) page 16: https://www.nrel.gov/docs/fy14osti/62130.pdf

previous experience analyzing 10-kW and 25-kW systems in an FY12 study[10] and 1-kW and 5-kW systems in an FY13 study[11], we have combined and updated costs associated with all four systems in this present study to provide a holistic understanding and analysis of Class I, II and III MHE.

The main objectives of the DOE-funded research are to advance fuel cell technology and reduce fuel cell and total system costs. Therefore, it is anticipated that the selection matrix will be reconsidered in future years based on technological advances and the results of work on this study.

In selecting system sizes for consideration, Battelle chose to retain the fuel cell system power sizes specified by the DOE to maintain a consistent basis for comparison. For example, if an application would ideally use a 3-kW fuel cell system size, Battelle would consider 1-kW and 5-kW systems. Based on our survey, it was found that a Class I/II power rating of one manufacturer may vary from 8 to 12 kW, while that of another manufacturer may lie between 13 and 14 kW. Class III systems typically require a power rating of less than 5 kW. Since the power rating for a given class was found to vary, analyzing the costs and markets in terms of pre-selected power ratings or "buckets" helps keep the analysis consistent and provide reference points to interpolate and estimate costs for a system with power ratings that fall within the range of the analyzed systems. Figure 3-2 shows the power output ranges for different classes considered in this study compared against the standard sizes used for analysis.

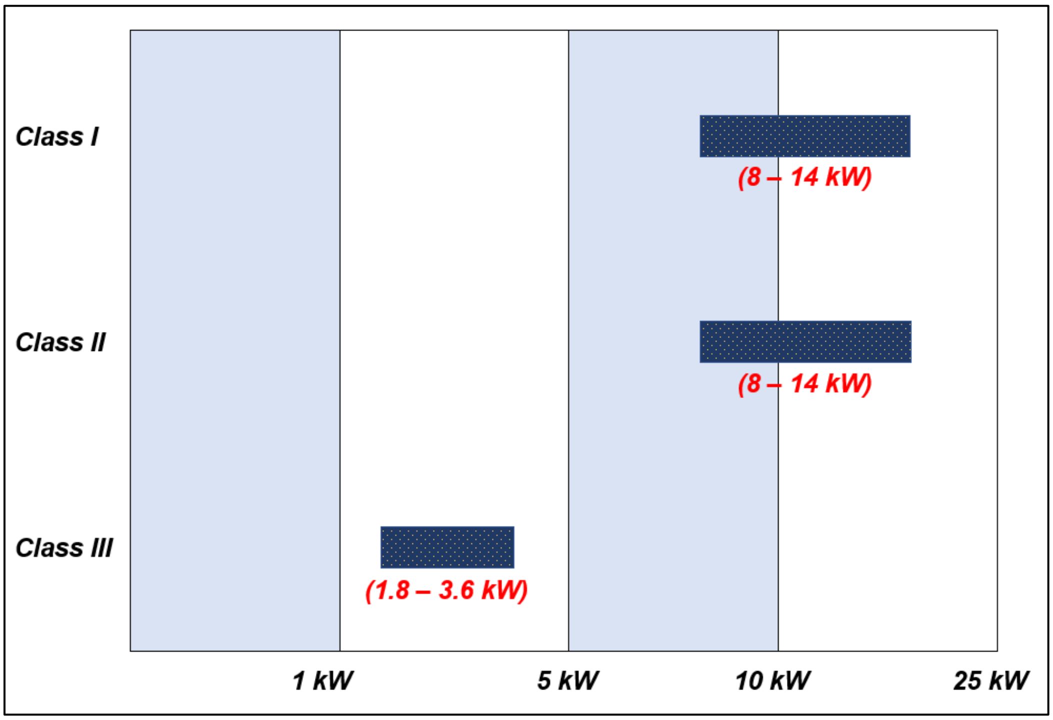


Figure 3-2. Output power ranges for commercially used fuel cell MHE classes

[10] Manufacturing Cost Analysis of 10 kW and 25 kW Direct Hydrogen Polymer Electrolyte Membrane (PEM) Fuel Cell for Material Handling Applications (Battelle Memorial Institute, March 2013) DOE Contract No. DE-EE0005250: https://energy.gov/sites/prod/files/2014/06/f16/fcto_battelle_cost_analysis_mhe_mar2013.pdf
[11] Manufacturing Cost Analysis of 1-kW and 5-kW Direct Hydrogen Polymer Electrolyte Membrane (PEM) Fuel Cell for Material Handling Applications (Battelle Memorial Institute, April 2014). DOE Contract No. DE-EE0005250

As identified in Table 3-1, existing AGV motor sizes run from less than 1 kW to 30 kW, with the majority in the 1 to 5 kW range. A 1 kW fuel cell system in a hybrid power module can meet the 1 to 5 KW requirement. Although it may be oversized for most applications, Battelle recommends that a 5 kW fuel cell system in a hybrid power module also be considered to better understand the effect of fuel cell system size on total cost.

3.3 Market Analysis Conclusion

Based on the results of the market analysis, Battelle proposed to conduct a cost analysis of a general fuel cell system for MHE that would meet the needs of several specific applications. Specifically, Battelle considered 80°C (nominal) PEM-hybrid systems of 1-, 5-, 10-, and 25-kW fuel cell system power with peak power capability of up to 300%. The fuel cell system would be designed for a lifetime of 10,000 hours and be capable of operating 24/7 with normal intervals of refueling. Through updated analysis of the technology selection matrix, it was determined that AGV and Class VI fuel cell markets have not developed as fully as markets for Classes I, II, and III MHE; therefore, AGV and Class VI markets are not considered in this report.

4. System Specifications

This section presents a general description of the fuel cell system for MHE, electrical system specifications, and assumptions.

4.1 General Description

Based on a market study that evaluated market requirements, technological readiness, and barriers to implementation, Battelle considered 1-kW, 5-kW, 10-kW, and 25-kW (net) fuel cell power systems for MHE. The 5-kW system design is applicable to equipment designated as Class I or Class II lift equipment (several lift codes), while the 1-kW system is applicable only to Class III equipment. The 25-kW system design is applicable to equipment designated as Class VI, Lift Code 1 (Sit-Down Rider, Draw Bar Pull over 999 lbs.). A 10-kW fuel cell power system is applicable to both Class VI equipment as well as several lift codes of Class I and II equipment.

The system is powered by a standard temperature PEM fuel cell hybridized with an appropriate means of energy storage (such as a battery) for peak demands and transient response. The system schematic for a generic 1-, 5-, 10-, and 25-kW MHE application is shown in Figure 4-1, and is similar in nature to the assumptions used in the FY12 and FY13 studies.

In the configuration shown in Figure 4-1, hydrogen is stored at 350 bar (~5,000 pounds per square inch gauge [psig]), passes through a dual-stage regulator, and then supplies the stack at 2 psi. Excess hydrogen is recirculated with an oil-free hydrogen blower. While recirculating hydrogen increases BOP cost, it improves overall stack life by preventing anode fuel starvation and expands operating range. Hydrogen purging is periodically required.

The cathode airstream is drawn from the atmosphere and passes through a chemical and particulate filter. The airstream is humidified as it flows through a humidifier, where moisture is drawn from the cathode exhaust. The process is an open-loop cycle where the cathode exhaust air provides moisture to the cathode inlet air. As the airstream flows through the stack, it inherently collects moisture, which is then transferred to the supply airstream via the transport membrane. What is remaining of the cathode exhaust is then released to the atmosphere. While humidification enables higher stack operating temperature and a broader operating range, it adds expense. Stack and humidifier manufacturers alike are constantly looking for cost reductions or, in the case of some stack vendors, ways to eliminate the need for humidification altogether.

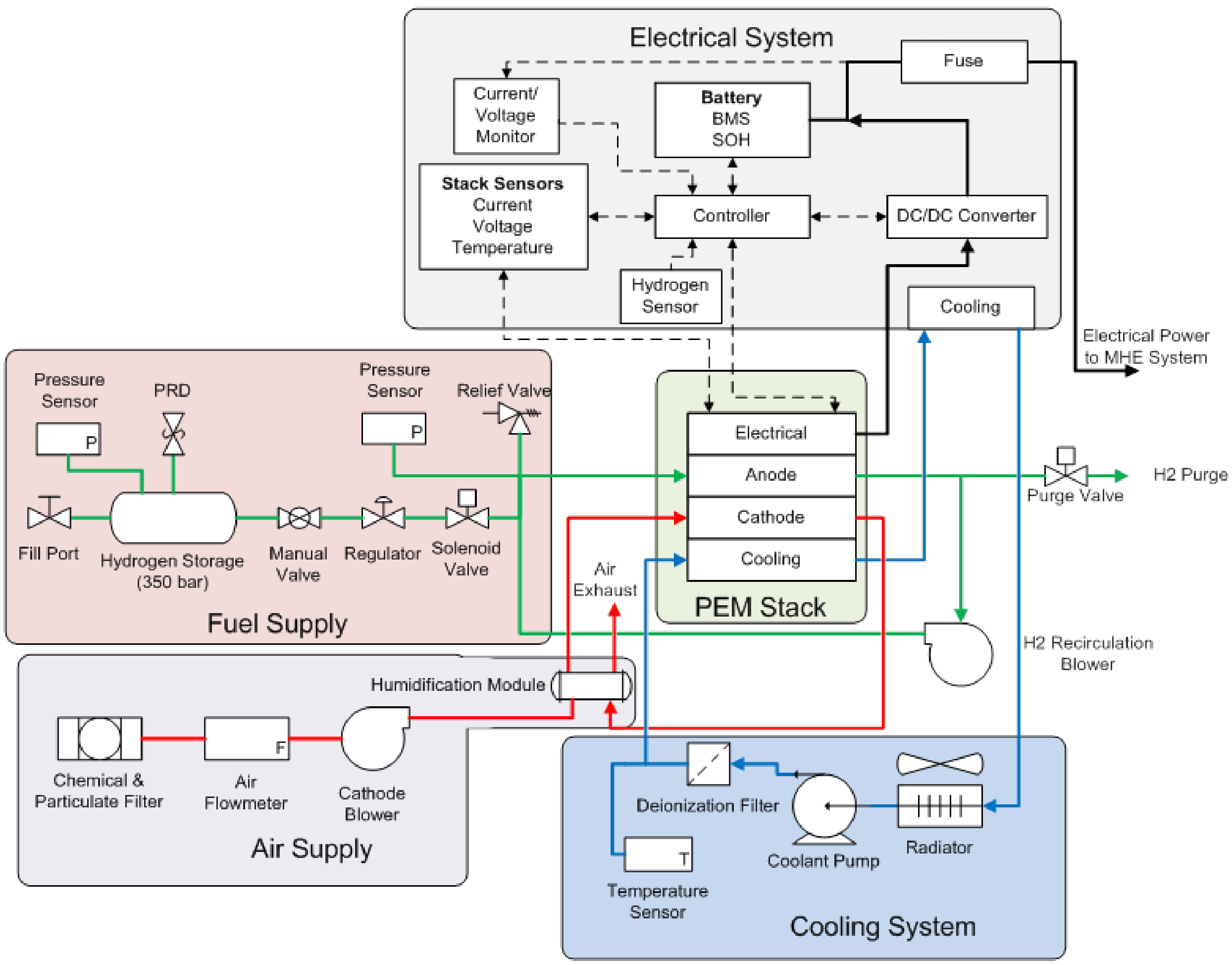


Figure 4-1. PEM system schematic for MHE applications

While anode humidification provides similar benefits to cathode humidification, industry surveys conducted in the Battelle FY12 study indicated that it was not a requirement; therefore, it was eliminated to reduce BOP cost.

Based on industry observations, the 1-kW system will be designed to operate at 24 volts DC (VDC), while the 5-, 10-, and 25-kW systems will operate on a 48-VDC system. Operating voltages are chosen in part to minimize the use and complexity of DC conversion equipment.

A liquid cooling loop circulates a water-glycol mixture throughout the system for thermal management. The liquid passes through a radiator heat exchanger, pump, and deionization filter before flowing through the channels in the stack's bipolar plates. Coolant temperature is monitored and can be used to modify the pump's performance if needed. Air-cooled stacks offer the potential for less complex architecture for system powers below 4-kW, particularly for applications when operation in freezing temperature is required; however, for this study only liquid-cooled systems were evaluated. Stack sensors (current, voltage, temperature) provide feedback and are connected to the control module to ensure that the stack is operating correctly. For safety concerns, a hydrogen sensor is installed onboard to identify any possible leaks during operation. The electrical control system, sensors, and some peripheral components are powered from a secondary DC/DC converter that connects to the 24-/48-VDC main power output. All electrical instrumentation is sent through a DC/DC converter, where it is adjusted to the desired 24/48 VDC.

Overall, the system schematic is the same for all systems. Many of the physical components need to be scaled up to accommodate the larger systems, but the general layout remains the same. Sizing accommodations were made appropriately for the mechanical, electrical, and computer components when costing both systems. Table 4-1 provides a summary of specifications by component function; Table 4-2 provides details on the fuel cell design.

Table 4-1. Specifications by Component Function

Component	Specification
Fuel (Anode)	□ 99.95% H_2, fueled at a centralized plant location □ Fuel stored onboard at 350 bar □ No humidification □ Regulated to 2 psig pressure at the stack □ Recirculation with periodic purges
Air (Cathode)	□ Filtered for particulates and chemicals (passive) □ Humidification □ Flow is 2.5X stoichiometric
Cooling	□ Liquid cooled (low conductivity ethylene-glycol/de-ionized water mixture in a closed-loop path)
Electric	□ 24 or 48 VDC regulated output □ Buck/boost DC/DC converter □ Hybridized system with lithium ion technology to supply short bursts of peak power □ Peak power requirements nominally 300% of net fuel cell power and last for 3 to 5 sec
General	□ 10,000-hr lifetime □ Includes ballast to maintain comparable system weight with competitor products

Table 4-2. Fuel Cell Design Characteristics

Parameter	1-kW	5-kW	10-kW	25-kW
Power Density (W/cm^2)	0.54			
Current Density (A/cm^2)	0.8			
Cell Voltage (VDC)	0.68			
Active Area Per Cell (cm^2)	200			400
Net Power (kW)	1	5	10	25
Gross Power (kW)	1.5	5.75	11.5	28.75
Number of Cells (#)	14	53	106	132
Full Load Stack Voltage (VDC)	9	36	72	90
Membrane Base Material	PFSA, 0.2mm thick, PTFE reinforced			
Catalyst Loading	0.4 mg Pt/cm^2 (total) Cathode is 2:1 relative to Anode			
Catalyst Application	Catalyst ink prepared, slot die coating deposition, heat dried, decal transfer			
Gas Diffusion Layer (GDL) Base Material	Carbon paper 0.2 mm thick			
GDL Construction	Carbon paper dip-coated with PTFE for water management			
Membrane Electrode Assembly (MEA) Construction	Hot press and die cut			
Seals	1 mm silicone, die cut			
Stack Assembly	Hand assembled, tie rods			
Bipolar Plates	Graphite composite, compression molded			
End Plates	Die cast and machined cast aluminum			

Note: W/cm^2 = watts per square centimeter
A/cm^2 = amperes per square centimeter
VDC = volts DC
PFSA = perfluorosulfonic acid
PTFE = polytetrafluoroethylene
mg Pt/cm^2 = milligrams of platinum per square centimeter

4.2 Electrical System

The major components of the fuel cell electrical system are DC/DC converters, energy storage, thermal management, control and sensors for feedback, protective devices, cables, and connectors. The assumed topology for this effort, which was selected based on industry feedback and general knowledge of the components and the application, is just one of many design possibilities. The primary role of the electrical system is to manage the transfer of power to the load. The components of this system are sized with the assumption that the fuel cell provides the base power consumed by the equipment and the power required to recharge the battery while the battery provides the power required in excess of the nominal power. These periods of excess power or peak loads were assumed to be no more than 3 times the maximum output power of the fuel cell for ten seconds or less. The following sections provide more detail on each of the major components in the electrical system.

4.3 DC/DC Converters

The high-power DC/DC converter is located between the fuel cell and the battery. This converter regulates the varying output voltage from the fuel cell and simultaneously acts as a battery charger. The converter can regulate the output voltage while monitoring current and can regulate the output current while monitoring voltage. In addition, it can communicate the voltage and current to the system controls.

The converters are step-up (boost) converters for 5-kW and 1-kW applications and step-down (buck) converters for 10-kW and 25-kW applications. These converter topologies were selected because they are well defined, consist of minimal components, and can be very efficient at high power levels. All topologies are non-isolated, and high current levels are often achieved by placing multiple modules in parallel; however, single modules that provide all the current are also an option.

A smaller DC/DC converter capable of 100 watts (W) or greater is used to power the control electronics and miscellaneous support equipment in the system. This converter generates a lower, more tightly regulated voltage from the 24-V or 48-V power bus for the electronics in the system.

4.3.1 Energy Storage

Lithium ion batteries are used for energy storage because of their high energy/power density relative to other battery technologies. This attribute allows the overall footprint of the battery to be smaller relative to other chemistries. In addition, they have no memory effect, are capable of high charge/discharge rates, and, when managed properly, have a long life. For this effort, the peak load requirement drove the selection of the batteries. It is assumed that a battery capable of handling the peak power requirement for this application has sufficient energy capacity for continuous operation without breaks for recharging.

It is also assumed that the battery has a battery management system (BMS), protection features built into the modules and perhaps even the cells inside the pack, and a method of communicating the state of health to the system controller. These features are included in the design because of the inherent safety risks when using lithium chemistries. The cost associated with these assumptions is built into the cost estimates for the battery pack.

Other energy storage options exist. Lead acid batteries are a more affordable solution than lithium and are tolerant to rapid charge and discharge, but the production volume constraints may limit the ability to incorporate this chemistry into the pack. Ultracapacitors are also an option, but the main limitation with this technology is its limited energy density. Certain applications where the load profile is less demanding could allow for an ultracapacitor solution, especially in the case of the 1-kW fuel cell. One fuel cell MHE manufacturer is currently employing ultracapacitors in conjunction with an oversized stack to compensate for the low power densities, claiming they are efficient and responsive in terms of providing quick power.

4.3.2 Thermal Management

The DC/DC converter and the batteries produce a significant amount of heat, and this heat must be rejected from the system. For both the 1- and 5-kW systems, the heat is rejected via the same liquid cooling loop used to cool the fuel cell components. The assumption is that the cooling plates are part of the design of each component.

4.3.3 Control and Sensors

A system controller is required to process sensor feedback signals, issue commands to components, monitor the status of system components and processes, and interface to any gauges or user feedback devices. The controller communicates with the fuel cell and battery to gauge the health and status of those components. Other sensors such as the hydrogen safety sensor, the output current transducer, and the voltage monitoring circuit provide feedback signals to the controller as well. All of these signals are used to control the operation of the system.

4.3.4 Protective Devices

Protective components are intended to prevent catastrophic failures and to protect the user from harm. Certain components may have internal protection devices, such as current limiting on the output of the DC/DC converter or fuses internal to the battery. In addition, there could be downstream protective devices on the MHE that negate the use of these components. The fuse on the output is there to prevent damage from a short circuit on the output.

Load contactors are required by the Occupational Safety and Health Administration (OSHA) on systems greater than 48 VDC. The system design for the 1-kW and 5-kW MHE requires a boost converter to obtain the required voltage (24 VDC for 1 kW, 48 VDC for 5 kW) and therefore does not require a load contactor, while the 10-kW and 25-kW systems do. However, it is generally good practice to include a load contactor to provide a positive shutoff between the stack and DC/DC converter. The estimated cost (provided by a single vendor quote) for the required contactor is less than $40 at the 10,000-unit production volume. This cost is considered to be within the error range for this report; therefore, costs for the contactors are not included in our cost analysis.

4.3.5 Connector and Cabling

The output connection of the fuel cell system must interface with the existing power plug. This is a high-current connection that must be maintained in order for the fuel cell power system to be a drop-in replacement for the lead acid battery. The connectors and cables that complete all the interconnections between electrical components in the system must be rated for the environment in which the equipment is to be used. As a result, automotive-style water resistance connectors are used in this design. The wire and cable are assumed to be same quality as those used in the automotive industry as well.

4.3.6 Alternative Electrical Systems

Alternative electrical system designs seek to simplify or reduce the component cost in the system by removing the DC/DC converter and directly connecting the fuel cell to the batteries. This approach eliminates the cost of the converter at the potential expense of more complicated battery management electronics, additional electronics to manage power flow, a more stringent battery selection, and possibly a more involved stack design.

In general, power pack designs are constrained by volume and weight to match the characteristics of the lead acid battery they are replacing. If a forklift were designed with the fuel cell system in mind, more space could be allocated to accommodate different battery technologies.

4.4 Balance of Plant (BOP)

The system specifications were used to derive the requirements for specific BOP components. Suitable components that met these requirements were identified from multiple manufacturers whenever possible.

The associated costs were then obtained by soliciting quotes or price estimates from a minimum of three manufacturers when possible. The multiple quotes were then compared to develop a generic cost estimate. However, three quotes could not be obtained in some instances, such as when a unique component was produced by one, widely accepted manufacturer or simply was not a commercial-off-the-shelf (COTS) part.

Most BOP components are readily available and costing could be estimated at the larger volumes of 10,000 and 50,000 units. For those few items that are currently not being produced at large quantities, either a vendor provided budgetary pricing, or Battelle assumed a discount comparable to other volume discounts for mass production. This was the case for blowers and hydrogen-specific components.

Three main components that are not readily available commercially are the cathode air flow meter, the electronic control unit (ECU), and the system controller. No suitable COTS item was identified for the cathode flow meter. Scientific instruments for measuring air flow are generally not suitable for system implementation due to the low flow and pressure drop requirements. PEM systems currently on the market use automotive original equipment manufacturer (OEM) parts that have been proprietarily modified or flow meters that are still undergoing research and development. Consequently, costs for the flow meter were obtained using retail prices for after-market automotive flow meters of approximately suitable size modified by typical quantity scaling factors.

Both the ECU and system controller are custom items in the control module. The ECU is designed to interface with the stack instrumentation and the system controller is designed to interface with the system as a whole. The cost of these custom parts was estimated by combining Battelle's general experience, end-user feedback, and OEM aftermarket auto sales of similar products. These three BOP items combined make up a maximum of 7% of the system costs (at 10,000 units/year production volume, 1-kW system); therefore, inaccuracies in estimating the cost of these items are assumed to have a minor impact on total system cost.

5. Manufacturing Cost Analysis

5.1 System Cost Scope

As outlined in Section 4, the stack and BOP designs for 1-, 5-, 10-, and 25-kW systems are similar. Due to these similarities in stack fabrication and BOP hardware, all different power rated systems were considered together in the sections below. In addition to the stack, Battelle also developed a representative design for the hydrogen fuel supply hardware and used BDI DFMA® analysis on some components for each system. The electrical system is the same for all systems; therefore, it is costed in a stand-alone section and then incorporated into the total system costs for all cases.

5.2 System Cost Approach

The manufacturing cost analysis approach includes:

- Developing cost estimates for each component and/or outsourced subassembly
- Designing a set of discrete steps to assemble the components into higher level subassemblies and then into the final overall system

- Defining a burn-in and test sequence for the subassemblies and overall assembly and any statistical processes that might be used for higher volume manufacturing
- Establishing a representative manufacturing station configuration including material handling and assembly machinery
- Evaluating capital, operation, supply, and maintenance costs for the representative manufacturing station

The estimated manufacturing cost was developed from the above factors, which were adjusted to the specifics of the system and production volumes.

Component and assembly costs were calculated from both custom models and the DFMA® library of manufacturing process models provided with the BDI software. The specifics of the subsystem/component costs are shown in Appendices A-1 through A-10. Purchased components were incorporated into the assembly sequence models to determine the assembly cost for each size and production volume. The final cost of producing the fuel cell systems includes a testing and burn-in sequence for the overall system. The output of the manufacturing models was also used to calculate the number of individual assembly stations or production stations required to support various product demand levels. From this, manufacturing equipment utilization was calculated and used to determine machine rates for the various manufacturing processes. The manufacturing capital cost model is also based on the number of process stations required, which provides the basis for calculating factory floor space and personnel requirements. We assumed that capital equipment expenditures for production would be amortized over a 20-year period (see Appendix A-1) and that the annual amortized cost would be distributed over the production volume for that year. Total system costs including capital expenditures were then estimated for the baseline system and projected improvements. The financial assumptions are consistent with the DOE Hydrogen Analysis (H2A) model.

5.2.1 System Manufacturing Cost Assumptions

General process cost assumptions are presented in Table 5-1.

Table 5-1. General Process Cost Assumptions

Process Category	Assumed Value
Energy cost	$0.07/kWh
Labor cost	$45.00/hour
Overall plant efficiency	85.00%

5.2.2 Machine Costs

The basic machine rate equation used in this analysis is a function of equipment capital costs, labor and energy costs, and utilization. To provide for easy comparison between various cost studies, Battelle followed the machine cost protocols described in James et al. (2014)[12]. Appendix A-1 provides details of

[12] James, B.D., Spisak, A.B., Colella, W.G., 2014, "Design for Manufacturing and Assembly (DFMA®) Cost Estimates of Transportation Fuel Cell Systems," *ASME Journal of Manufacturing Science and Engineering*, New York, NY: ASME, Volume 136, Issue 2, p. 024503.

our machine rate calculations for the various production processes used to manufacture the MHE systems.

For each production or machine station, utilization is calculated as the fraction of the total available time needed to produce the required annual volume of systems. We assume that total available manufacturing time consists of three 8-hour shifts per day for 250 days per year, or 6,000 hours per year. The total required machine time is the product of the number of systems to be produced and the time required to produce the required components for each system. The number of machines required is calculated as:

No. of machines = roundup (total required machine time / 6,000)

For each machine, utilization is calculated as the fraction of the total available time required to produce the required annual volume of stacks:

Utilization = total required machine time / (6,000 $\times$ No. of machines)

The base (100% utilization) machine rate is divided by the utilization to determine the machine rate used to produce the components for that level of system production.

At low utilizations, job shops may make parts at a lower cost because their machines are used by multiple customers. This is particularly true for flexible Computer Numerically Controlled (CNC) tooling that can be applied to diverse industries. Additional job shop costs include the profit charged by the job shop and any overhead incurred by the manufacturer as a result of contract administration, shipping, and incoming parts inspection. For consistency across all types of tooling, we assume a job shop will base their cost on 65% machine utilization overall and 40% markup for profit plus overhead when calculating their rate. Refer to Appendix A-1 for details of the job shop machine rate calculations and the details of the make vs. buy decision.

5.2.3 Material Costs

Material cost on a per unit basis (e.g. per kilogram, per square meter) tends to decrease with increasing purchase volumes, due primarily to the manufacturer’s ability to produce larger volumes of material from a single production run setup. Material cost estimates at various discrete purchase volumes can be estimated for intermediate volumes using a learning curve analysis. Refer to Appendix A-2 for details of the analysis and learning curve parameters for the various materials used in the MHE system manufacturing process.

5.3 PEM System Manufacturing Costs

A PEM system, as described in Section 4, includes multiple fuel cell stacks and the BOP (support hardware, fuel and air supply, controls and sensors and electrical equipment). This section discusses the stack manufacturing process used to achieve the design specifications in Table 4-2, followed by consideration of custom fabricated BOP components, and finally by a summary of subassemblies created from commercially available hardware.

5.3.1 PEM Stack Manufacturing Process

Each stack consists of end plates, bipolar plates, seals, and membrane electrode assemblies (MEAs) as shown in Figure 5-1, which illustrates the manufacturing process in flow chart format. The four branches leading to stack assembly are:

- End plate fabrication
- Bipolar plate fabrication
- Gasket/seal fabrication
- MEA fabrication

Only the primary manufacturing and assembly processes are shown. As indicated in Figure 5-1, a stack consists of two end plates and the appropriate number of repeat units. Repeat units include:

- One MEA
- Cathode and Anode bipolar plates
    - The Anode and Cathode plates are back to back to provide coolant flow channels)
- Seals between each item (three seals per each repeat unit)

The seals between the two bipolar plates are similar to the seals between the bipolar plates and MEAs, with slight differences.

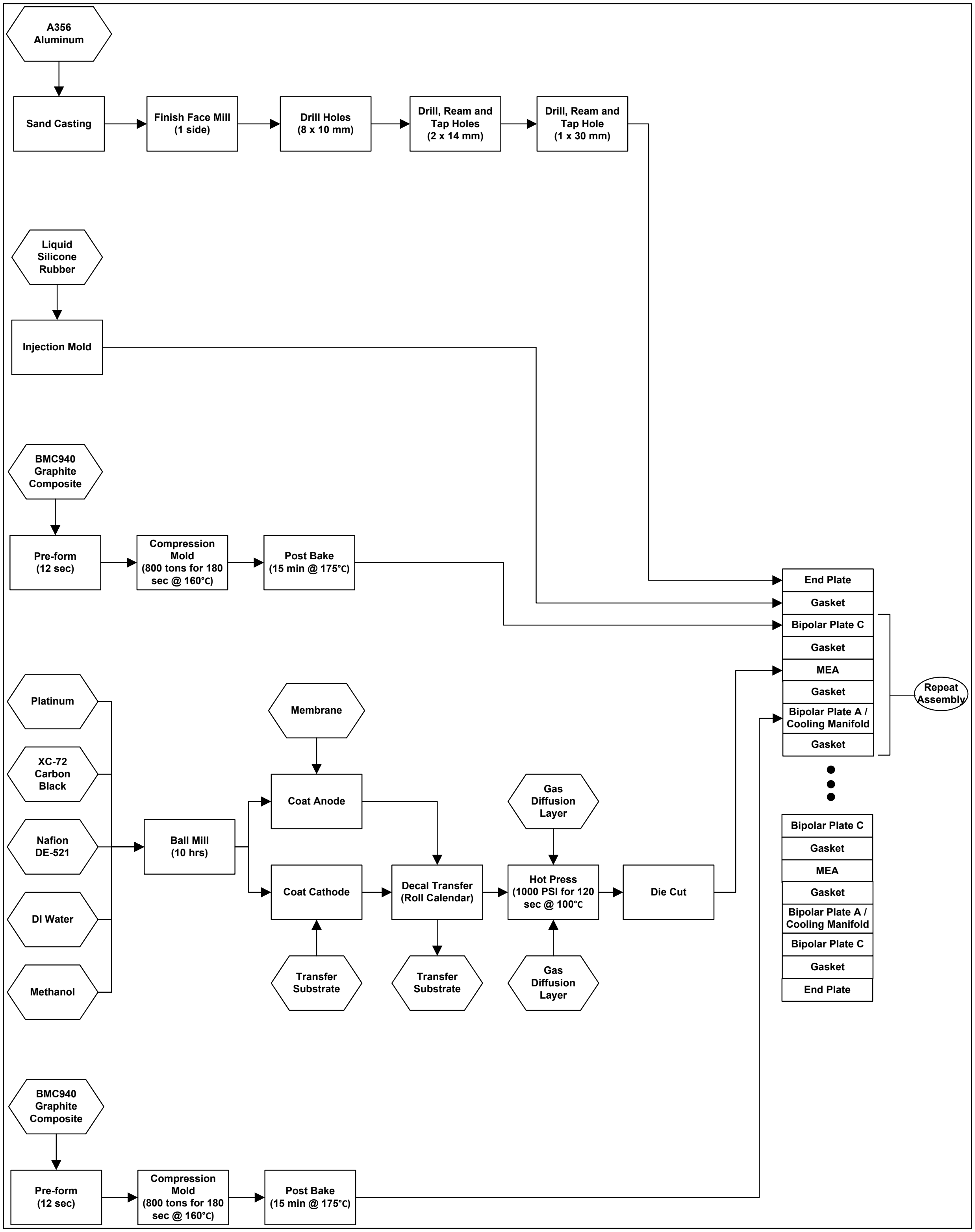


Figure 5-1. PEM fuel cell stack manufacturing process

5.3.1.1 PEM Stack Component Size and MEA Manufacturing Setup

MEA components for the stack are identical for all systems, but the active area is different in that it is 200 square centimeters (cm^2) for 1-, 5-, and 10-kW stacks and 400 cm^2 for the 25-kW stack. Using a length-to-width ratio of 1.3, the active cell size was determined to be 125 millimeters (mm) by 160 mm for the 1-, 5-, and 10-kW systems and 200-mm by 200-mm for the 25-kW system. Using a 30-mm margin on all sides to allow for gas channels and tie rod holes, the overall cell sizes were determined to be 185 mm by 220 mm for the 1-, 5-, and 10-kW systems and 260 mm by 260 mm for the 25-kW system.

The cell configurations are shown in Figure 5-2 and Figure 5-3.

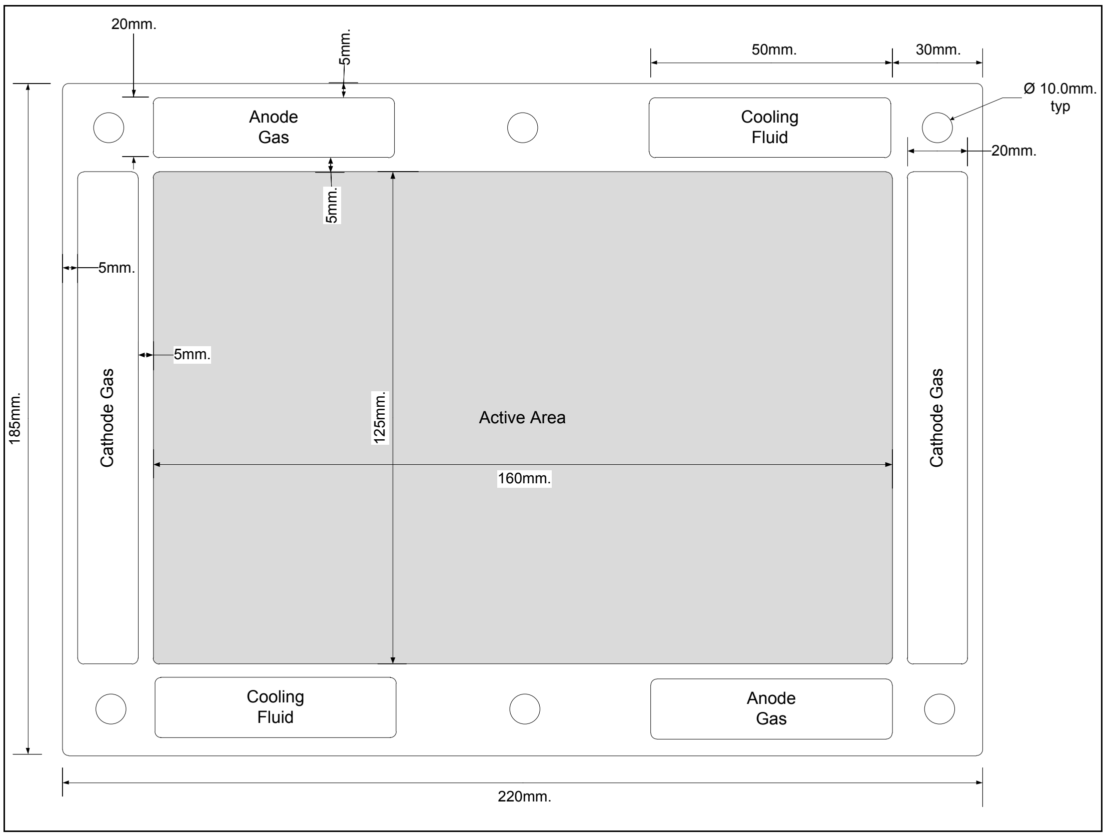


Figure 5-2. PEM MEA configuration for 200 cm^2 active area

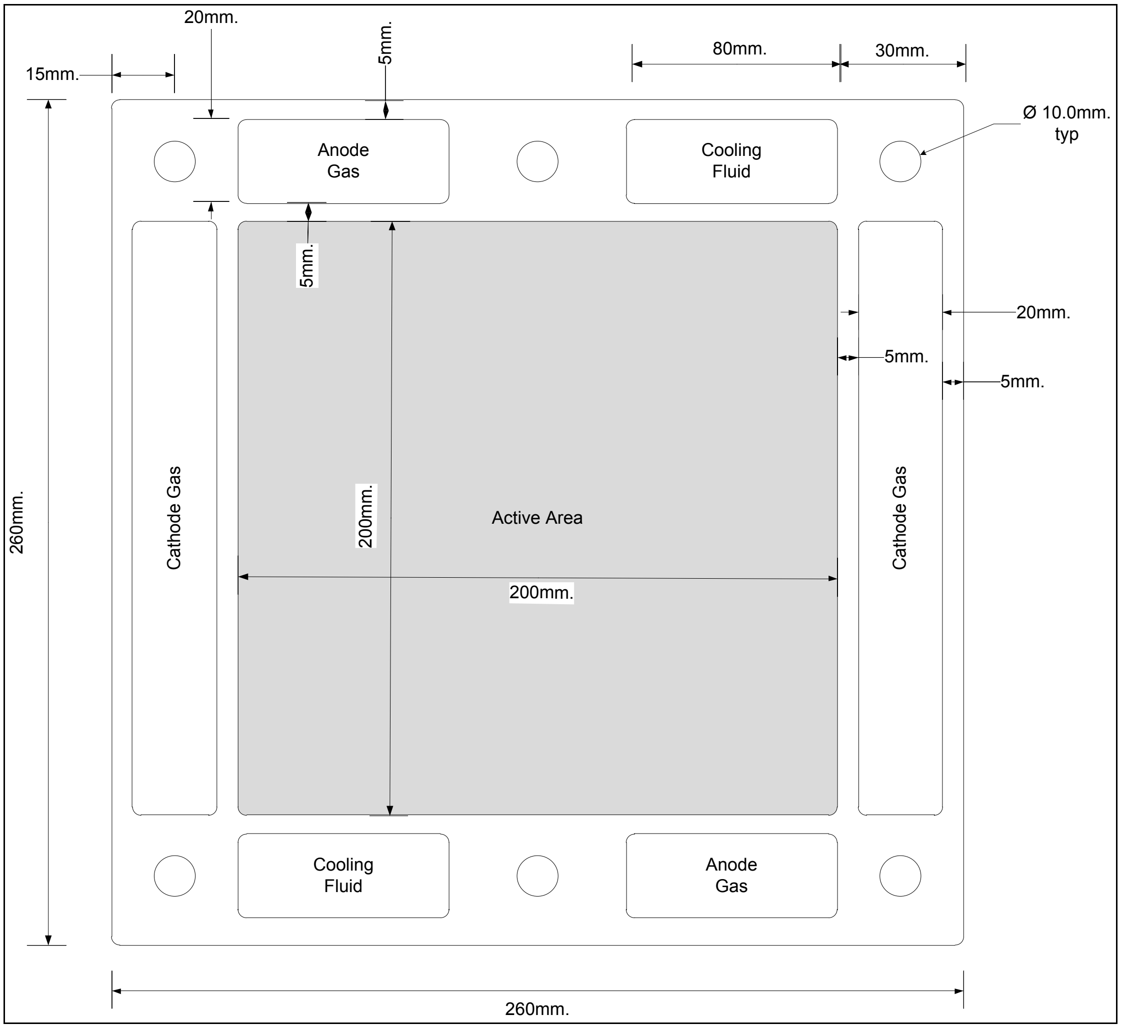


Figure 5-3. PEM MEA configuration for 400 cm^2 active area

5.3.1.2 PEM Membrane Electrode Assembly (MEA)

The MEA is built up in layers starting with the catalyzed membrane. The components of the catalyst ink are ball-milled into a uniform suspension. The anode layer is selectively slot die coated directly on the hydrated membrane and dried. The cathode layer is selectively slot die coated onto a transfer substrate and dried. The coated membrane and transfer substrate layers are heated and roll pressed, with the transfer substrate peeled away from the cathode layer following pressing. The catalyzed membrane is then hot pressed between two gas diffusion layers (GDLs) and die cut to final cell dimensions. The catalysts and GDLs are applied only to the active area. The die cutting process includes cutouts for the manifolds as shown in Figure 5-2 and Figure 5-3. Details of the analysis are shown in Appendix A-7. For all production volumes, the component reject rate was assumed to be 2.5% for catalyst production, 2.5% for catalyst application, 3.0% for decal transfer, 0.5% for hot pressing, and 3.0% for die cutting. A detailed breakdown of material cost by MEA layer is provided in Table 5-2 and Table 5-4. The MEA cost summary is provided in Table 5-3 and Table 5-5.

Table 5-2. PEM MEA Material Cost Summary: 1-kW and 5-kW Systems

Cost Category	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Catalyst	$4.72	$4.21	$3.90	$3.77	$4.39	$4.01	$3.79	$3.69
Membrane	$12.40	$7.51	$4.55	$3.21	$9.28	$5.63	$3.41	$2.40
GDL	$91.05	$26.54	$7.74	$3.27	$44.65	$13.02	$3.79	$1.60
Transfer Substrate	$3.01	$0.41	$0.06	$0.01	$0.95	$0.13	$0.02	$0.01
Total Material Cost	**$111.19**	**$38.68**	**$16.25**	**$10.26**	**$59.28**	**$22.78**	**$11.01**	**$7.71**

Although the cells are identical for the 1.5-kW and 5.75-kW stacks, the higher volume production associated with the 5-kW stacks results in material and labor cost savings. Note that the GDL dominates the cost at low volume, becoming much less important at high production rates.

Table 5-3. PEM MEA Cost Summary: 1-kW and 5-kW Systems

Cost Category	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$111.19	$38.68	$16.25	$10.26	$59.28	$22.78	$11.01	$7.71
Labor	$0.51	$0.31	$0.30	$0.30	$0.32	$0.30	$0.30	$0.30
Machine	$0.77	$0.50	$0.47	$0.47	$0.52	$0.47	$0.47	$0.36
Scrap	$3.36	$1.14	$0.47	$0.29	$1.77	$0.66	$0.31	$0.22
Tooling	$10.70	$1.07	$0.19	$0.13	$2.83	$0.28	$0.14	$0.13
Part Total	**$126.53**	**$41.70**	**$17.68**	**$11.45**	**$64.71**	**$24.50**	**$12.23**	**$8.71**
# per Stack	14	14	14	14	53	53	53	53
Stack Total	**$1,771.47**	**$583.84**	**$247.49**	**$160.31**	**$3,429.88**	**$1,298.59**	**$648.42**	**$461.88**

Table 5-4. PEM MEA Material Cost Summary: 10-kW and 25-kW Systems

Cost Category	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Catalyst	$4.25	$3.93	$3.74	$3.66	$8.21	$7.69	$7.39	$7.25
Membrane	$7.98	$4.84	$2.93	$2.07	$11.91	$7.22	$4.37	$3.50
GDL	$30.81	$8.98	$2.62	$1.22	$41.82	$12.19	$3.55	$3.03
Transfer Substrate	$0.53	$0.07	$0.01	$0.01	$0.47	$0.06	$0.02	$0.02
Total Material Cost	**$43.57**	**$17.82**	**$9.30**	**$6.96**	**$62.41**	**$27.16**	**$15.33**	**$13.80**

Table 5-5. PEM MEA Cost Summary: 10-kW and 25-kW Systems

Cost Category	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$43.57	$17.82	$9.30	$6.96	$62.41	$27.16	$15.33	$13.80
Labor	$0.31	$0.30	$0.30	$0.30	$0.56	$0.54	$0.54	$0.54
Machine	$0.49	$0.47	$0.43	$0.24	$0.89	$0.86	$0.71	$0.34
Scrap	$1.29	$0.52	$0.26	$0.19	$1.84	$0.78	$0.43	$0.38
Tooling	$1.41	$0.25	$0.13	$0.13	$1.11	$0.20	$0.14	$0.14
Part Total	**$47.08**	**$19.36**	**$10.43**	**$7.81**	**$66.81**	**$29.55**	**$17.16**	**$15.20**
# per Stack	106	106	106	106	132	132	132	132
Stack Total	**$4,990.22**	**$2,051.75**	**$1,105.62**	**$828.12**	**$8,818.43**	**$3,900.21**	**$2,264.54**	**$2,006.74**

5.3.1.3 PEM System End Plates

The end plates are the same length and width as the MEA with the exception of the tie-rod projection on either end of the end plates. Six of the eight tie rods pass through the MEA to provide alignment (note the round holes in Figure 5-2 and Figure 5-3). Each end plate has three reamed and tapped holes for mounting fuel, cooling, and air connectors, as shown schematically in Figure 5-4 and Figure 5-5. The large hole and entrance transition are for the air. The others are for cooling and fuel. The upper and lower end plates are identical: they must be oriented correctly in assembly. Correct orientation could be confirmed by fixtures based on the hydrogen and cooling water inlets.

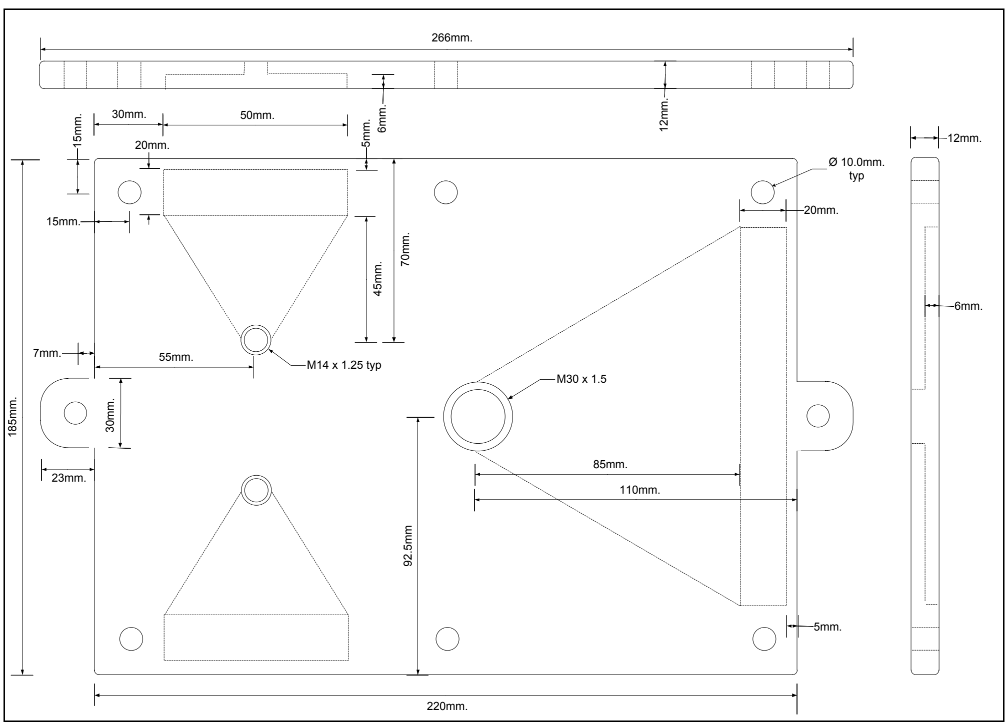


Figure 5-4. PEM system end plate size – 200-cm^2 active area

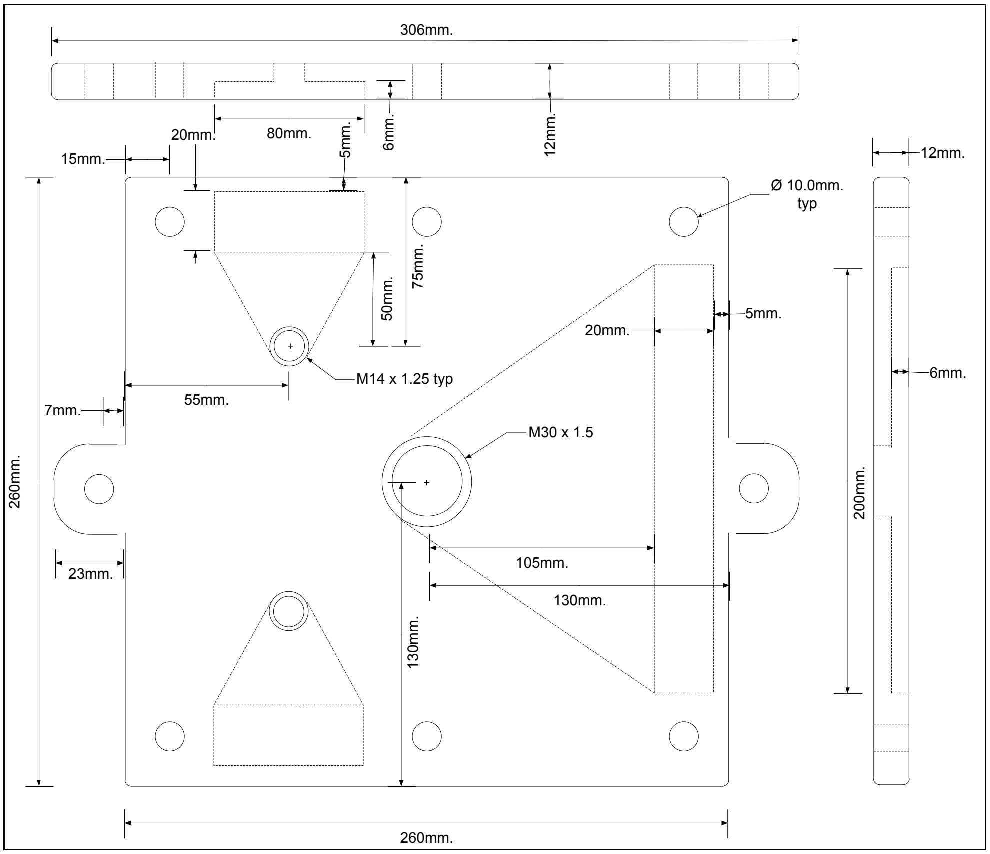


Figure 5-5. PEM system end plate size – 400-cm^2 active area

The process selected to produce the end plates was near net shape sand casting of A356 aluminum followed by cell machining. Costs were calculated using the DFMA® software, as shown in Appendix A-5. The process scrap rate was assumed to be 0.5%. The end plate cost summary is provided in Table 5-6 and Table 5-7.

Table 5-6. PEM End Plate Cost Summary: 1-kW and 5-kW Systems

Cost Category	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$3.61	$3.30	$3.30	$3.30	$3.61	$3.30	$3.30	$3.30
Labor	$9.89	$5.65	$5.23	$5.19	$9.89	$5.65	$5.23	$5.19
Machine	$35.36	$20.21	$18.69	$6.07	$35.36	$20.21	$18.69	$6.07
Scrap	$0.25	$0.15	$0.14	$0.07	$0.25	$0.15	$0.14	$0.07
Tooling	$7.98	$0.80	$0.08	$0.05	$7.98	$0.80	$0.08	$0.05
Part Total	**$57.08**	**$30.11**	**$27.44**	**$14.68**	**$57.08**	**$30.11**	**$27.44**	**$14.68**
# per Stack	2	2	2	2	2	2	2	2
Stack Total	**$114.16**	**$60.22**	**$54.89**	**$29.36**	**$114.16**	**$60.22**	**$54.89**	**$29.36**

Table 5-7. PEM End Plate Cost Summary: 10-kW and 25-kW Systems

Cost Category	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$3.61	$3.30	$3.30	$3.30	$5.78	$5.42	$5.42	$5.42
Labor	$9.89	$5.65	$5.23	$5.19	$10.75	$6.52	$6.09	$6.06
Machine	$35.36	$20.21	$18.69	$6.07	$38.45	$23.30	$21.79	$4.34
Scrap	$0.25	$0.15	$0.14	$0.07	$0.28	$0.18	$0.17	$0.08
Tooling	$7.98	$0.80	$0.08	$0.05	$6.79	$0.68	$0.07	$0.04
Part Total	**$57.08**	**$30.11**	**$27.44**	**$14.68**	**$62.05**	**$36.09**	**$33.53**	**$15.93**
# per Stack	2	2	2	2	2	2	2	2
Stack Total	**$114.16**	**$60.22**	**$54.89**	**$29.36**	**$124.10**	**$72.18**	**$67.06**	**$31.85**

5.3.1.4 PEM System Bipolar Plates

The bipolar plates are a compression molded graphite/thermoset-polymer composite material. The material is preformed into the approximate rectangular shape of the plate, then compressed into final shape in a 1,000-ton press at 160°C for 230 seconds. Six 200-cm^2 plates or three 400-cm^2 plates can be formed during each machine cycle. The anode plate includes the cooling channels (two-sided plate) and is 1.5 times as thick as the cathode plate; however, processing time is considered to be equivalent for both plates. Following molding, the plates are removed from the molds and baked at 175°C for 15 minutes in a free-standing batch oven. The process scrap rate was assumed to be 2.5%. Details of the process calculations are shown in Appendix A-6. The anode bipolar plate cost summary is provided in Table 5-8 and Table 5-9; the cathode bipolar plate cost summary is provided in Table 5-10 and Table 5-11.

Table 5-8. PEM Anode Bipolar Plate Cost Summary: 1-kW and 5-kW Systems

Cost Category	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.69	$0.52	$0.52	$0.52	$0.52	$0.52	$0.52	$0.52
Labor	$0.54	$0.35	$0.33	$0.33	$0.39	$0.34	$0.33	$0.33
Machine	$2.09	$1.76	$1.19	$0.89	$1.83	$1.73	$0.94	$0.68
Scrap	$0.09	$0.07	$0.05	$0.04	$0.07	$0.07	$0.05	$0.04
Tooling	$15.81	$1.58	$0.30	$0.21	$4.39	$0.44	$0.21	$0.19
Part Total	**$19.22**	**$4.28**	**$2.40**	**$1.99**	**$7.19**	**$3.09**	**$2.04**	**$1.76**
# per Stack	15	15	15	15	54	54	54	54
Stack Total	**$288.35**	**$64.18**	**$35.93**	**$29.81**	**$388.53**	**$167.09**	**$109.96**	**$95.02**

Table 5-9. PEM Anode Bipolar Plate Cost Summary: 10-kW and 25-kW Systems

Cost Category	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.52	$0.52	$0.52	$0.52	$0.86	$0.86	$0.86	$0.86
Labor	$0.36	$0.34	$0.33	$0.33	$0.67	$0.65	$0.65	$0.65
Machine	$1.78	$1.73	$0.73	$0.65	$3.40	$2.79	$1.24	$1.24
Scrap	$0.07	$0.07	$0.04	$0.04	$0.13	$0.11	$0.07	$0.07
Tooling	$2.22	$0.22	$0.19	$0.19	$1.24	$0.35	$0.27	$0.26
Part Total	**$4.94**	**$2.87**	**$1.81**	**$1.72**	**$6.30**	**$4.75**	**$3.08**	**$3.07**
# per Stack	107	107	107	107	133	133	133	133
Stack Total	**$528.38**	**$306.94**	**$193.77**	**$184.34**	**$837.24**	**$632.06**	**$409.85**	**$408.57**

Table 5-10. PEM Cathode Bipolar Plate Cost Summary: 1-kW and 5-kW Systems

Cost Category	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.46	$0.34	$0.34	$0.34	$0.34	$0.34	$0.34	$0.34
Labor	$0.54	$0.35	$0.33	$0.33	$0.39	$0.34	$0.33	$0.33
Machine	$2.09	$1.76	$1.19	$0.89	$1.83	$1.73	$0.94	$0.68
Scrap	$0.08	$0.06	$0.05	$0.04	$0.07	$0.06	$0.04	$0.03
Tooling	$15.81	$1.58	$0.30	$0.21	$4.39	$0.44	$0.21	$0.19
Part Total	**$18.99**	**$4.10**	**$2.22**	**$1.81**	**$7.02**	**$2.92**	**$1.86**	**$1.58**
# per Stack	15	15	15	15	54	54	54	54
Stack Total	**$284.79**	**$61.53**	**$33.28**	**$27.16**	**$378.99**	**$157.55**	**$100.42**	**$85.48**

Table 5-11. PEM Cathode Bipolar Plate Cost Summary: 10-kW and 25-kW Systems

Cost Category	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.34	$0.34	$0.34	$0.34	$0.57	$0.57	$0.57	$0.57
Labor	$0.36	$0.34	$0.33	$0.33	$0.67	$0.65	$0.65	$0.65
Machine	$1.78	$1.73	$0.73	$0.65	$3.40	$2.79	$1.24	$1.24
Scrap	$0.06	$0.06	$0.04	$0.03	$0.12	$0.10	$0.06	$0.06
Tooling	$2.22	$0.22	$0.19	$0.19	$1.24	$0.35	$0.27	$0.26
Part Total	**$4.76**	**$2.69**	**$1.63**	**$1.55**	**$6.00**	**$4.46**	**$2.79**	**$2.78**
# per Stack	107	107	107	107	133	133	133	133
Stack Total	**$509.48**	**$288.04**	**$174.87**	**$165.45**	**$798.24**	**$593.07**	**$370.85**	**$369.57**

5.3.1.5 PEM System Seals

The seals are injection molded from two-part liquid silicone rubber (LSR) material using a four-cavity tool-steel mold. The component reject rate was assumed to be 0.5%. Details of the analysis are shown in Appendix A-7. The anode and cooling seal cost summary is provided in Table 5-12 and Table 5-13; the cathode seal cost summary is provided in Table 5-14 and Table 5-15. With the configuration shown in Figure 5-2, the seal between the anode bipolar plate and the anode side of the MEA is identical to the seal between the back-to-back bipolar plates; the installed orientation is simply reversed. Thus, a single tool may be used for two of the three seals, increasing equipment utilization for the anode/cooling seal production. The seals require an orientation feature (tab) to provide external evidence that the seals are correctly installed.

Table 5-12. PEM Anode and Cooling Seal Cost Summary: 1-kW and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.21	$0.20	$0.19	$0.19	$0.20	$0.20	$0.19	$0.18
Labor	$0.04	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Machine	$0.05	$0.03	$0.03	$0.03	$0.03	$0.03	$0.03	$0.01
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$4.25	$0.42	$0.08	$0.06	$1.12	$0.11	$0.07	$0.06
Part Total	**$4.55**	**$0.67**	**$0.32**	**$0.29**	**$1.38**	**$0.35**	**$0.30**	**$0.27**
# per Stack	28	28	28	28	106	106	106	106
Stack Total	**$127.29**	**$18.87**	**$9.05**	**$8.20**	**$146.46**	**$37.53**	**$31.97**	**$28.49**

Table 5-13. PEM Anode and Cooling Seal Cost Summary: 10-kW and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.20	$0.19	$0.19	$0.18	$0.22	$0.21	$0.20	$0.20
Labor	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Machine	$0.03	$0.03	$0.03	$0.01	$0.03	$0.03	$0.03	$0.01
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$0.56	$0.11	$0.06	$0.06	$0.64	$0.13	$0.09	$0.08
Part Total	**$0.81**	**$0.35**	**$0.29**	**$0.27**	**$0.91**	**$0.39**	**$0.34**	**$0.31**
# per Stack	212	212	212	212	264	264	264	264
Stack Total	**$172.25**	**$74.51**	**$62.34**	**$56.68**	**$239.87**	**$101.68**	**$89.33**	**$82.45**

Table 5-14. PEM Cathode Seal Cost Summary: 1-kW and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.17	$0.17	$0.16	$0.16	$0.17	$0.16	$0.16	$0.15
Labor	$0.05	$0.02	$0.02	$0.02	$0.03	$0.02	$0.02	$0.02
Machine	$0.08	$0.03	$0.03	$0.03	$0.04	$0.03	$0.03	$0.01
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$7.43	$0.74	$0.07	$0.06	$2.16	$0.22	$0.06	$0.06
Part Total	**$7.73**	**$0.96**	**$0.28**	**$0.26**	**$2.40**	**$0.43**	**$0.27**	**$0.24**
# per Stack	16	16	16	16	55	55	55	55
Stack Total	**$123.72**	**$15.40**	**$4.49**	**$4.18**	**$132.00**	**$23.46**	**$14.72**	**$13.10**

Table 5-15. PEM Cathode Seal Cost Summary: 10-kW and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.17	$0.16	$0.16	$0.15	$0.17	$0.16	$0.16	$0.15
Labor	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Machine	$0.03	$0.03	$0.03	$0.01	$0.04	$0.03	$0.03	$0.01
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$1.11	$0.11	$0.07	$0.06	$1.27	$0.13	$0.09	$0.09
Part Total	**$1.33**	**$0.32**	**$0.27**	**$0.24**	**$1.49**	**$0.34**	**$0.29**	**$0.27**
# per Stack	108	108	108	108	134	134	134	134
Stack Total	**$143.62**	**$34.35**	**$28.88**	**$25.57**	**$200.04**	**$45.07**	**$38.99**	**$35.91**

5.3.1.6 PEM System Stack Assembly

The stack components are assembled as illustrated in Figure 5-1. Pressure is applied to the completed stack using a hydraulic press, and the tie rods are installed to complete the stack assembly. Tie rod costs were estimated to be between $5.36 and $54.64 per stack depending on stack height, and gas fittings and other assembly hardware (inserts, washers, nuts) were estimated to be $38.87 per stack before applying learning curve analysis. Stack assembly times were estimated using the DFMA® software, and ranged from 0.30 to 2.32 hours depending on cell count. After applying learning curve analysis to the assembly times and multiplying by the standard labor rate of $45.00/hour, the average stack assembly costs were calculated as shown in Table 5-16 and Table 5-17. Details of the process calculations are provided in Appendix A-8.

Table 5-16. PEM Stack Assembly Costs: 1-kW and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$43.35	$40.54	$37.91	$36.17	$47.35	$44.28	$41.41	$39.51
Labor	$16.17	$12.92	$12.59	$12.56	$38.43	$30.70	$29.92	$29.85
Total Assembly Cost	**$59.53**	**$53.46**	**$50.50**	**$48.74**	**$85.79**	**$74.98**	**$71.33**	**$69.36**

Table 5-17. PEM Stack Assembly Costs: 10-kW and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$54.43	$50.89	$47.59	$45.41	$58.83	$55.01	$51.44	$49.08
Labor	$68.68	$54.86	$53.47	$53.35	$79.96	$63.86	$62.25	$62.11
Total Assembly Cost	**$123.11**	**$105.75**	**$101.06**	**$98.76**	**$138.79**	**$118.87**	**$113.69**	**$111.19**

5.3.1.7 PEM Stack Testing and Conditioning

Following assembly, the PEM stack is tested and conditioned to determine its fitness for installation into the system. Based on industry input, the total test time is assumed to be 2.5 hours. Stack testing requires connection to appropriate sources for air, hydrogen, and cooling and to an appropriately controlled load bank. The anode outlet may be blocked for burn-in and power testing. Anode flow conditions may be tested with nitrogen before and after the test, thus purging the stack of hydrogen before it is moved to the system assembly area. The testing process is reportedly subject to a high failure rate, probably due to the immaturity of the production processes for stacks being produced currently. We have assumed a failure rate of 5% for this analysis (lower than the industry reported values, but still high for a mature production process) regardless of production volume. Stacks failing the test are reworked by disassembling the stack, replacing the defective part, and reassembling the stack. The cost of the rework is included in the scrap cost. Details of the analysis are shown in Appendix A-9. The stack testing and conditioning costs were calculated as shown in Table 5-18 and Table 5-19. The high stack failure rate would usually be expected to come down as higher volumes are reached and additional automation and quality control measures are instituted. In the absence of information on why the stack failure rates are high, we must assume that the rate does not change with production volume. A sharp drop in machine cost per stack as production volumes change from 100 to 1,000 units/year reflects the low utilization rate in the case of the 100 unit volumes as well as the assumption that all stack testing is performed in-house regardless of production volume.

Table 5-18. PEM Stack Testing and Conditioning Cost Summary: 1-kW and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$14.76	$6.06	$2.77	$1.70	$23.39	$10.81	$5.18	$3.16
Labor	$72.29	$71.95	$71.91	$71.91	$74.63	$73.82	$73.74	$73.73
Machine	$1,222.22	$101.26	$15.92	$15.92	$1,222.22	$101.26	$15.92	$15.92
Scrap	$68.91	$9.43	$4.77	$4.71	$69.49	$9.78	$4.99	$4.88
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	**$1,378.19**	**$188.70**	**$95.37**	**$94.24**	**$1,389.73**	**$195.67**	**$99.83**	**$97.70**
# per Stack	1	1	1	1	1	1	1	1
Stack Total	**$1,378.19**	**$188.70**	**$95.37**	**$94.24**	**$1,389.73**	**$195.67**	**$99.83**	**$97.70**

Table 5-19. PEM Stack Testing and Conditioning Cost Summary: 10-kW and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$34.46	$16.26	$7.81	$4.74	$62.89	$29.85	$14.38	$10.25
Labor	$77.82	$76.36	$76.22	$76.20	$79.00	$77.31	$77.14	$77.13
Machine	$1,222.22	$101.26	$15.92	$15.92	$1,222.22	$101.26	$15.92	$15.92
Scrap	$70.24	$10.20	$5.26	$5.10	$71.80	$10.97	$5.66	$5.44
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	**$1,404.73**	**$204.08**	**$105.21**	**$101.96**	**$1,435.91**	**$219.38**	**$113.10**	**$108.74**
# per Stack	1	1	1	1	1	1	1	1
Stack Total	**$1,404.73**	**$204.08**	**$105.21**	**$101.96**	**$1,435.91**	**$219.38**	**$113.10**	**$108.74**

5.3.1.8 PEM Stack Cost Summary

Total stack costs are summarized in Table 5-20 and Table 5-21 (components) and Table 5-22 and Table 5-23 (manufacturing).

Table 5-20. PEM Stack Component Cost Summary: 1-kW and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
MEA	$1,771.47	$583.84	$247.49	$160.31	$3,429.88	$1,298.59	$648.42	$461.88
Anode / Cooling Gasket	$127.29	$18.87	$9.05	$8.20	$146.46	$37.53	$31.97	$28.49
Cathode Gasket	$123.72	$15.40	$4.49	$4.18	$132.00	$23.46	$14.72	$13.10
Anode Bipolar Plate	$288.35	$64.18	$35.93	$29.81	$388.53	$167.09	$109.96	$95.02
Cathode Bipolar Plate	$284.79	$61.53	$33.28	$27.16	$378.99	$157.55	$100.42	$85.48
End Plates	$114.16	$60.22	$54.89	$29.36	$114.16	$60.22	$54.89	$29.36
Assembly Hardware	$43.35	$40.54	$37.91	$36.17	$47.35	$44.28	$41.41	$39.51
Assembly Labor	$16.17	$12.92	$12.59	$12.56	$38.43	$30.70	$29.92	$29.85
Test and Conditioning	$1,378.19	$188.70	$95.37	$94.24	$1,389.73	$195.67	$99.83	$97.70
Total	**$4,147.49**	**$1,046.20**	**$531.01**	**$402.01**	**$6,065.54**	**$2,015.09**	**$1,131.53**	**$880.40**
Cost per kW_{net}	**$4,147.49**	**$1,046.20**	**$531.01**	**$402.01**	**$1,213.11**	**$403.02**	**$226.31**	**$176.08**

Table 5-21. PEM Stack Component Cost Summary: 10-kW and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
MEA	$4,990.22	$2,051.75	$1,105.62	$828.12	$8,818.43	$3,900.21	$2,264.54	$2,006.74
Anode / Cooling Gasket	$172.25	$74.51	$62.34	$56.68	$239.87	$101.68	$89.33	$82.45
Cathode Gasket	$143.62	$34.35	$28.88	$25.57	$200.04	$45.07	$38.99	$35.91
Anode Bipolar Plate	$528.38	$306.94	$193.77	$184.34	$837.24	$632.06	$409.85	$408.57
Cathode Bipolar Plate	$509.48	$288.04	$174.87	$165.45	$798.24	$593.07	$370.85	$369.57
End Plates	$114.16	$60.22	$54.89	$29.36	$124.10	$72.18	$67.06	$31.85
Assembly Hardware	$54.43	$50.89	$47.59	$45.41	$58.83	$55.01	$51.44	$49.08
Assembly Labor	$68.68	$54.86	$53.47	$53.35	$79.96	$63.86	$62.25	$62.11
Test and Conditioning	$1,404.73	$204.08	$105.21	$101.96	$1,435.91	$219.38	$113.10	$108.74
Total	**$7,985.94**	**$3,125.64**	**$1,826.64**	**$1,490.25**	**$12,592.61**	**$5,682.53**	**$3,467.41**	**$3,155.02**
Cost per kW_{net}	**$798.59**	**$312.56**	**$182.66**	**$149.02**	**$503.70**	**$227.30**	**$138.70**	**$126.20**

Table 5-22. PEM Stack Manufacturing Cost Summary: 1-kW and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1,647.82	$615.81	$295.66	$208.82	$3,296.69	$1,345.28	$711.88	$532.25
Labor	$133.53	$112.06	$109.95	$109.78	$196.13	$171.13	$168.67	$168.46
Machine	$1,369.24	$202.78	$96.76	$62.36	$1,523.50	$358.51	$183.59	$121.88
Scrap	$118.92	$27.75	$13.15	$10.25	$171.25	$52.38	$26.75	$20.66
Tooling	$877.98	$87.80	$15.48	$10.79	$877.98	$87.80	$40.64	$37.15
Part Total	**$4,147.49**	**$1,046.20**	**$531.01**	**$402.01**	**$6,065.54**	**$2,015.09**	**$1,131.53**	**$880.40**

Table 5-23. PEM Stack Manufacturing Cost Summary: 10-kW and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$4,866.87	$2,113.30	$1,196.66	$941.85	$8,640.38	$3,947.74	$2,364.60	$2,155.28
Labor	$283.24	$251.61	$248.48	$248.19	$441.40	$406.09	$402.60	$402.30
Machine	$1,735.23	$570.39	$265.05	$193.87	$2,333.23	$1,014.29	$493.92	$403.16
Scrap	$222.13	$79.18	$41.98	$33.79	$348.59	$143.12	$81.05	$74.41
Tooling	$878.47	$111.17	$74.47	$72.54	$829.01	$171.28	$125.24	$119.87
Part Total	**$7,985.94**	**$3,125.64**	**$1,826.64**	**$1,490.25**	**$12,592.61**	**$5,682.53**	**$3,467.41**	**$3,155.02**

Breakdowns of stack cost volume trends are shown in Figure 5-6 through Figure 5-9.

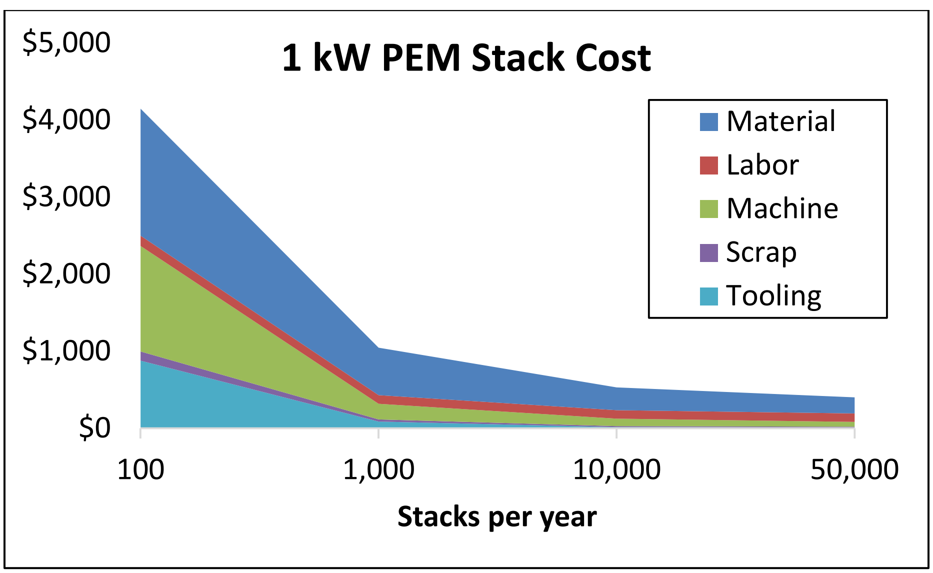


Figure 5-6. 1-kW PEM fuel cell stack cost volume trends

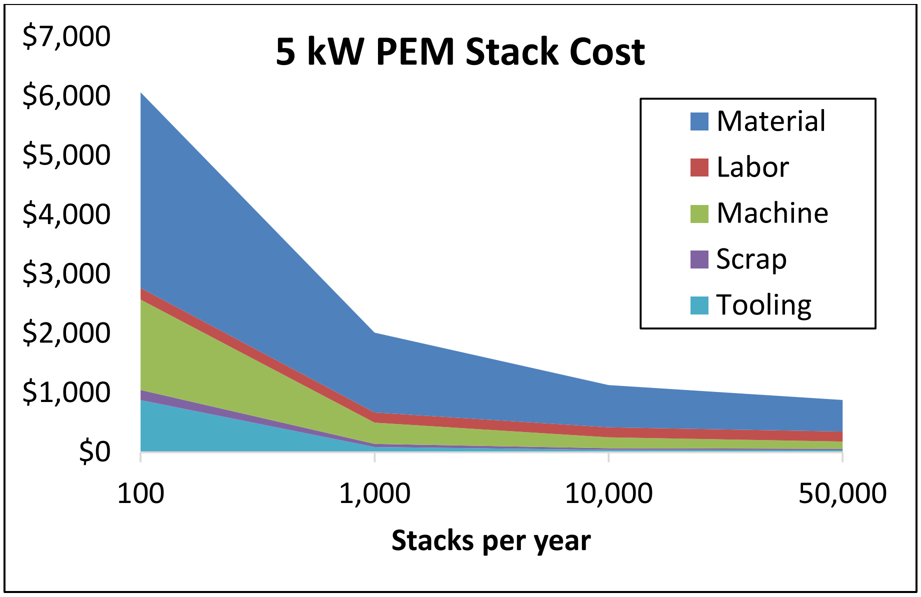


Figure 5-7. 5-kW PEM fuel cell stack cost volume trends

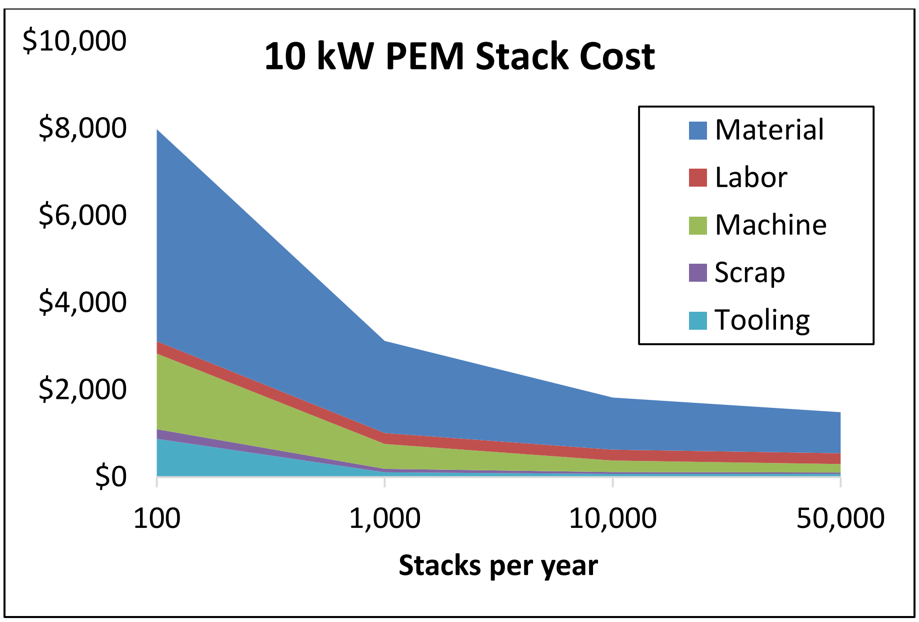


Figure 5-8. 10-kW PEM fuel cell stack cost volume trends

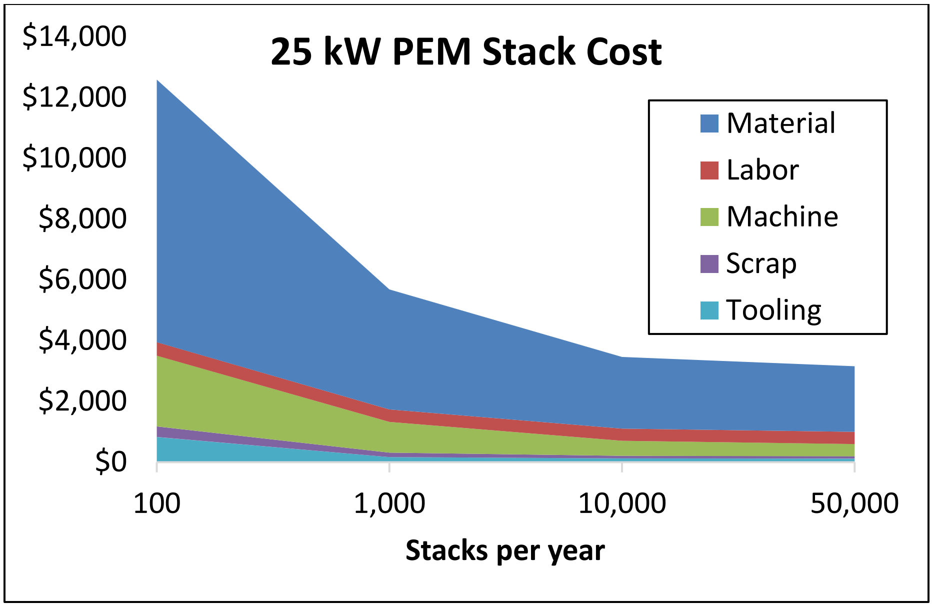


Figure 5-9. 25-kW PEM fuel cell stack cost volume trends

5.3.2 PEM System BOP Cost Assumptions

The costs associated with the BOP components are tabulated in Table 5-24 and Table 5-25. Figure 5-10 through Figure 5-13 compare component costs at a subcategory level similar to the system schematic. At a production rate of 1,000 systems a year, the BOP hardware is estimated to cost around $8,000 for one 1-kW system, increasing to a little less than $12,000 for 25-kW at the same production volume. Many component costs, including most sensors and regulators, remain the same regardless of system size, and are therefore similar to costs presented in the FY13 study.[13]

A category titled "Additional Work Estimate" is included to capture small contingencies not specifically itemized in this report. These include components such as heat sinks and fans for additional electrical cooling, supplementary temperature or pressure sensors, and any extra assembly hardware. This estimate is based on a 20% buffer to the electrical subsystem cost, not including the power inverter or converter, and a 10% buffer to all remaining hardware.

[13] Battelle. 2014. Manufacturing Cost Analysis of 1-kW and 5-kW Direct Hydrogen Polymer Electrolyte Membrane (PEM) Fuel Cell for Material Handling Applications. DOE Contract No. DE-EE0005250.

Table 5-24. PEM BOP Cost Summary: 1-kW and 5-kW Systems

Subassembly	Component Description	Annual Production: 1-kW PEM Systems				Annual Production: 5-kW PEM Systems			
		(100)	(1,000)	(10,000)	(50,000)	(100)	(1,000)	(10,000)	(50,000)
Fuel Storage	Tank Fill Port	$212	$190	$171	$154	$212	$190	$171	$154
	Hydrogen Tank	$521	$425	$347	$283	$521	$425	$347	$283
	Tank Pressure Sensor	$445	$430	$405	$381	$445	$430	$405	$381
	Tank Manual Valve	$225	$210	$200	$190	$225	$210	$200	$190
	Hydrogen Regulator	$896	$796	$696	$596	$896	$796	$696	$596
	Tank Solenoid Valve (Shutoff)	$71	$65	$63	$61	$71	$65	$63	$61
Instrumentation	Stack Anode Pressure Sensor	$375	$375	$375	$375	$375	$375	$375	$375
Fuel Storage	Relief Valve	$155	$150	$150	$150	$155	$150	$150	$150
H2 Recirculation	H2 Recirc Blower & Controller	$920	$530	$500	$472	$920	$530	$500	$472
	Purge Valve	$92	$78	$72	$66	$92	$78	$72	$66
Air Supply	Filter & Housing (Cathode Air)	$215	$166	$134	$108	$215	$166	$134	$108
	Blower (Cathode Air)	$307	$276	$248	$241	$418	$376	$339	$329
	Humidifier	$541	$378	$156	$89	$420	$290	$200	$165
	Flowmeter (Cathode Air)	$112	$100	$94	$88	$112	$100	$94	$88
Cooling System	Pump (Coolant Water)	$145	$130	$115	$102	$145	$130	$115	$102
	Radiator	$340	$340	$340	$340	$340	$340	$340	$340
	Deionization Filter	$63	$54	$43	$34	$63	$54	$43	$34
Electronics	DC/DC Converter (Power)	$515	$373	$327	$286	$1,829	$1,324	$1,117	$943
Energy Storage	Battery	$1,250	$900	$625	$519	$2,500	$1,800	$1,250	$1,038
Electronics	Fuel Cell ECU	$500	$300	$175	$102	$500	$300	$175	$102
	System Controller	$500	$300	$175	$102	$500	$300	$175	$102
	Bus Bar	$6	$5	$4	$3	$11	$9	$8	$7
	Fuses	$4	$3	$2	$1	$31	$25	$14	$8
	DC/DC Converter (Controls)	$111	$105	$98	$91	$52	$47	$42	$38
	Connector Power	$8	$4	$4	$4	$11	$9	$8	$7
Instrumentation and Controls	Temperature Sensors	$95	$55	$40	$29	$95	$55	$40	$29
	Current Sensor	$14	$11	$9	$7	$14	$11	$9	$7
	Voltage Sensor	$50	$43	$39	$35	$50	$43	$39	$35
	H2 Sensor	$132	$106	$97	$89	$132	$106	$97	$89
Assembly Components	Assorted Plumbing/Fittings	$165	$150	$135	$122	$165	$150	$135	$122
Electronics	Wiring & Connectors	$55	$50	$45	$41	$55	$50	$45	$41
Assembly Components	Assembly Hardware	$33	$30	$27	$24	$33	$30	$27	$24
	Frame & Housing	$209	$190	$171	$154	$209	$190	$171	$154
Additional Work Est.	Additional Work Estimate	$400	$300	$300	$200	$600	$400	$400	$300
TOTAL BOP COST		**$9,681**	**$7,619**	**$6,381**	**$5,541**	**$12,411**	**$9,554**	**$7,996**	**$6,941**

Table 5-25. PEM BOP Cost Summary: 10-kW and 25-kW Systems

Subassembly	Component Description	Annual Production: 10-kW PEM Systems				Annual Production: 25-kW PEM Systems			
		(100)	(1,000)	(10,000)	(50,000)	(100)	(1,000)	(10,000)	(50,000)
Fuel Storage	Tank Fill Port	$212	$190	$171	$154	$212	$190	$171	$154
	Hydrogen Tank	$804	$754	$731	$709	$804	$754	$731	$709
	Tank Pressure Sensor	$445	$430	$405	$381	$445	$430	$405	$381
	Tank Manual Valve	$225	$210	$200	$190	$225	$210	$200	$190
	Hydrogen Regulator	$896	$796	$696	$596	$896	$796	$696	$596
	Tank Solenoid Valve (Shutoff)	$71	$65	$63	$61	$71	$65	$63	$61
Instrumentation	Stack Anode Pressure Sensor	$375	$375	$375	$375	$375	$375	$375	$375
Fuel Storage	Relief Valve	$155	$150	$150	$150	$155	$150	$150	$150
H2 Recirculation	H2 Recirc Blower & Controller	$920	$530	$500	$472	$920	$530	$500	$472
	Purge Valve	$92	$78	$72	$66	$92	$78	$72	$66
Air Supply	Filter & Housing (Cathode Air)	$215	$166	$134	$108	$215	$166	$134	$108
	Blower (Cathode Air)	$617	$555	$500	$485	$672	$605	$545	$528
	Humidifier	$790	$553	$227	$130	$750	$550	$450	$420
	Flowmeter (Cathode Air)	$112	$100	$94	$88	$112	$100	$94	$88
Cooling System	Pump (Coolant Water)	$145	$130	$115	$102	$176	$158	$140	$124
	Radiator	$340	$340	$340	$340	$340	$340	$340	$340
	Deionization Filter	$127	$108	$86	$68	$127	$108	$86	$68
Electronics	DC/DC Converter (Power)	$3,171	$2,297	$1,900	$1,571	$8,000	$5,800	$4,800	$3,972
Energy Storage	Battery	$2,500	$1,800	$1,250	$1,038	$2,500	$1,800	$1,250	$1,038
Electronics	Fuel Cell ECU	$500	$300	$175	$102	$500	$300	$175	$102
	System Controller	$500	$300	$175	$102	$500	$300	$175	$102
	Bus Bar	$17	$16	$14	$12	$50	$47	$47	$47
	Fuses	$37	$37	$36	$36	$48	$44	$39	$35
	DC/DC Converter (Controls)	$76	$72	$68	$36	$76	$72	$68	$64
	Connector Power	$24	$21	$18	$15	$49	$42	$35	$29
Instrumentation and Controls	Temperature Sensors	$95	$55	$40	$29	$95	$55	$40	$29
	Current Sensor	$14	$11	$9	$7	$14	$11	$9	$7
	Voltage Sensor	$50	$43	$39	$35	$50	$43	$39	$35
	H2 Sensor	$132	$106	$97	$89	$132	$106	$97	$89
Assembly Components	Assorted Plumbing/Fittings	$165	$150	$135	$122	$165	$150	$135	$122
Electronics	Wiring & Connectors	$55	$50	$45	$41	$55	$50	$45	$41
Assembly Components	Assembly Hardware	$33	$30	$27	$24	$33	$30	$27	$24
	Frame & Housing	$231	$210	$189	$170	$231	$210	$189	$170
Additional Work Est.	Additional Work Estimate	$700	$600	$500	$400	$1,200	$900	$800	$700
TOTAL BOP COST		**$14,841**	**$11,628**	**$9,576**	**$8,305**	**$20,286**	**$15,565**	**$13,121**	**$11,437**

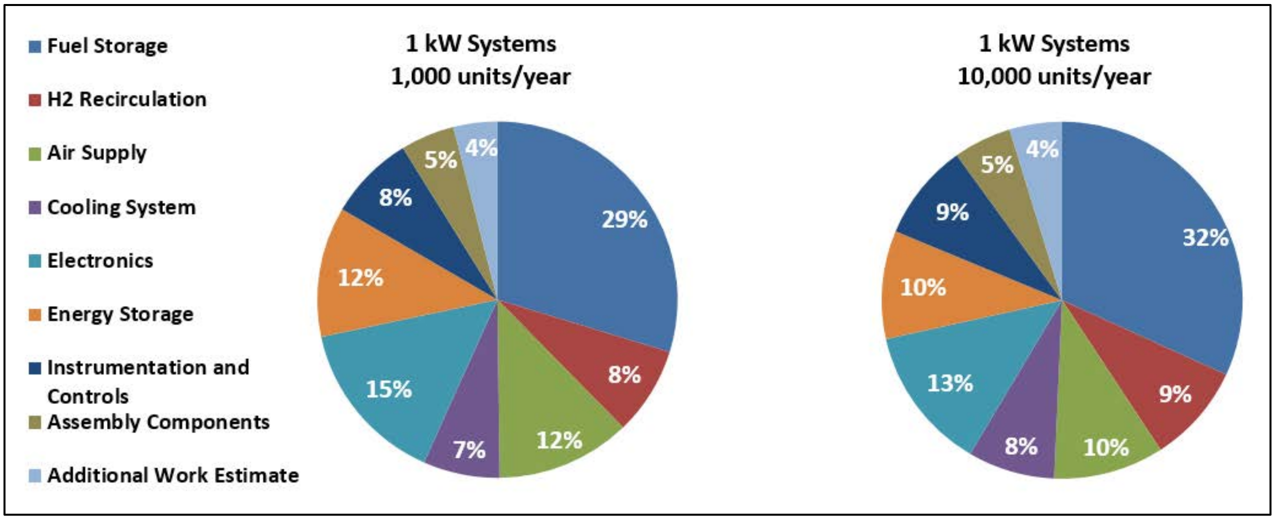


Figure 5-10. 1-kW PEM system BOP cost distribution

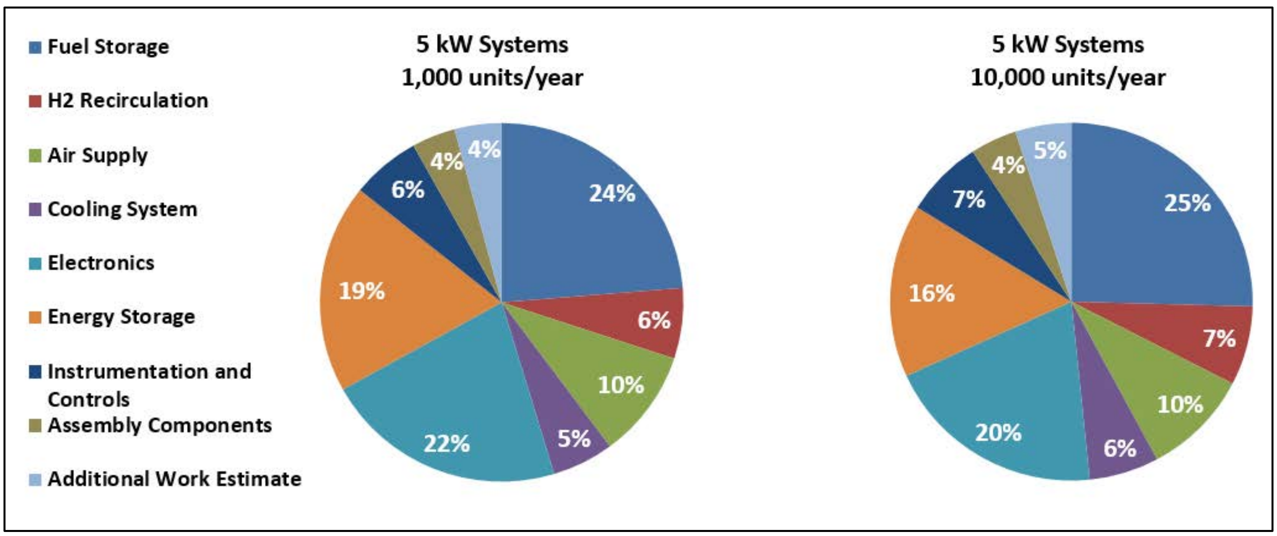


Figure 5-11. 5-kW PEM system BOP cost distribution

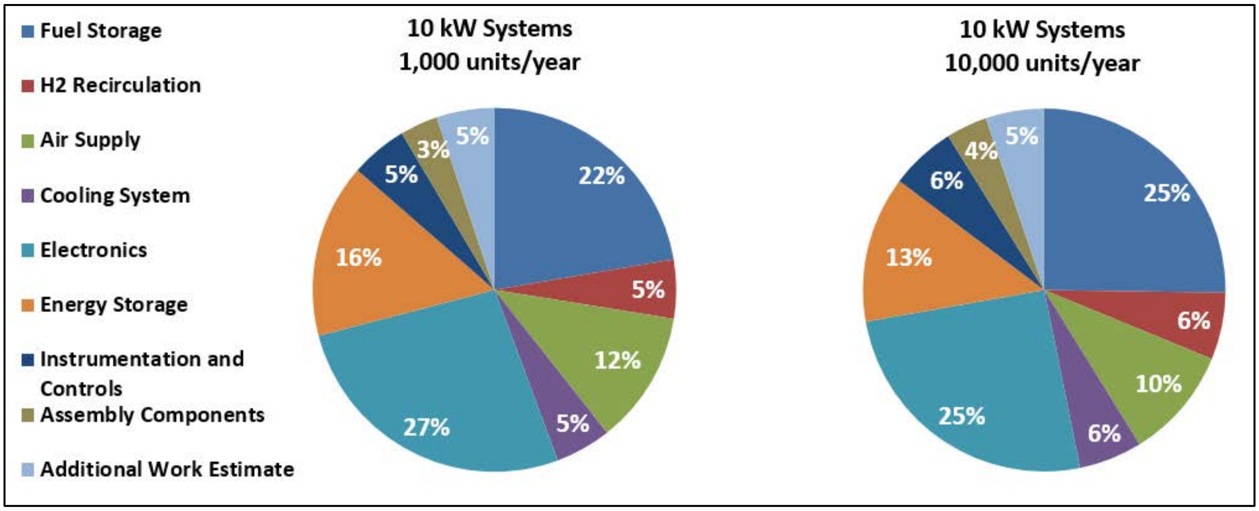


Figure 5-12. 10-kW PEM system BOP cost distribution

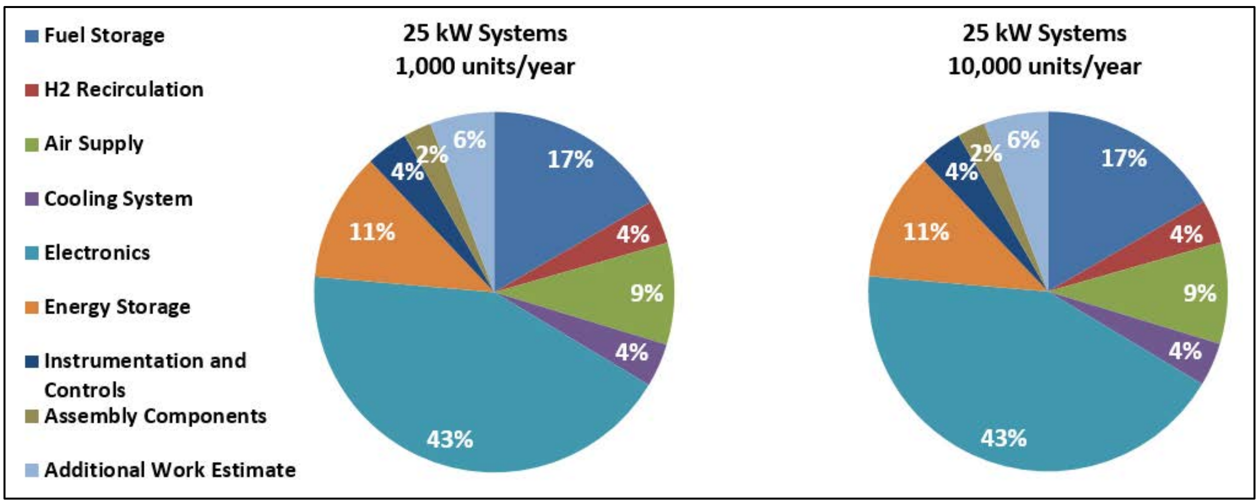


Figure 5-13. 25-kW PEM system BOP cost distribution

Cost trends for PEM system BOP elements are shown in Figure 5-14 through Figure 5-17.

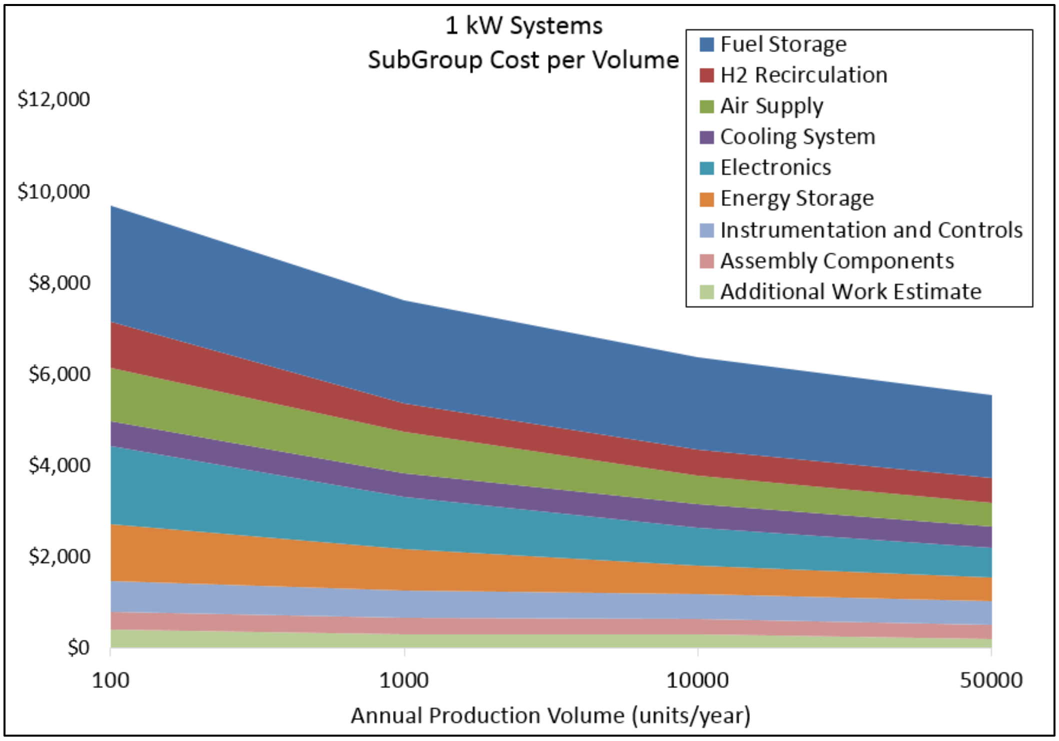


Figure 5-14. 1-kW PEM system BOP cost volume trends

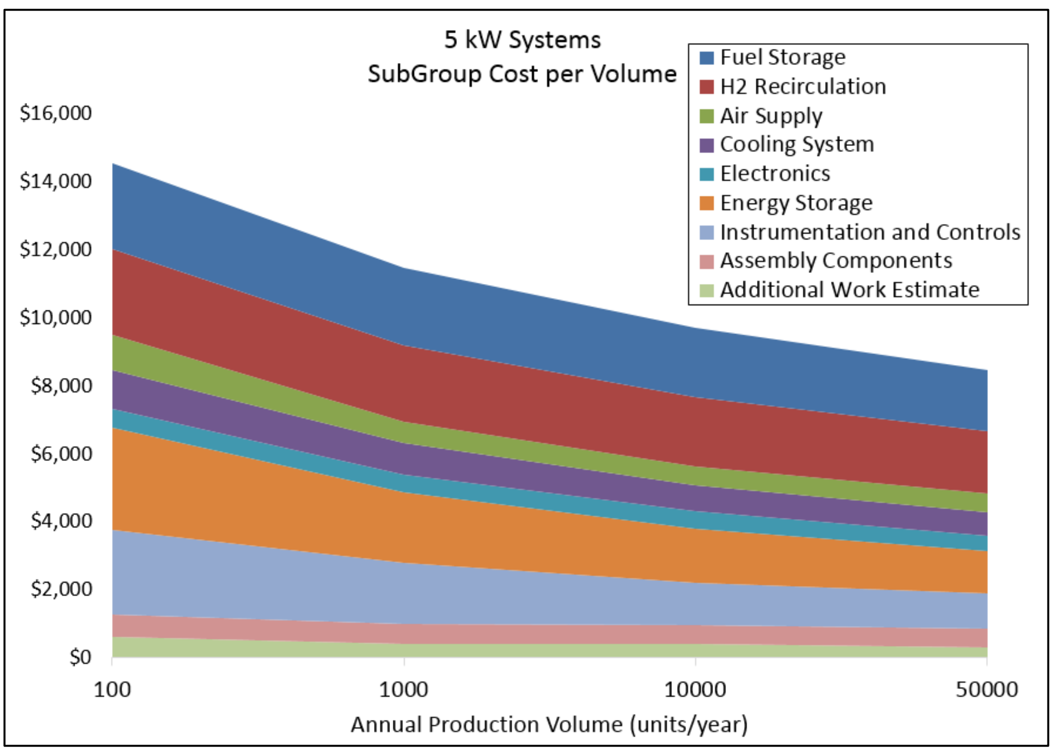


Figure 5-15. 5-kW PEM system BOP cost volume trends

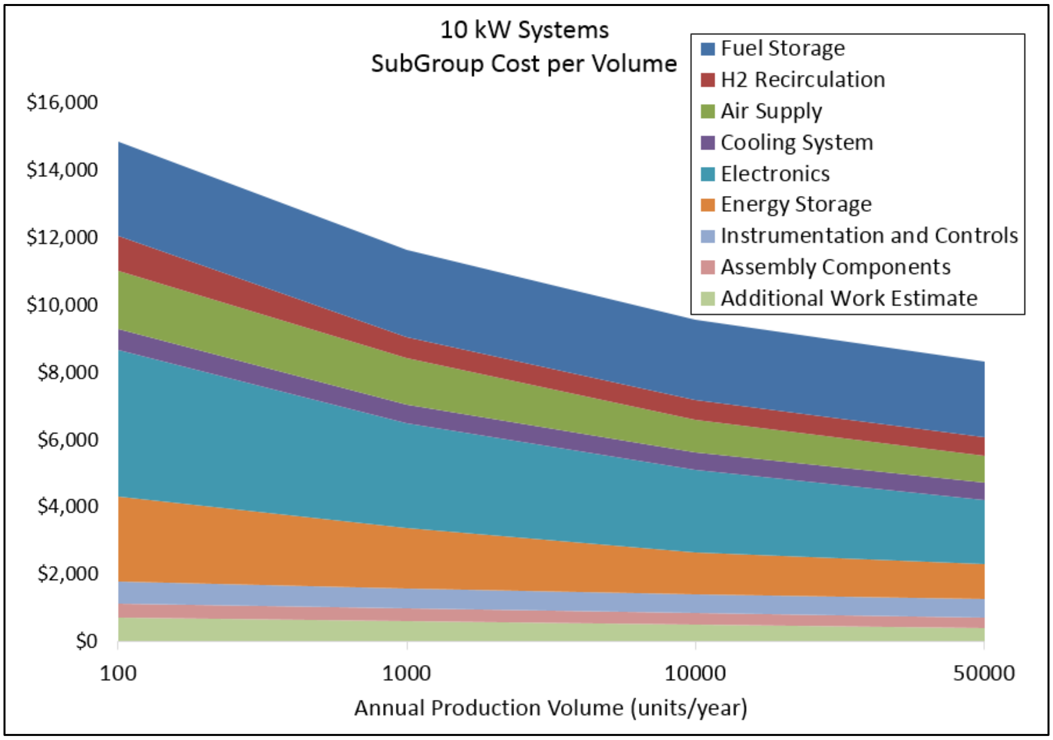


Figure 5-16. 10-kW PEM system BOP cost volume trends

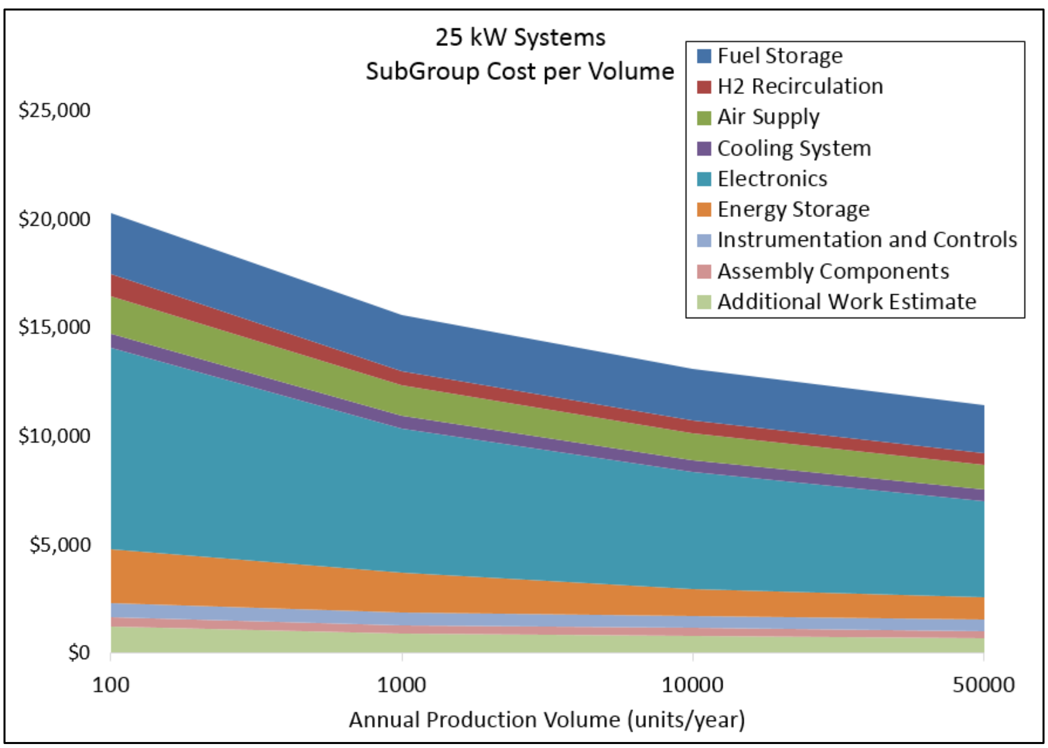


Figure 5-17. 25-kW PEM system BOP cost volume trends

5.3.3 PEM System Assembly and Learning Curve Assumptions

PEM system assembly hardware costs are accounted for in the BOP cost calculations. System assembly times were estimated using the DFMA® software. After applying learning curve analysis to the assembly times and multiplying by the standard labor rate of $45/hour, the average system assembly costs were calculated as shown in Table 5-26 and Table 5-27. Details of the learning curve analysis are provided in Appendix A-3.

Table 5-26. PEM Assembly Costs: 1-kW and 5-kW Systems

Cost Category	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$43.35	$40.54	$37.91	$36.17	$47.35	$44.28	$41.41	$39.51
Labor	$16.17	$12.92	$12.59	$12.56	$38.43	$30.70	$29.92	$29.85
Total Assembly Cost	**$59.53**	**$53.46**	**$50.50**	**$48.74**	**$85.79**	**$74.98**	**$71.33**	**$69.36**

Table 5-27. PEM Assembly Costs: 10-kW and 25-kW Systems

Cost Category	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$54.43	$50.89	$47.59	$45.41	$58.83	$55.01	$51.44	$49.08
Labor	$68.68	$54.86	$53.47	$53.35	$79.96	$63.86	$62.25	$62.11
Total Assembly Cost	**$123.11**	**$105.75**	**$101.06**	**$98.76**	**$138.79**	**$118.87**	**$113.69**	**$111.19**

5.3.4 PEM System Testing

Following assembly, the PEM system was tested and conditioned to determine its fitness for installation in the field. The total test time was assumed to be 2.5 hours. Systems failing the test are reworked by disassembly, replacement of the defective part, and reassembly. The failure rate was assumed to be 3%. The failure cost was treated as 3% of the testing cost, which roughly accounts for the cost of disassembly, part replacement, and reassembly of the defective portion of the system. System failure costs are included in the scrap costs. Details of the analysis are the same as stack testing and conditioning as shown in Appendix A-3. The calculated system testing costs are shown in Table 5-28 and Table 5-29.

Table 5-28. PEM Testing Cost Summary: 1-kW and 5-kW Systems

Cost Category	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$14.76	$6.06	$2.77	$1.70	$23.39	$10.81	$5.18	$3.16
Labor	$72.29	$71.95	$71.91	$71.91	$74.63	$73.82	$73.74	$73.73
Machine	$1,222.22	$101.26	$15.92	$15.92	$1,222.22	$101.26	$15.92	$15.92
Scrap	$68.91	$9.43	$4.77	$4.71	$69.49	$9.78	$4.99	$4.88
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	**$1,378.19**	**$188.70**	**$95.37**	**$94.24**	**$1,389.73**	**$195.67**	**$99.83**	**$97.70**

Table 5-29. PEM Testing Cost Summary: 10-kW and 25-kW Systems

Cost Category	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$34.46	$16.26	$7.81	$4.74	$62.89	$29.85	$14.38	$10.25
Labor	$77.82	$76.36	$76.22	$76.20	$79.00	$77.31	$77.14	$77.13
Machine	$1,222.22	$101.26	$15.92	$15.92	$1,222.22	$101.26	$15.92	$15.92
Scrap	$70.24	$10.20	$5.26	$5.10	$71.80	$10.97	$5.66	$5.44
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	**$1,404.73**	**$204.08**	**$105.21**	**$101.96**	**$1,435.91**	**$219.38**	**$113.10**	**$108.74**

5.3.5 PEM System Capital Cost Assumptions

Table 5-30 summarizes the cost assumptions for the components that make up the total PEM system capital cost.

Table 5-30. Summary of PEM Capital Cost Assumptions

Capital Cost	Unit Cost	Assumption/Reference
Construction Cost	$250/ft^2	Includes electrical costs ($50/ ft^2) Varies with anticipated annual production volumes
Expected lifetime of capital equipment	20 years	N/A
Discount Rate	7%	Guidance for government project cost calculations per OMB Circular 94
Forklift Cost	$30,000	With extra battery and charger.
Crane Cost	$7,350	Assumes 1-ton capacity jib crane with hoist
Real Estate Cost	$125,000/acre	Assumes vacant land, zoned industrial Columbus, OH
Contingency Margin	10%	Assumed 10% additional work estimate

Production station use was estimated to determine the number of individual process stations required to support various product demand levels. This information, along with equipment cost quotes, was used to determine production station equipment costs. The production facility estimation is based on the floor area required for production equipment, equipment operators, and support personnel. Guidelines used for this analysis were developed by Prof. Jose Ventura at Pennsylvania State University[14] and are detailed in Appendix A-4. Capital cost summaries are provided in Table 5-31and Table 5-32.

Table 5-31. PEM Capital Cost Summary: 1-kW and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Production Stations	4	4	17	83	4	5	24	117
Construction Cost	$472,263	$472,263	$1,900,263	$9,308,856	$472,263	$599,463	$2,650,475	$13,222,678
Forklifts	$12,000	$12,000	$51,000	$249,000	$12,000	$15,000	$72,000	$351,000
Cranes	$14,700	$14,700	$62,475	$305,025	$14,700	$18,375	$88,200	$429,975
Real Estate	$47,151	$47,151	$87,427	$244,571	$47,151	$49,862	$100,317	$329,393
Contingency	$54,611	$54,611	$210,116	$1,010,745	$54,611	$68,270	$291,099	$1,433,305
Total Cost	**$600,725**	**$600,725**	**$2,311,281**	**$11,118,197**	**$600,725**	**$750,970**	**$3,202,091**	**$15,766,351**
Equivalent Annual Capital Cost	$56,704	$56,704	$218,169	$1,049,479	$56,704	$70,886	$302,255	$1,488,232
Annual Capital Cost per System	**$567.04**	**$56.70**	**$21.82**	**$20.99**	**$567.04**	**$70.89**	**$30.23**	**$29.76**

[14] Ventura, J.A. 2001. Facility Layout and Material Handling MS PowerPoint Presentations. Penn State Personal Web Server. Accessed January 2017. http://www.personal.psu.edu/jav1/.

Table 5-32. PEM Capital Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Production Stations	4	5	30	145	4	7	49	241
Construction Cost	$472,263	$599,463	$3,410,038	$17,028,191	$472,263	$871,863	$5,749,397	$28,380,422
Forklifts	$12,000	$15,000	$90,000	$435,000	$12,000	$21,000	$147,000	$723,000
Cranes	$14,700	$18,375	$110,250	$532,875	$14,700	$25,725	$180,075	$885,675
Real Estate	$47,151	$49,862	$124,216	$400,968	$47,151	$55,476	$171,536	$617,767
Contingency	$54,611	$68,270	$373,450	$1,839,703	$54,611	$97,406	$624,801	$3,060,686
Total Cost	**$600,725**	**$750,970**	**$4,107,954**	**$20,236,737**	**$600,725**	**$1,071,470**	**$6,872,808**	**$33,667,551**
Equivalent Annual Capital Cost	$56,704	$70,886	$387,762	$1,910,205	$56,704	$101,139	$648,744	$3,177,979
Annual Capital Cost per System	**$567.04**	**$70.89**	**$38.78**	**$38.20**	**$567.04**	**$101.14**	**$64.87**	**$63.56**

6. Limitations of the Analysis

The analytical approach employed here was to create a generic system that is representative of current industry technology and practice. The generic system is made from the merged non-proprietary input from multiple industry representatives and is defined at a high level. There are numerous tradeoffs to be considered when choosing a specific design feature or system specification characteristic. Since the decisions made to define the design and specification are the basis for the cost analysis, it is worthwhile to explicitly consider the impact and limitations of, as well as the justification for, the choices made.

6.1 PEM Manufacturing Costs

Many fuel cell cost studies focus on stack manufacturing costs with little or no consideration of the BOP necessary to support the stack. However, stack fabrication techniques and materials for PEM stacks have advanced so that stack cost is no longer the majority of a system cost—in fact, stack cost may represent only about 20% of the overall cost. In no case did stack cost for this study exceed 30% of the overall system cost. This stresses the importance of the BOP design and component selection. Based on past experience and industry input, reasonable choices regarding the overall system design were selected: a limitation of this analysis is dependence on representative system designs, not field tested hardware.

6.1.1 PEM Stack Manufacturing Costs

Stack costs are based on the use of high-volume processes (i.e., roll-to-roll) to fabricate the MEA. These processes include catalyst deposition, decal transfer and hot pressing. Individual MEA stack components are die cut following hot pressing. The assumption of the use of roll-to-roll processes for low annual production volumes could result in artificially low stack cost estimates at these production levels since the specialized machinery may not yet be available and minimum purchase quantities for roll-to-roll materials would not be justified for small production volumes. Because of the power levels associated with this study and the number of stacks per system, the number of MEA units is relatively high so this limitation is less of a concern for this study than for previous lower power studies.

Alternative and innovative manufacturing techniques were not evaluated. Industry feedback indicates that the techniques used for the cost analysis are consistent with existing processes used by stack component manufacturers. One possible exception is with the bipolar plates, for which some manufacturers use compression molded graphite composite material and others use stamped and coated metal material. For this analysis, graphite composite bipolar plates were chosen due to longevity concerns associated with the MHE application. Table 6-1 summarizes the manufacturing processes that were evaluated.

Table 6-1. PEM Manufacturing Processes Evaluated

Process	Method Evaluated	Alternatives not Evaluated
Catalyst deposition	Selective slot die coating with decal transfer	Tape casting Nanostructure Thin Film (NSTF)
	Single head slot die with decal transfer (not chosen)	Dual head slot die Multi-pass slot die
	Screen printing (not chosen)	
	Spray coating (not chosen)	
Bipolar plate forming	Compression molding	Die stamping and coating (metal plates)
MEA forming	Ruler blade die cutting	Laser cutting
Gasket/seal forming	Injection molding	Laser cutting
	Die cutting (not chosen)	
End plate forming	Sand casting + final machining	Stamping, welding
	Die Casting (not chosen)	
	Machine from block (not chosen)	

The cost analysis assumed that membrane and gas diffusion layer (GDL) materials were purchased in roll form. This could result in slightly higher stack cost compared to in-house production of these materials. However, the membrane and GDL materials are manufactured using complex, highly specialized, multi-step processes.[15] Consequently, in-house production may not be justified until yearly volumes reach the larger production volumes considered here. However, for consistency with prior reports we assumed both membrane and GDL materials would be purchased materials for all production volumes.

6.1.2 PEM BOP Hardware Costs

BOP hardware costs were observed to be lower than those in the previous studies. Several factors contributed to these reduced costs, such as reduction in prices of major cost driving components as well as discounted pricing with increase in production volumes. Some of the major cost drivers include

[15] James, B.D., J.A. Kalinoski, and K.N. Baum. 2010. *Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications: 2010 Update.* NREL Report No. SR-5600-49933. Directed Technologies, Inc. Available at http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/dti_80kwW_fc_system_cost_analysis_report_2010.pdf

equipment for hydrogen and power storage. Based on discussions with major fuel cell manufacturers, it was found that the cost of hydrogen storage was much lower due to incorporation of steel tanks in place of costlier composites. Composites were being used earlier as they provided lower weight and flexibility in design. However, manufacturers claim they prefer steel tanks as their weight provides ballast to the fuel cell and their price is lower by 75%. Prices of other high-cost components such as the hydrogen regulator or recirculation blower have also dropped. The cost of electrical storage components such as the DC/DC converter and lithium ion battery have reduced considerably. For instance, the unit price of a lithium ion battery for a 5-kW system at 1,000 units of production has come down by 40% of its price in the previous study.

Blower selection depends significantly on system pressure drop at design flow rate. Absent an actual design, we assumed a modest pressure drop. As pressure requirements increase through the cathode, blower requirements may increase notably with an attendant increase in cost. In most cases, the system designer has some leeway in the design to minimize pressure drop. However, based on the pressure drop requirements established through our previous studies, the cost of the blower dropped by 75% from the earlier study as cheaper quotes were available from multiple vendors.

7. Cost Trends Analysis

This section presents the results of the analyses of four manufacturing volumes for 1-, 5-, 10- and 25-kW MHE PEM fuel cell systems, including the fuel cell stack, BOP and overall system costs. In addition, this section discusses potential cost components whose prices could be reduced based on our market survey.

7.1 Cost Analysis Results for PEM MHE Systems

Figure 7-1 and Figure 7-2 show the distribution of costs for each system size for a production volume of 10,000 units/year. For small systems, the fuel cell BOP hardware dominates the cost because the cost of controls and sensors is mostly independent of size.

The manufacturing capital cost (the investment required to produce the systems) is relatively small on a per-stack basis even for a limited numbers of units. This is largely due to the use of job-shop/outsource manufacturing for lower volumes, while production machine and labor efficiency benefit the overall cost as volumes increase and manufacturing is brought in house to better manage costs and quality. Although a relatively small number on a per-stack basis, the investment needed can be substantial. Capital costs are assumed to be amortized over the projected lifetime of the machine, or 20 years, whichever is shorter. Since most machines, particularly at the lower volumes, are non-specialized, they may be used for other products when not making fuel cell parts. Use for other products is considered when estimating job shop costs, resulting in lower machine charges but somewhat higher labor cost. When the system components are manufactured in house, the machines are assumed to be dedicated to the fuel cell so that each fuel cell cost includes a portion of the total yearly cost of the machine. We did not consider the potential for producing more than one size system using the same machines. Since the cell sizes are equivalent for the 1- and 5-kW stacks, better machine utilization (and attendant lower per-system cost) could be achieved in some, but not all, cases, because machine utilization generally becomes higher at high production volumes. This may not be true for cases where a small increase in production volume requires the commissioning of another station that would have (at least initially) low utilization.

All systems and sizes assume that final testing and evaluation will be done in house as a quality control measure.

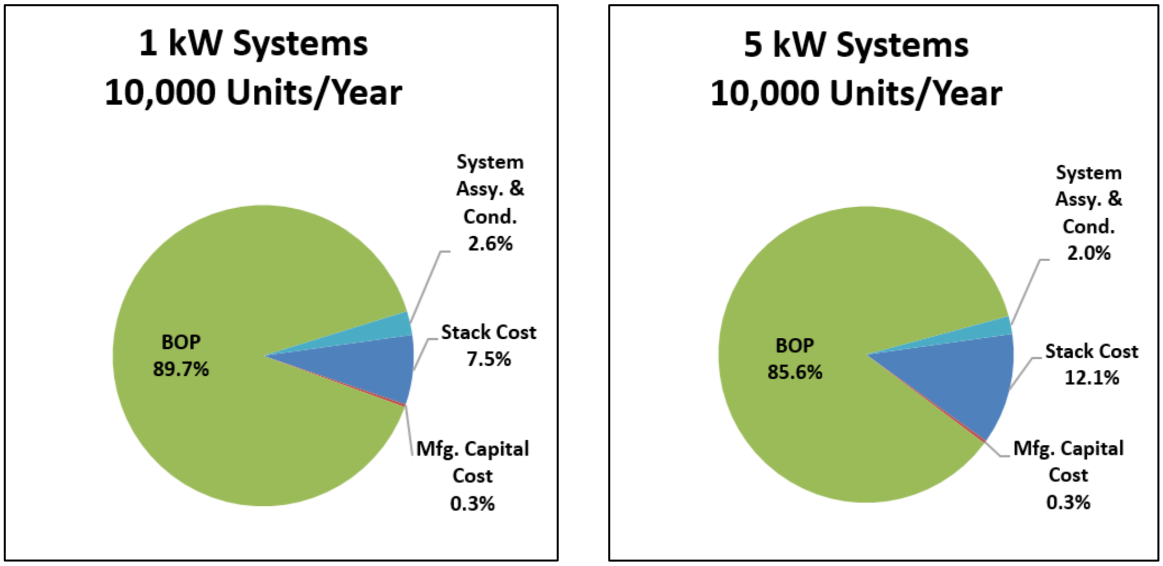


Figure 7-1. 1-kW and 5-kW PEM system costs at 10,000 units per year

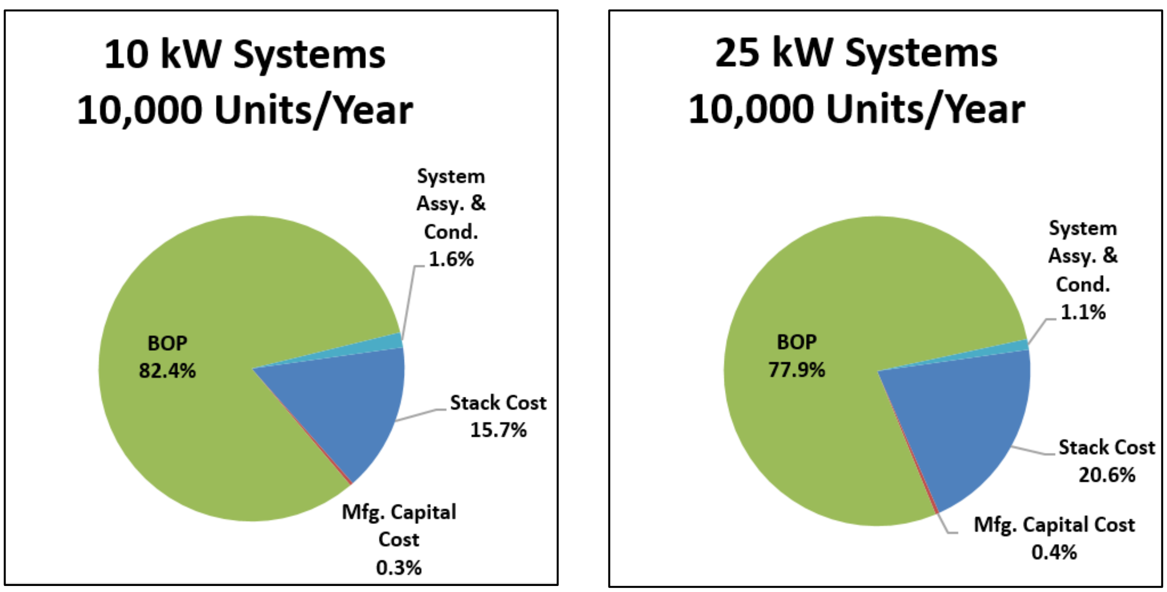


Figure 7-2. 10-kW and 25-kW PEM system costs at 10,000 units per year

Figure 7-3 through Figure 7-6 provide the estimated costs for each size at 1,000- and 10,000-unit production volumes. Figure 7-7 through figure 7-10 show the pre-markup cost trend with increasing manufacturing volume that is represented in Table 7-1 through Table 7-4.

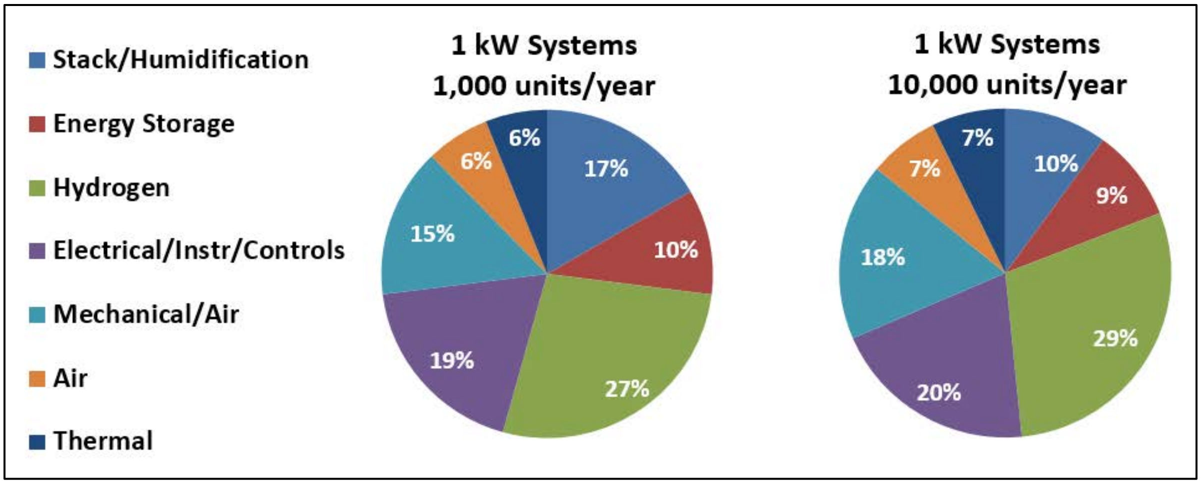


Figure 7-3. 1-kW PEM system cost distribution

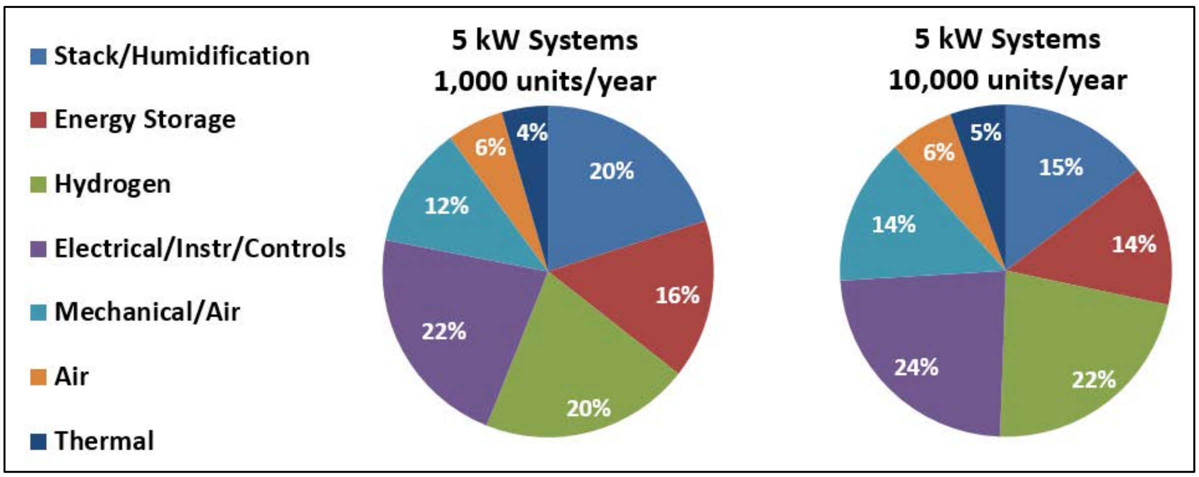


Figure 7-4. 5-kW PEM system cost distribution

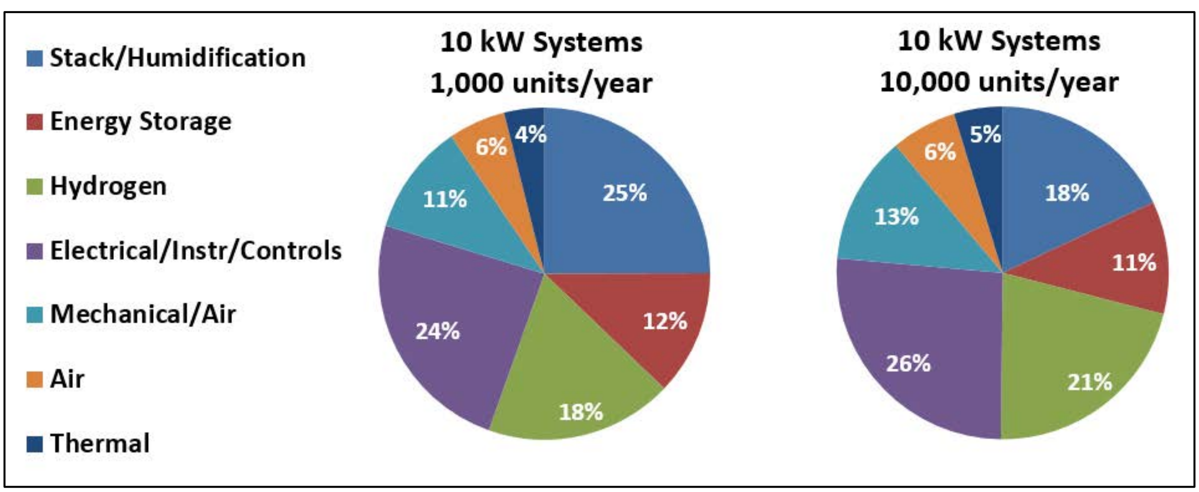


Figure 7-5. 10-kW PEM system cost distribution

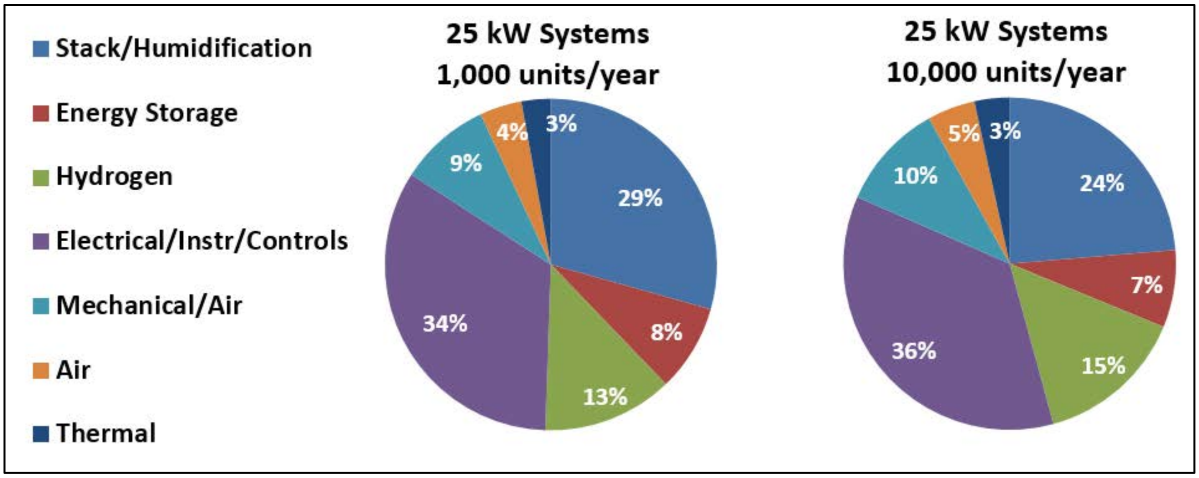


Figure 7-6. 25-kW PEM system cost distribution

Table 7-1. Cost Summary for 1-kW System

Description	100 Units/Year	1,000 Units/year	10,000 Units/Year	50,000 Units/Year
Total stack manufacturing cost, with scrap	$4,147	$1,046	$531	$402
Stack manufacturing capital cost	$567	$57	$22	$21
FC BOP	$9,681	$7,619	$6,381	$5,541
System assembly, test, and conditioning	$1,431	$259	$185	$184
Total system cost, pre-markup	$15,826	$8,980	$7,118	$6,149
System cost per kW_{net}, pre-markup	$15,826	$8,980	$7,118	$6,149
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$23,739	$13,471	$10,678	$9,223
System cost per kW_{net}, with markup	$23,739	$13,471	$10,678	$9,223

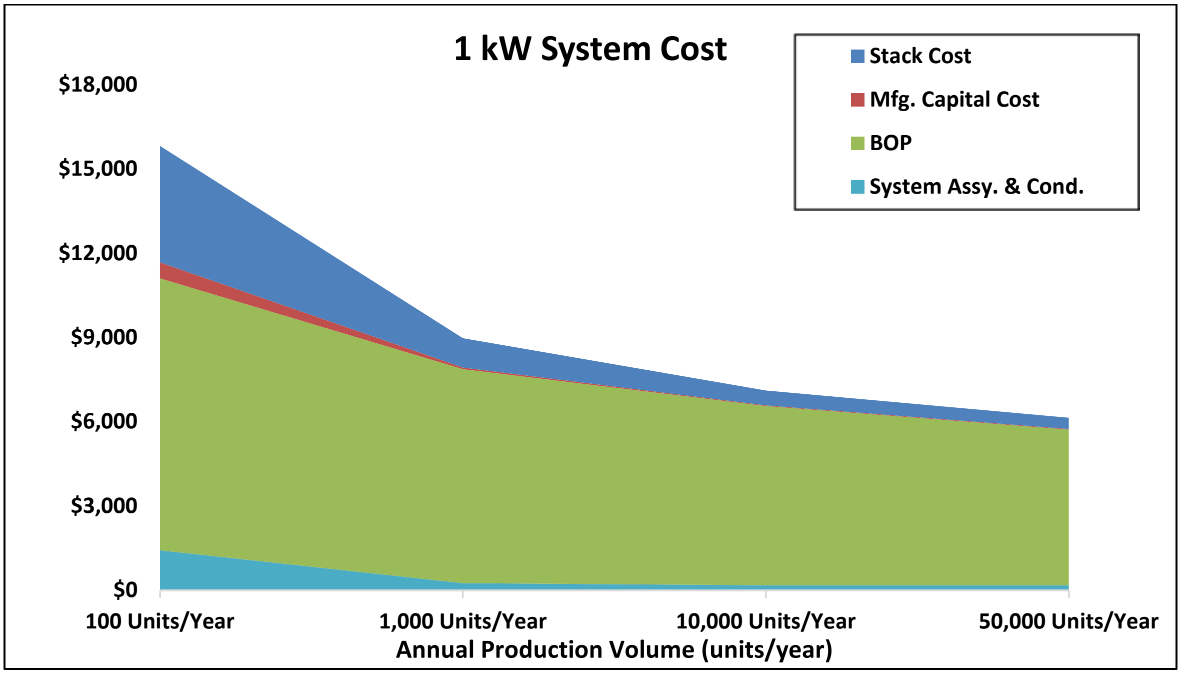


Figure 7-7. 1-kW PEM system cost volume trends

Table 7-2. Cost Summary for 5-kW System

Description	100 Units/Year	1,000 Units/year	10,000 Units/Year	50,000 Units/Year
Total stack manufacturing cost, with scrap	$6,066	$2,015	$1,132	$880
Stack manufacturing capital cost	$567	$71	$30	$30
FC BOP	$12,411	$9,554	$7,996	$6,941
System assembly, test, and conditioning	$1,429	$257	$183	$183
Total system cost, pre-markup	$20,473	$11,897	$9,341	$8,034
System cost per kW$_{net}$, pre-markup	$4,095	$2,379	$1,868	$1,607
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$30,709	$17,845	$14,011	$12,051

System cost per kW_{net}, with markup	$6,142	$3,569	$2,802	$2,410

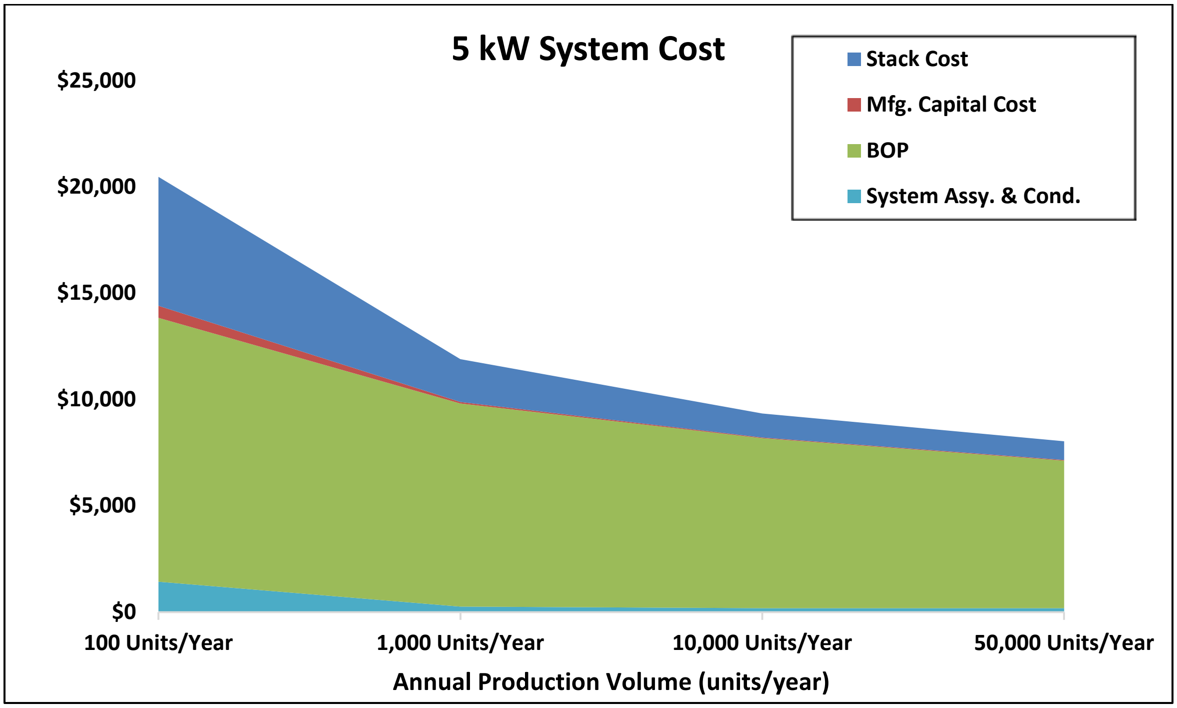


Figure 7-8. 5-kW PEM system cost volume trends

Table 7-3. Cost Summary for 10-kW System

Description	100 Units/Year	1,000 Units/Year	10,000 Units/Year	50,000 Units/Year
Total stack manufacturing cost, with scrap	$7,986	$3,126	$1,827	$1,490
Stack manufacturing capital cost	$567	$71	$39	$38
FC BOP	$14,841	$11,628	$9,576	$8,305
System assembly, test, and conditioning	$1,431	$259	$185	$184
Total system cost, pre-markup	$24,825	$15,084	$11,626	$10,018
System cost per kW_{net}, pre-markup	$2,482	$1,508	$1,163	$1,002
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$37,237	$22,626	$17,439	$15,028

System cost per kW_{net}, with markup	$3,724	$2,263	$1,744	$1,503

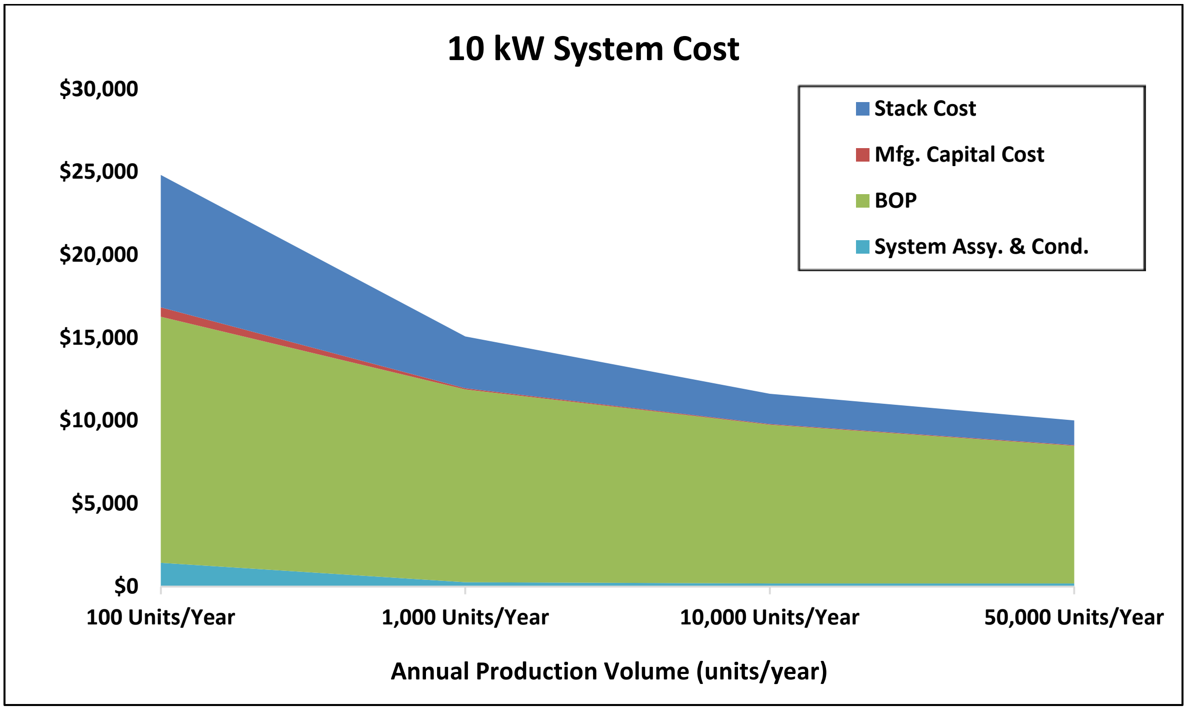


Figure 7-9. 10-kW PEM system cost volume trends

Table 7-4. Cost Summary for 25-kW System

Description	100 Units/Year	1,000 Units/Year	10,000 Units/Year	50,000 Units/Year
Total stack manufacturing cost, with scrap	$12,593	$5,683	$3,467	$3,155
Stack manufacturing capital cost	$567	$101	$65	$64
FC BOP	$20,286	$15,565	$13,121	$11,437
System assembly, test, and conditioning	$1,432	$260	$186	$185
Total system cost, pre-markup	$34,877	$21,609	$16,839	$14,841
System cost per kW_{net}, pre-markup	$1,395	$864	$674	$594
Sales markup	50%	50%	50%	50%

Total system cost, with markup	$52,316	$32,413	$25,259	$22,262
System cost per kW_{net}, with markup	$2,093	$1,297	$1,010	$890

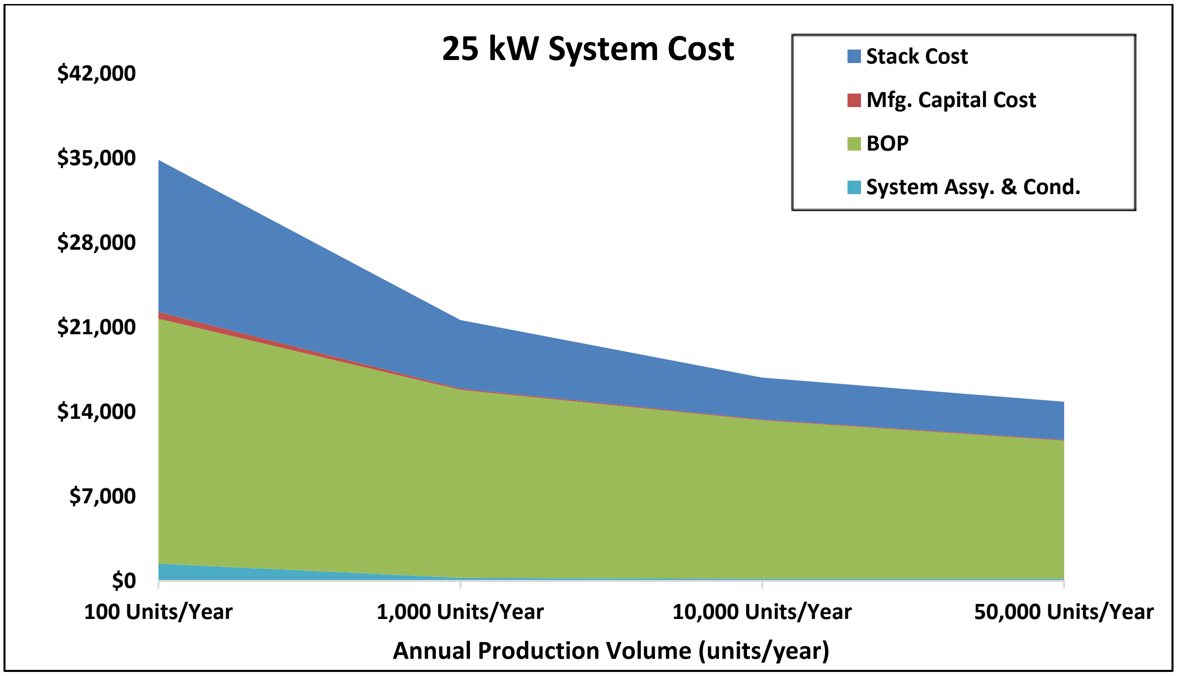


Figure 7-10. 25-kW PEM system cost volume trends

Figure 7-11 shows the cost per kilowatt (excluding mark-up) for each of the sizes and production volumes. As expected, there is benefit to increased total production and system size on cost-per-kilowatt capacity. The trends in Figure 7-1 influence the life cycle cost analysis. When considering a 5-year life for the system and the higher production rate, larger-capacity systems offer attractive payback periods because they can generate electrical power at rates competitive with utility rates. The cost analysis does not place any value on grid outage response, though that may be a significantly beneficial factor in many locations.

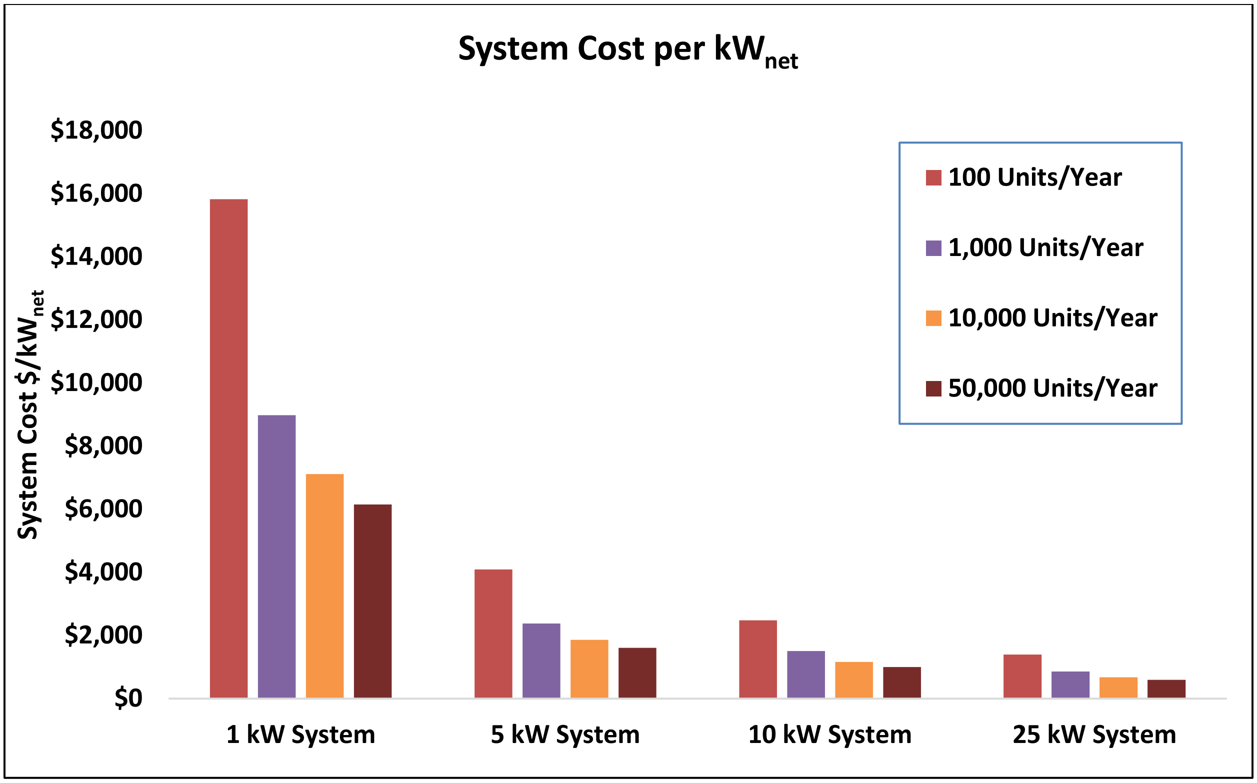


Figure 7-11. Pre-markup cost per kilowatt for PEM systems

7.2 Future Cost Reductions

Many cost reduction strategies for 1, 5, 10 and 25 kW systems remain the same as previously reported.

7.2.1 Energy Management

Energy storage is a major hardware expense to the BOP; the lithium ion battery storage accounts for 9% to 15% of the total BOP hardware cost depending on the annual production rate and system size. In general, power pack manufacturers have designed packs that are constrained by volume and weight to match the characteristics of the lead acid batteries they are replacing. If a forklift were designed with the fuel cell system in mind, more space could be allocated to accommodate different battery technologies.

The DC/DC converter is a substantial expense as well. Depending on the system analyzed and the annual production rate, the main power DC/DC converter can account to as much as 40% of the overall BOP hardware cost. Existing alternative electrical system designs seek to simplify or reduce the component cost in the system by removing the DC/DC converter and directly connecting the fuel cell to the load controller. One manufacturer has adopted this approach and eliminated the DC/DC converter in its systems while employing a contactor switch to regulate current flow and voltage outputs. The effect of this approach on the final system price is significant and is explained in the following sections. Many motor controllers can also accommodate the load-varying voltage of a fuel cell so that a DC/DC converter becomes unnecessary. Ultra capacitors are typically used to provide surge power for these applications.

7.2.2 Cathode Humidification

Stakeholder feedback suggests that research is being conducted to eliminate the need for cathode humidification. In addition to reducing BOP cost, a secondary driver for removing humidification equipment is to reduce system footprint to allow for ease of integration into existing MHE.

8. Sensitivity Analysis

The sensitivity analysis of the costs for the 10-kW system at the 1,000 and 10,000 unit production volumes explores the impact of slight variations to the assumptions for the major contributing cost factors and highlights their significance. The cost factors for the analysis were chosen because of their significant contribution to the cost and/or the difficult nature of precisely assessing their magnitude, such as the cost of platinum. The analysis demonstrates the effect to the overall cost of the system based on reasonable variations to each factor. The results of the sensitivity analyses are shown in Figure 8-1 and Figure 8-2, which show the relative importance of the major cost drivers.

The cost factors that were varied for the analysis include:

- DC/DC Converter
  - Eliminated to reflect market data
  - 20% of the cost retained to account for additional instrumentation that might be required to facilitate this change
- Battery
  - Assumed to be $1,800 and $1,250 for 1,000 and 10,000 units respectively
  - Varied by ±20%
- Current Density
  - Assumed to be 0.8 A/cm^2
  - Adjusted to 1.0 and 1.2 A/cm^2 to see effect
  - Adjusting current density generated the need to modify the active area to keep the electrical system assumptions consistent
- Platinum Loading
  - Assumed to be 0.4 mg/cm^2
  - Varied by + 0.1 mg/cm^2, - 0.25 mg/cm^2
- Platinum Cost
  - Assumed to be $1,294/tr. oz. (troy ounce)
  - Varied by ±50%
- Membrane Cost
  - Assumed to be $50/m^2

  – Varied by ±20%

- GDL Cost
  - Assumed to be $78/m^2$
  - Varied by ±20%
- Bipolar Plate Material Cost
  - Assumed to be $2.43/kg
  - Varied by ±20%

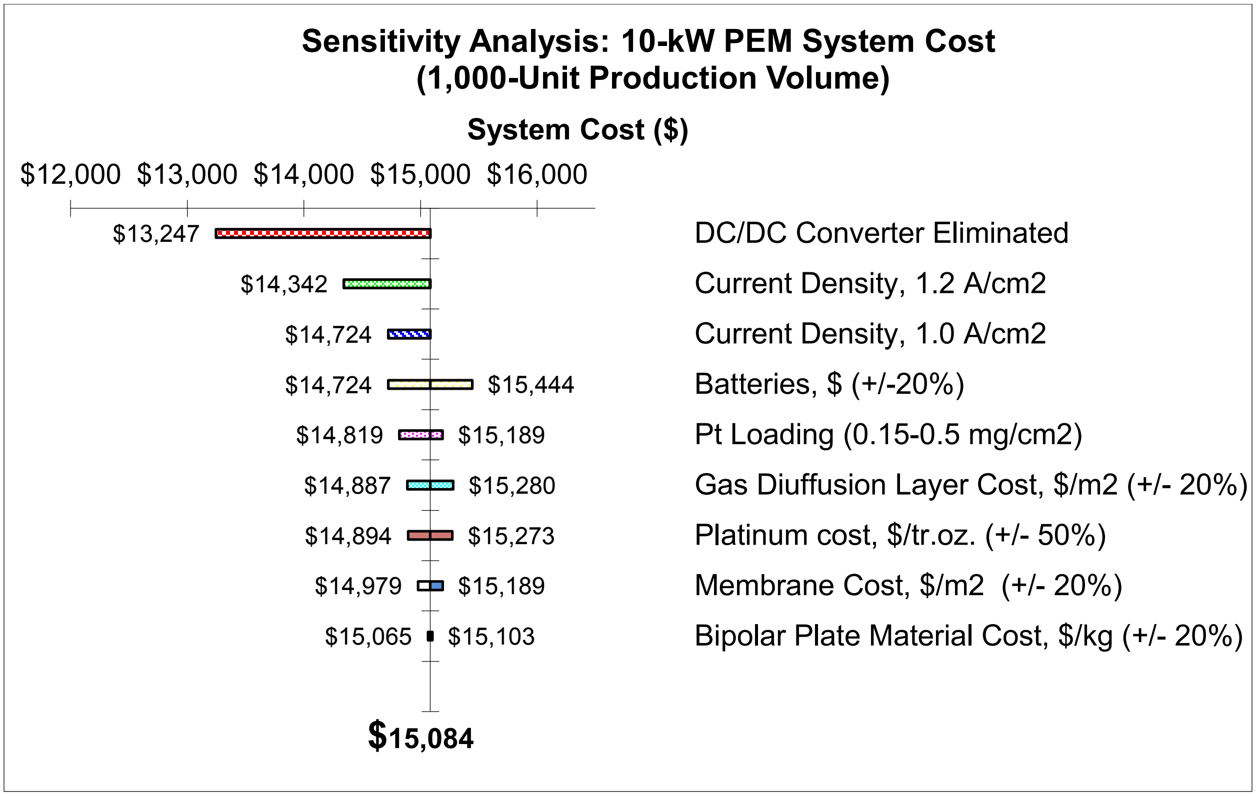


Figure 8-1. Sensitivity Analysis: 10-kW PEM system cost – 1,000-unit production volume

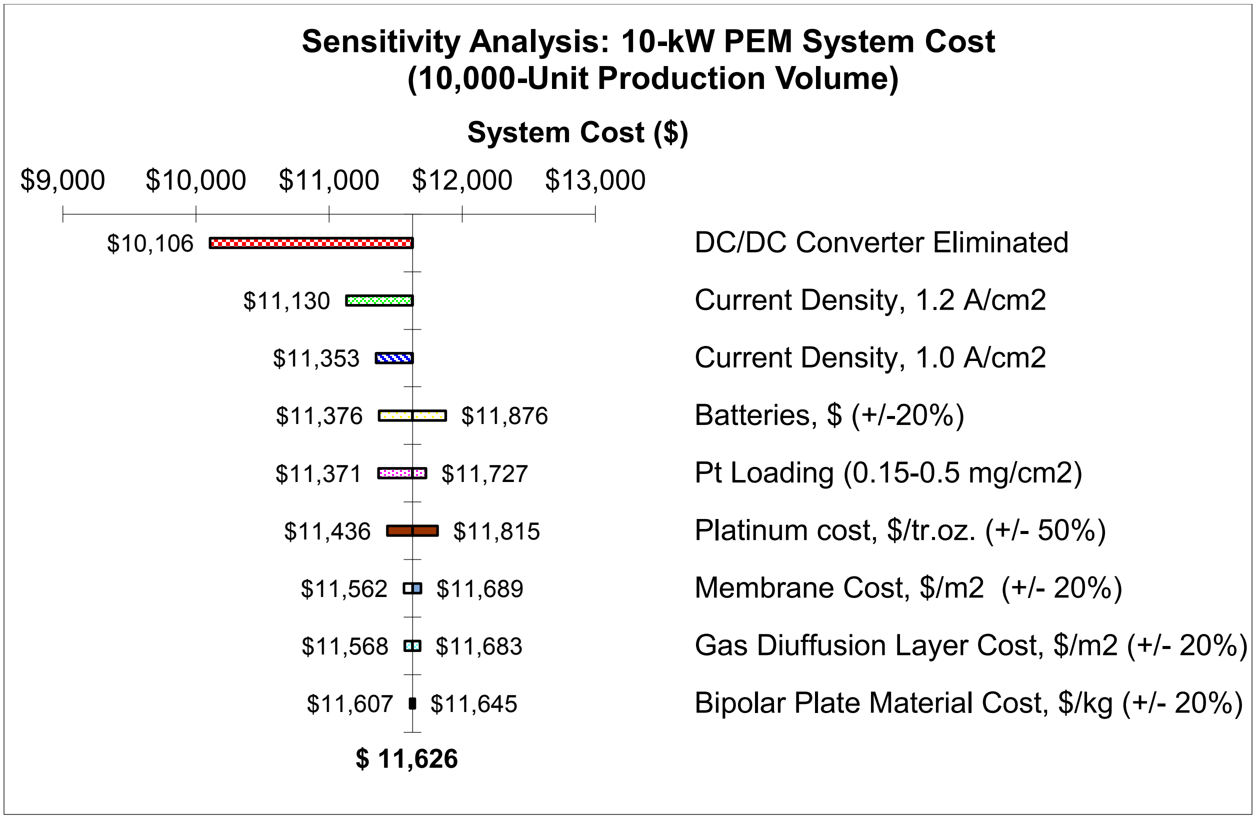


Figure 8-2. Sensitivity Analysis: 10-kW PEM system cost – 10,000-unit production volume

Elimination of the DC/DC converter had the highest impact on system price as can be observed from the tornado charts above. This strategy is being employed by one manufacturer who, as stated earlier, is utilizing other electrical equipment such as a contactor switch to divert the flow of current and regulate voltages and power storage within the system. Fluctuation in the price of lithium ion batteries also affects the price considerably, as they continue to be one of the major cost driving components of the fuel cell system. Current density and platinum loading are the other major factors affecting the cost of system. The platinum loading used in the model (0.4 mg/cm^2) is conservative, and stack producers are already pushing this down to save cost. The current density of 0.8 A/cm^2 is the state of the art, but likewise there is a trend for stack producers to begin to drive this higher. Current density and platinum loading need to be considered together, as the platinum loading will affect what current density is achievable.

Platinum cost is somewhat of a wild card and is difficult to predict. For this analysis, it was varied by ±50%, but the cost could vary even more. This also contributes greatly to other factors such as the catalyst application scrap rate and platinum loading.

Material costs for the membrane, GDL, and bipolar plate also need to be considered, but varying any of these by ±20% had minor consequence on the overall stack cost. The GDL cost holds the most potential at 1,000 units of production, while its impact is lowered at 10,000 units.

9. Life Cycle Cost Analyses of Fuel Cells

Fuel cell systems will compete with battery-powered systems and internal combustion engine systems for application in warehousing operations. Fuel cell forklifts offer a number of advantages over conventional technologies, including increased productivity, reduced maintenance, environmental benefits, and cost savings from reduced battery infrastructure. However, fuel cell systems continue to have a higher initial cost than conventional alternatives.

This analysis compares the life cycle costs of fuel-cell-powered systems to battery systems for a 10-kW system for Class I/II forklifts to identify the primary cost drivers. The analysis is based on Battelle's evaluation of the manufacturing costs of the fuel cell system. The characteristics of operation are based on early market validation projects conducted by the DOE at various Defense Logistics Agency warehouses and on private conversations with industry suppliers and industry stakeholders. In this analysis, the early market deployments at warehouses are assumed to operate for 8 hours a day for two or three shifts per day. Based on a fuel cell life of 10,000 hours, the fuel cell and battery are replaced every five years when used for three shifts/day (3 shifts/day × 8 hours/shift × 0.25 pedal time × 363 days/year × 10 years = 21,780 hours, which requires a power system replacement in year 5 and year 10). The assumed lifetime for the forklift is 10 years. A $6.70-per-kilogram cost of hydrogen was used in this analysis for a small fleet (≤75 forklifts), which assumes that storage and delivery costs are amortized in the hydrogen cost. A value of $6.00 was used for large fleets (>75 forklifts), which accounts for cost savings by enabling bulk purchasing and cryogenic storage. It should be noted, though, that the cost of hydrogen can vary greatly depending on the supplier and location. In contrast, electricity cost was $0.12 per kilowatt-hour (kW-hr). A discount rate of 8% and an inflation rate of 1.9%[16] are applied, and the loan repayment period was set to 10 years to coincide with the lifetime of the assets. No disposal costs are assumed for any of the technologies, and a salvage value of 20% of the initial cost was applied at the end of life for both fuel-cell-powered and battery-powered forklifts. Depreciation was accounted for using a 5-year Modified Accelerated Cost Recovery System (MACRS) depreciation schedule (Table 9-1).

During actual operation, forklifts may operate at full power or at a reduced power during a slow approach to a target for pickup. Forklifts are also idle at times. Both factors could be captured by allowing a variable for average power and pedal time (*i.e.* the fraction of time the forklift is not idling). The average power and the pedal time will both affect fuel costs over the lifetime. The amount of time the fuel cell is operated though (*i.e.* the pedal time) is the primary factor in the stack life which is found to be about 10,000 hours at full power. The stack life at a reduced average power is not exactly quantified. The expectation is that cells operate somewhere at 40% to 60% of maximum power at about 40% to 60% the total shift time. In this analysis, we use pedal time to capture the effects of actual operation time and average power. We are therefore using a nominal value of around 0.25 for pedal time (which is equivalent to 50% of total power for average power times the 50% of the total shift time for shift pedal time). It would be desirable to break up pedal time into each variable. However, without better data to understand how average power affects stack life, we have decided to use a single variable in this analysis.

Fuel cell systems have a few other distinct advantages that were incorporated into the analysis. First, cell refuel is a quick process (~2 to 4 minutes) versus the time required to change a battery (~12 to 15 minutes). In this analysis, we use a value of 3.3 minutes for the refuel time (this value was used in

[16] The inflation rate was calculated from the 10-year average of data published by the Bureau of Labor Statistics: https://data.bls.gov/timeseries/CUUR0000SA0L1E?output_view=pct_12mths

previous reports) and 13.5 minutes for battery replacement, which is an average of the value used in a previous report and the 15 minutes claimed on the website of a fuel cell manufacturer[17]. In addition, productivity is increased because fuel cell performance does not diminish as fuel is consumed; this is in contrast to a battery, where power output decays as the battery discharges. This effect was factored in using proprietary data and was found to be $14,218 per forklift per year, or around $39 per forklift per day (assuming a labor rate of $25.00/hour, which equates to around 19.5% of a full-time equivalent). We ratio this value against the labor rate used in this analysis to account for varying labor rates (e.g., for a $20.00/hour rate, we calculate $20.00/$25.00×$14,218=$11,374 per forklift per year, or around $31 per forklift per day at 19.5% full-time equivalent). In addition, conversion to fuel cell technology allows floor space to be recovered as the battery room is eliminated. Battery room maintenance is also no longer needed. These effects were factored in again using proprietary data. Maintenance was partially accounted for in the differential of 13.5 minutes to 3.3 minutes for recharge versus refuel. The land recovery was factored in with a cost of $399 per forklift per year.

Hydrogen infrastructure costs were calculated based on data in a report from the National Renewable Energy Laboratory[18]. The data in the report indicates the H_2 infrastructure costs were expected to be $3.09M for a 600 kg/day capacity in 2016. The cost for the H_2 needs in this analysis were calculated by dividing the kg/day necessary capacity by 600 kg/day and subsequently multiplying the value by $3.09M. In addition to the fixed infrastructure for H_2 storage, additional infrastructure is needed to transport and distribute the H_2 onsite. Based on discussions with industry stakeholders, the value is about $8,000 per month for small fleets (75 trucks) and $9,000 per month for large fleets (300 trucks). These two data points establish a linear trend used for all other fleet sizes considered in the analysis. Similarly, battery room costs (including cranes/hoists, HVAC, electricity, and land) vary with fleet size as well where larger fleets typically lead to higher efficiencies and better use of space. A value of $6,600 per truck was used for small fleets (75 trucks) and $4,000 per truck for large fleets (300 trucks). Again, a linear trend was used to calculate values set through the linear relationship calculated from these two data points. Charger costs were fixed at $1,800 per charger with one charger per truck[19].

[17] For example, see: http://www.plugpower.com/products/gendrive/
[18] Melaina, M.W., Penev, M., "Hydrogen Refueling Infrastructure Cost Analysis", Department of Energy Fuel Cell Technologies Program Annual Merit Review, Project ID: AN020, Arlington, VA, May 15, 2012. See slide 14.
[19] Mahadevan, K., et al., "Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets", Prepared for the U.S. Department of Energy, Contract No. DE-FC36-03GO13110, April 2007. See Table 3-18.

Table 9-1. Input for the Life Cycle Assessment Assuming a Production Volume of 1,000 Fuel Cell Units

Input Data	Fuel Cell	Battery
Cost of forklift	$25,000	$25,000
Cost of power system	$17,439*	$14,600
Power system replacement time, hours	10,000	10,000
Power system replacement cost	$3,075§	$14,600
Operational days per year	363	363
Shifts per day	2-3	2-3
Power factor, hours per 8 hour shift	1.6	1.6
Total number of shifts in life cycle	7,260-10,890	7,260-10,890
Power system replacement events	2-3	2-3
Number of times recharged/refueled per day	2-3	2-3
Labor time for refuel/recharge, minutes	3.3	13.5
Labor cost per day for refuel/recharge	$2.20-$3.30	$9.00-$13.50
Fuel usage per hour at full power, kg	0.64¶	
Electricity use per recharge, kW-hr		40
Daily consumables cost	$13.71-$20.56	$7.68-$11.52

* Calculated from a detailed bill of materials for all fuel cell component parts, which includes the fuel cell stack ($3,075) and the BOP ($14,364) plus up to two additional stack replacements for the three–shift case considered in this table ($6,149) totaling $23,588.

§ After 10,000 hours, the analysis assumes the fuel cell stack needs to be replaced while all BOP components are assumed to have a lifetime in excess of the 10-year window analyzed herein.

¶ Calculated from stoichiometric requirements of the fuel cell at 100% power (0.64 kg/hour).

9.1 Life Cycle Assessment Results for Baseline Scenarios

For the life cycle assessment, the annual cash flows are calculated for years 1-10. In this analysis, all cash flows are expenses, though the fuel cell operations do represent lower expenses in the form of reduced labor, increased productivity, floor space recovery, and less expensive parts replacement. As a result, the delta in cash flows can be calculated to provide a measure of the savings recovered in fuel cell operations versus traditional battery-powered forklifts. The net present value (NPV) of the recovered funds was calculated. The return on investment (ROI) and payback period were calculated using the price savings and net capital investment of fuel cell operations. The equivalent annual cost (EAC) was also calculated for battery-powered and fuel-cell-powered options, and the delta between those options was also calculated (ΔEAC). The results from the life cycle assessment are summarized in Table 9-2.

Table 9-2. Life Cycle Assessment Results for 10-kW Forklifts with a 1,000-Unit Production Volume

10-kW System at 1,000 Units				
Fleet size	75	75	300	300
Shifts	2	3	2	3
NPV of Savings, $M	$6.44	$10.10	$27.65	$42.27
ROI, %	44.94	69.28	48.25	72.59
Payback Period, years	2.23	1.44	2.07	1.38
ΔEAC, $M	$0.76	$1.18	$3.24	$4.95

As demonstrated, there is an appreciable benefit of using fuel-cell-powered forklifts in all scenarios. The payback is substantially faster for an increased number of shifts. The payback is marginally faster for larger fleets.

This analysis can be repeated using figures produced assuming fuel cells are manufactured at a volume of 10,000 units. In this scenario, fuel cell prices are reduced by manufacturing in bulk. As a result, the stack costs $2,050 and the cost of the power system, with replacements figured in, is $15,725. These savings result in the modifications in Table 9-3.

Table 9-3. Life Cycle Assessment Results for 10-kW forklifts with a 10,000 Unit Production Volume

10-kW System at 10,000 units				
Fleet size	75	75	300	300
Shifts	2	3	2	3
NPV of Savings, $M	$6.36	$9.99	$27.33	$41.84
ROI, %	44.22	68.42	47.53	71.73
Payback Period, years	2.26	1.46	2.10	1.39
ΔEAC, $M	$0.75	$1.17	$3.20	$4.90

Table 9-3 shows similar trends to Table 9-2 but, in all cases, the savings are more significant and payback is faster than in the 1,000 unit manufacturing volume case.

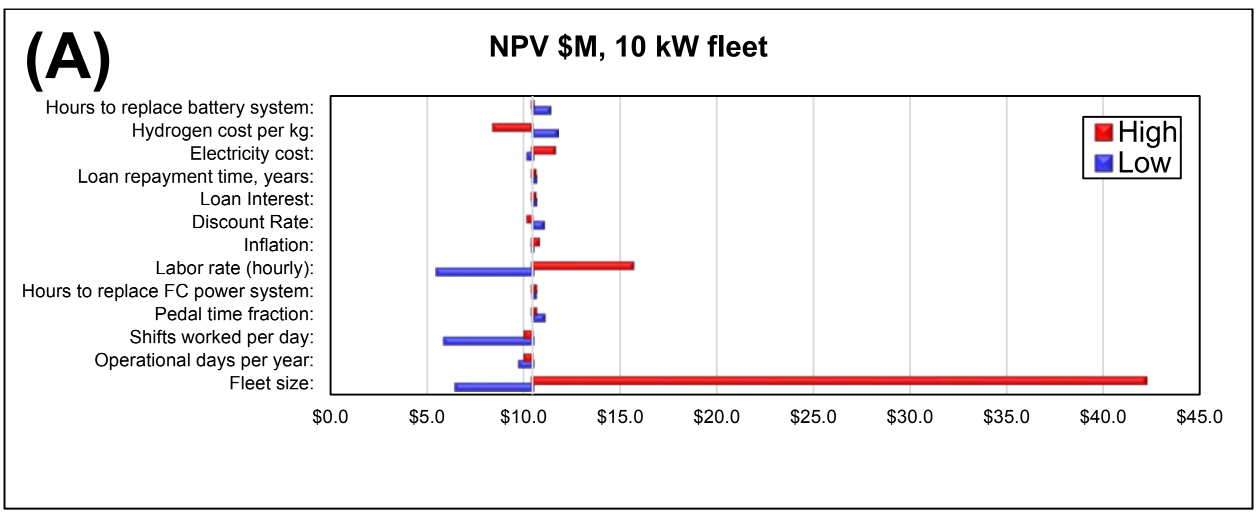
9.2 Life Cycle Assessment Sensitivity Analysis

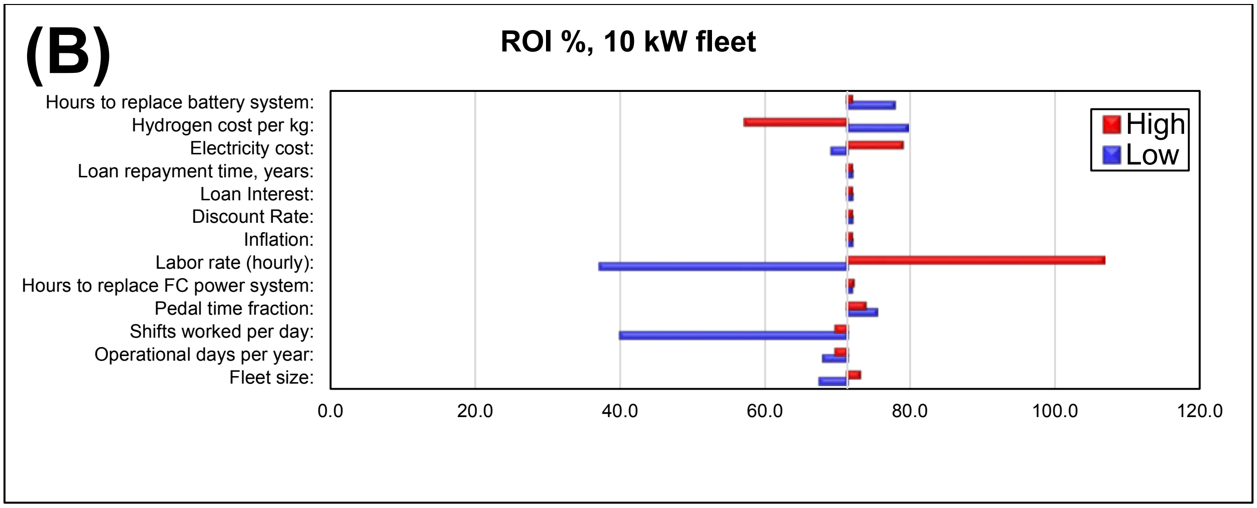
The previous scenarios indicate the cost-benefit for a few realistic scenarios. In addition to these scenarios, we also want to understand the sensitivity of the economics to several variables. This was achieved using two different techniques: tornado charts and Monte Carlo analysis. First, all parameters of interest where identified and a reasonable nominal value was set along with a maximum and minimum value (Table 9-4). Fleet size was varied between 50 and 300 forklifts. Operational days assumed 5, 6, and 7 days a week (260, 312, and 363 days a year). Two to three shifts were allowed with fractional pedal time varying between 0.15 and 0.25 of the total 8-hour shift (1.2 to 2.8 hours per shift). Total mean hours to replace the fuel cell and the battery system were set at 10,000±20% (i.e. 8,000 to 12,000 hours). The mean inflation for the last 10 years was calculated using data from the Bureau of Labor Statistics with a standard deviation added/subtracted to inflation to bound the analysis. Loan discount rate varied from 7% to 9% with interest ranging from 2% to 4% and a repayment time of 5 to 15 years. Finally, electricity costs were varied between $0.10 and $0.17 per kilowatt-hour.

Table 9-4. Parameter Settings Used in Sensitivity Analysis

Variable	Low	Nominal	High
Fleet size	50	75	300
Operational days per year	260	312	363
Shifts worked per day	2	3	3
Pedal time fraction	0.15	0.20	0.25
Hours before battery system replaced	7,500	10,000	12,500
Hours before fuel cell stack system replaced	5,000	10,000	15,000
Labor rate per hour	$15	$25	$35
Inflation rate	1.45%	1.91%	2.38%
Discount rate	7%	8%	9%
Loan interest rate	2%	3%	4%
Loan repayment time, years	5	10	15
Electricity cost, $/kW-hr	$0.10	$0.12	$0.17
Hydrogen cost, $/kg	$5.00	$6.70	$9.00

Tornado charts are generated by setting all variables to the nominal value and calculating the baseline result. Then, each parameter is individually adjusted to the minimum and maximum value. The NPV of the savings for converting to fuel cell operations is recorded, as are the ROI and payback period in years. The results for 10-kW forklifts with fuel cells manufactured at a volume of 1,000 units are shown in Figure 9-1.





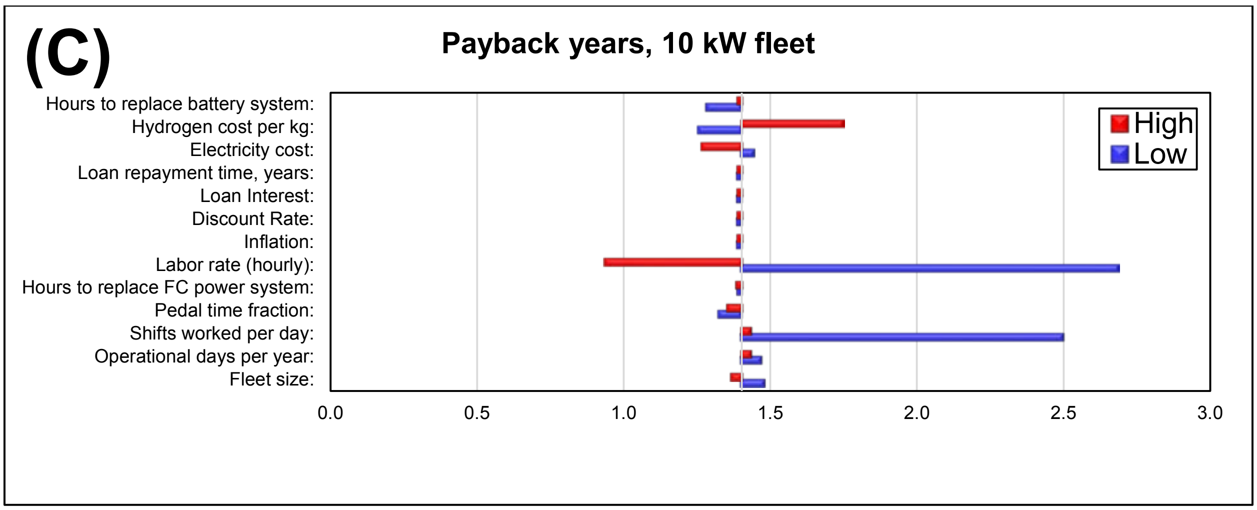


Figure 9-1. Sensitivity analysis results

As seen in Figure 9-1, the NPV of the savings associated with converting to fuel cells is strongly influenced by fleet size. This is expected since NPV is not a normalized economic metric and instead scales with the capital used. That is, the more forklifts you convert, the larger the ultimate savings. The downside is that it is not always possible to have the capital set aside to achieve such a large NPV benefit.

Conversely, ROI is calculated as the average annual return per year by the fixed capital investment (which normalizes the calculation since the fixed capital investment and the average annual return per year both scale linearly with fleet size). Payback period is calculated similarly where the net capital investment is divided by average annual return (again, both scale linearly with fleet size normalizing the calculation). Therefore, on a normalized basis, ROI and payback period both exhibit different sensitivities than does NPV. The main factors these metrics are sensitive to include labor rate, shifts worked, hydrogen costs, electricity costs, and the battery lifetime.

In aggregate, decreasing battery replacement time and hydrogen fuel costs improves the economic metrics as ROI is increased and payback period is decreased. Conversely, increasing the electricity costs, labor rate, and number of shifts worked all increase ROI and decrease payback period as well. One interesting finding is that the calculation is relatively insensitive to fuel cell stack replacement time. This is due to the fact that the stack is relatively inexpensive when compared to the battery system ($3,075 for the stack, assuming the BOP remains viable, versus $14,600 for a battery system as summarized in Table 9-1).

As an alternative to the tornado chart sensitivity analysis, a Monte Carlo simulation was performed where the values in Table 9-4 were randomly set by drawing a uniformly distributed random number between 0 and 1, which was used to select a value evenly between the minimum and maximum values in Table 9-4. For each iteration, all parameters were randomly selected. This process was performed for 10,000 iterations and a cash flow diagram was generated. The mean cash flow (solid line) and cash flows with plus/minus a standard deviation (upper and lower dashed lines) were then plotted. This analysis gives the expected cash flows along with error bounds for all the variables across the range of practical values. The results are shown in Figure 9-2.

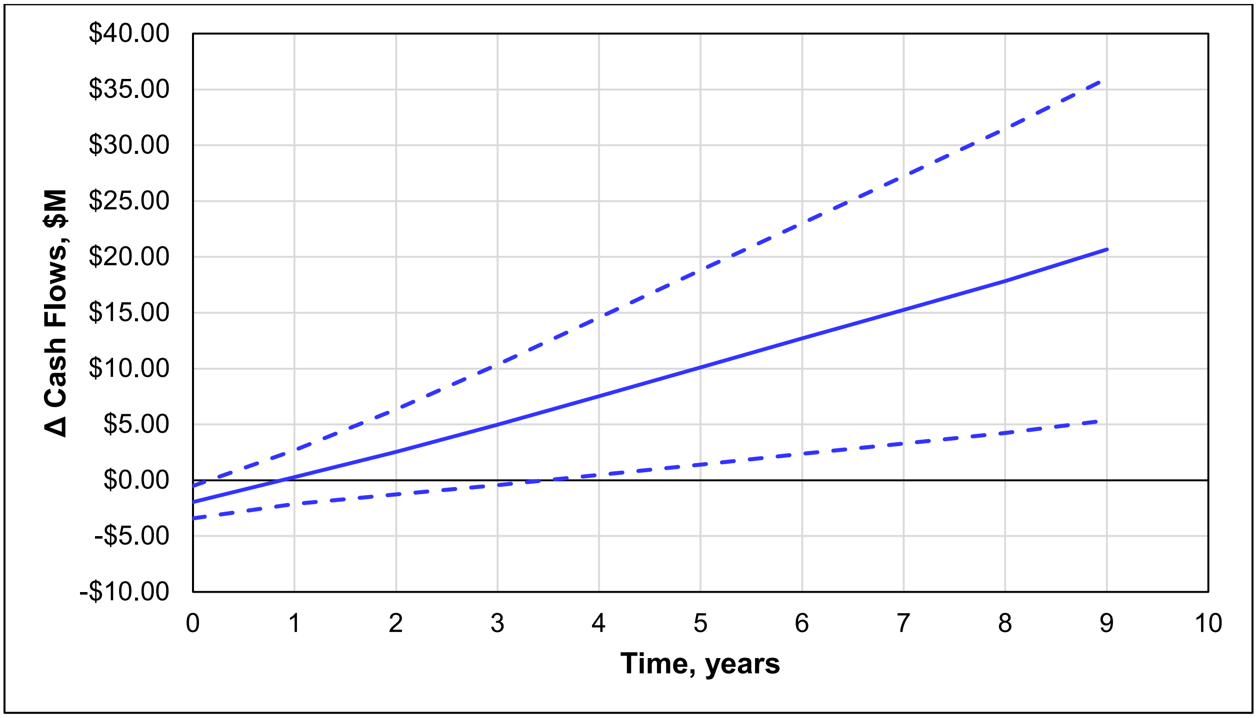


Figure 9-2. Monte Carlo results for expected change in cash flow

The changes in cash flow were plotted as a function of time, which is the change in annual cash flow between selecting fuel cells over batteries. The analysis was performed assuming a manufacturing volume of 10,000 units. As shown in Figure 9-2, the mean break-even point is around 3 years but could be as low as 2 years or as high as 4 years, depending on the values of parameters selected from Table 9-4. It should be noted that the financial results will differ based on the costs to borrow money. In addition, the capital costs can be alleviated through leasing programs that are not considered herein.

In summary, the economics show a strong case for fuel cell power for 10-kW Class I/II forklifts. The NPV of the dollars saved is maximized by increasing the fleet size. Thereafter, the tradeoff between fuel cells and batteries is more pronounced for increased labor rates, electricity costs, and shifts per day, or decreased battery life and hydrogen costs.

10. Conclusions

10.1 System Cost Summary

A high-level summary of the final costs is shown in Table 10-1 through Table 10-4, which emphasize that the BOP dominates the final cost; at most, it is estimated to account for 90% of the final cost before markup at high production volumes. In all sizes and production rates analyzed, the BOP was responsible for no less than 58% of the pre-markup price. Overall, the final cost is analyzed in four distinct categories: the capital cost of manufacturing equipment, the direct cost of material and assembly of the stack, the expense of BOP hardware, and the final cost of complete system assembly and testing. Anticipated scrap is also captured in the stack manufacturing cost.

A sales markup of 50% was integrated at the end and is called out separately. At high production volumes, the final ticket price is estimated to be $10,678 per kilowatt for a 1-kW MHE PEM system. The cost of a system per kilowatt decreases with increasing system capacity and production volume. This price decreases nearly 91% to $1,010 per kilowatt for a 25-kW system. For a visual representation of the cost breakdown pre-markup, refer to the corresponding pie charts in Figure 10-1 through Figure 10-4.

Table 10-1. Cost per Unit Summary for 1-kW MHE PEM Fuel Cell System

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$4,147	$1,046	$531	$402
Stack manufacturing capital cost	$567	$57	$22	$21
BOP	$9,681	$7,619	$6,381	$5,541
System assembly, test, and conditioning	$1,431	$259	$185	$184
Total system cost, pre-markup	$15,826	$8,980	$7,118	$6,149
System cost per net kW, pre-markup	$15,826	$8,980	$7,118	$6,149
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$23,739	$13,471	$10,678	$9,223
System cost per net kW, with markup	$23,739	$13,471	$10,678	$9,223

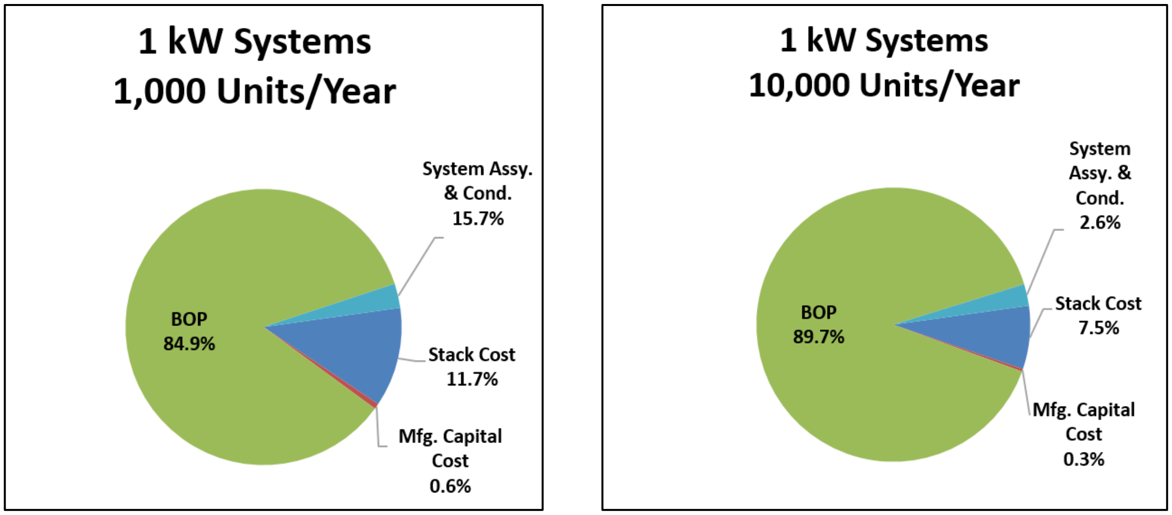
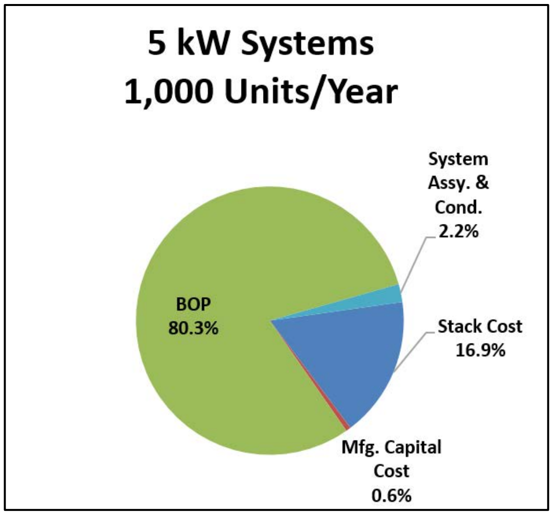


Figure 10-1. Distribution of costs for 1-kW system at 1,000 and 10,000 units/year

Table 10-2. Cost per Unit Summary for 5-kW MHE PEM Fuel Cell System

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$6,066	$2,015	$1,132	$880
Stack manufacturing capital cost	$567	$71	$30	$30
BOP	$12,411	$9,554	$7,996	$6,941
System assembly, test, and conditioning	$1,429	$257	$183	$183
Total system cost, pre-markup	$20,473	$11,897	$9,341	$8,034
System cost per gross kW, pre-markup	$4,095	$2,379	$1,868	$1,607
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$30,709	$17,845	$14,011	$12,051
System cost per gross kW, with markup	$6,142	$3,569	$2,802	$2,410



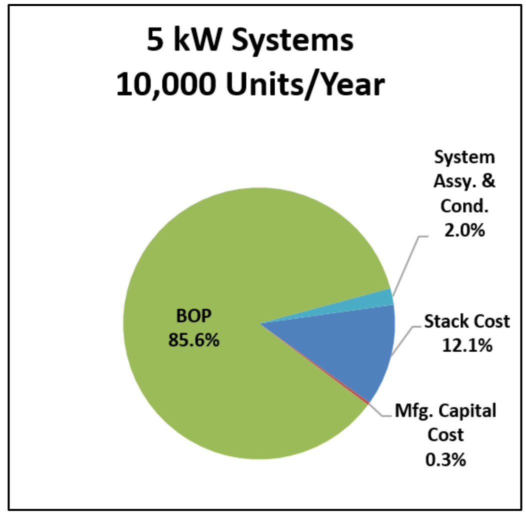


Figure 10-2. Distribution of costs for 5-kW system at 1,000 and 10,000 units/year

Table 10-3. Cost per Unit Summary for 10-kW MHE PEM Fuel Cell System

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$7,986	$3,126	$1,827	$1,490
Stack manufacturing capital cost	$567	$71	$39	$38
BOP	$14,841	$11,628	$9,576	$8,305
System assembly, test, and conditioning	$1,431	$259	$185	$184
Total system cost, pre-markup	$24,825	$15,084	$11,626	$10,018
System cost per net kW, pre-markup	$2,482	$1,508	$1,163	$1,002
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$37,237	$22,626	$17,439	$15,028
System cost per net kW, with markup	$3,724	$2,263	$1,744	$1,503

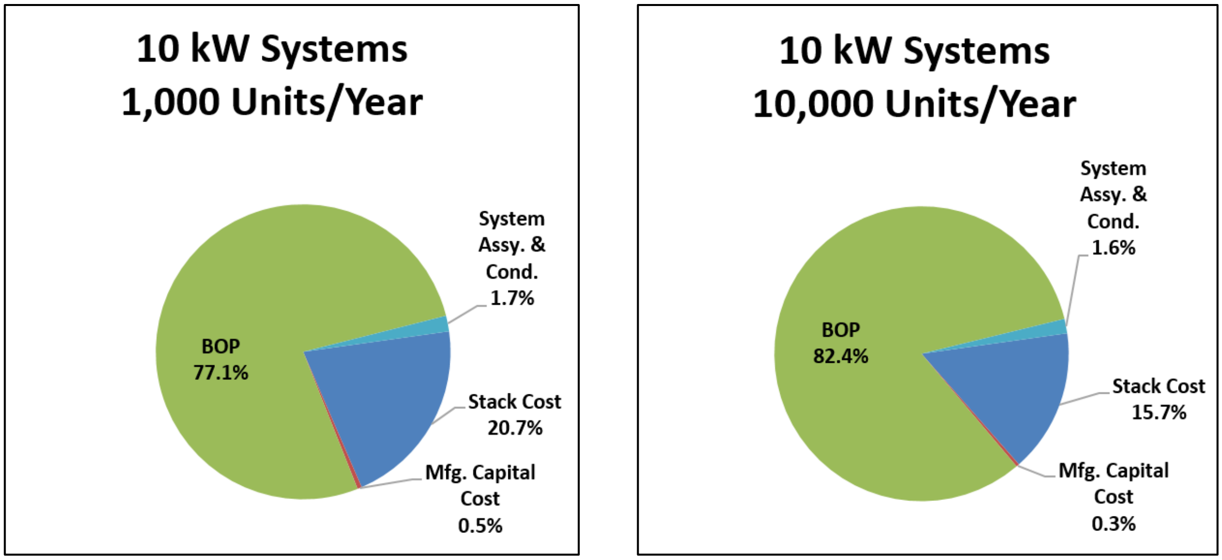


Figure 10-3. Distribution of costs for 10-kW system at 1,000 and 10,000 units/year

Table 10-4. Cost per Unit Summary for 25-kW MHE PEM Fuel Cell System

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$12,593	$5,683	$3,467	$3,155
Stack manufacturing capital cost	$567	$101	$65	$64
BOP	$20,286	$15,565	$13,121	$11,437
System assembly, test, and conditioning	$1,432	$260	$186	$185
Total system cost, pre-markup	$34,877	$21,609	$16,839	$14,841
System cost per gross kW, pre-markup	$1,395	$864	$674	$594
Sales markup	50%	50%	50%	50%
Total system cost, with markup	$52,316	$32,413	$25,259	$22,262
System cost per gross kW, with markup	$2,093	$1,297	$1,010	$890

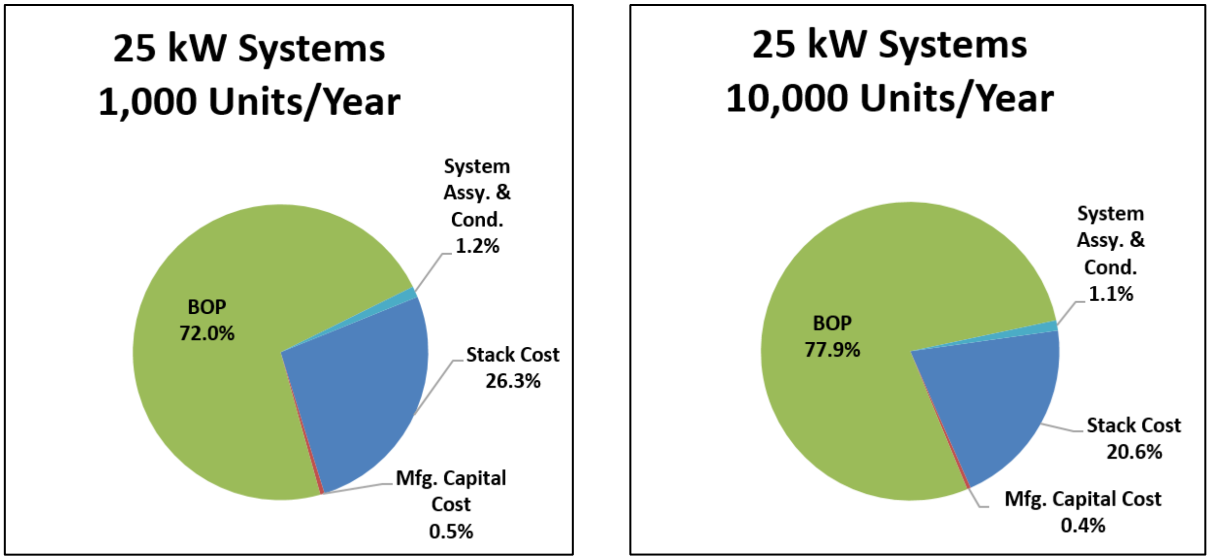


Figure 10-4. Distribution of costs for 25-kW system at 1,000 and 10,000 units/year

10.2 Value Proposition

Fuel-cell-powered MHE offers great value in terms of productivity, as the equipment requires less downtime for battery changes and offers longer load cycles compared to battery-operated equipment. Less dependence on batteries also means eliminating the need for dedicated battery rooms that require chargers, high-cost electric power supply, and personnel to oversee these operations. These advantages, coupled with lower emissions, and environmental benefits, have drawn the attention of leading grocery and consumer chains, which have begun switching their conventional battery-powered fleet to fuel-cell-powered alternatives. The value proposition also depends on the size of the fleet as well as the load handled by a facility. Maximum value can be extracted from fuel-cell-powered MHE in facilities operating with a large fleet that runs for long cycles, while the switch may not be as attractive in facilities with smaller fleets and fewer operating hours. In most cases studied by Battelle, customers were willing to replace beyond 50 to 70 trucks per facility. Moreover, sensitivity analyses indicate payback period is generally in the range of 1-3 years depending on the costs of fuel (hydrogen and electricity), labor rate, and the use rate of the forklifts.

It is also essential to note that government subsidies incentivize and motivate industry to adopt fuel-cell-powered technologies for MHE; without these subsidies, the growth of this market, which is starting to become sustainable, may be hindered. As one end user noted, these types of projects need every source of income possible to move through the pilot phase toward the break even point.

10.3 Sensitivity and Future Market Impact

The sensitivity analysis indicates that eliminating the DC/DC converter as learned from one of the manufacturers reduces the overall system cost by 12%. BOP components such as the DC/DC converter and batteries contribute to a sizeable portion of the system price and any variation in their pricing can significantly affect the overall system price. As noted earlier, a manufacturer has been employing this strategy to bring down system costs and succeeded in doing so. Hence it is safe to say the focus of fuel cell system manufacturers would be to reduce the number of components or replace high cost ones with lower cost substitutes and to adopt a standardized system design. Section 8 also indicates that some factors, such as current density and platinum loading, which are likely to improve in the future, will have sizeable overall cost benefits. Platinum cost, which is highly variable, seems to have no effect on the overall system price.

Production volumes had a steeper effect on stack cost compared to the BOP components. This is because most of the components that constitute BOP are COTS parts with smaller price differential by volume compared to custom made stack components that are expensive at very low volumes and much cheaper at higher volumes owing to high material and machining infrastructure costs. However, increasing production volumes points towards a positive trend as material costs are much lower compared to low volume prices. Similarly, stack design parameters would be further optimized to reduce costs without compromising on power output which would result in further cost reduction.

Appendix A-1: Machine Rate with Make-Buy Calculations

The basic machine rate equation from James et al. (2014)[20] is:

$$R_M = C_{Cap}\frac{\left(F_{Inst} * F_{Cap} + F_{Maint} + F_{Misc}\right)}{T_R + T_S} + C_P * P + C_L * L$$

where:

$$F_{Cap} = \frac{\left[\frac{R_I(1+R_I)^{T_L}}{(1+R_I)^{T_L}-1}\right] - \frac{R_{Tax}}{T_L}}{[1-R_{Tax}]}$$

To calculate a baseline production station cost, we assume that the station is capable of operating three 8-hour shifts per day for 250 days per year. Therefore, total available production time for both operation and setup ($T_R + T_S$) at 100% utilization is 6,000 hours per year. The actual production time based on utilization (U) can be calculated as:

$$(T_R + T_S) = 6{,}000 * U$$

Input assumptions based on our previous work and on the assumptions shown in Table 3 of the James et al. paper[20] results in the following:

Expected equipment lifetime	20 years
Discount rate	7.00%
Corporate income tax rate	38.90%
Installation cost factor	1.4
Annual maintenance cost factor	6.00% of C_{Cap}
Annual miscellaneous cost factor	12.00% of C_{Cap}
Energy Cost	$0.07/kW-hr

F_{Cap} is calculated as:

$$F_{Cap} = \frac{\left[\frac{0.07(1+0.07)^{20}}{(1+0.07)^{20}-1}\right] - \frac{0.389}{20}}{[1-0.389]} = 0.122656$$

Total capital cost over the assumed 20-year production life is calculated as:

$$C_{Cap} = \sum_{i=1}^{n} N_i C_i \left(\left\lceil\frac{20}{L_i}\right\rceil\right)$$

[20] James B.D., Spisak A.B., and Colella W.G., 2014, "Design for Manufacturing and Assembly (DFMA) Cost Estimates of Transportation Fuel Cell Systems," *ASME Journal of Manufacturing Science and Engineering*, New York, NY: ASME, Volume 136, Issue 2, 024503.

where:

n = unique pieces of equipment making up production station

N_i = number of item i required for production station

C_i = capital cost of item i

L_i = expected life of item i

As an example, the bipolar plate compression molding station consists of the following items:

Bipolar Plate Compression Molding		**Cost**	**Units Per station**	**Expected Life (years)**
1,000-ton fast-acting press	Wabash 1000H-48	$600,000	1	20
Heated platens, 15 inches x 12 inches, 4.5 kW, controller	Custom Engineering	$12,500	1	10
Arbor or hand-operated hydraulic pre-mold press	Central Hydraulics 6-ton bench-top press w/ pump	$400	1	20
Electronic scale, industrial, gram resolution	Mettler-Toledo WM3002	$6,000	1	10
Small industrial oven	Grieve NBS-400	$1,000	1	20

Applying this information to the above equation yields the following:

Bipolar Plate Compression Molding	**N_i**	**C_i**	**L_i**	**C_{Cap}**
1,000-ton fast-acting press	1	$600,000	20	$600,000
Heated platens, 15 inches x 12 inches, 4.5 kW, controller	1	$12,500	10	$25,000
Arbor or hand-operated hydraulic pre-mold press	1	$400	20	$400
Electronic scale, industrial, gram resolution	1	$6,000	10	$12,000
Small industrial oven	1	$1,000	20	$1,000
Total				**$638,400**

Energy costs to operate the station are a function of the power required to operate each piece of equipment. For cost-estimating purposes, the total power draw of the production station can be calculated in similar fashion to the total capital cost as follows:

$$P = \sum_{i=1}^{n} N_i V_i \, A_i D_i$$

where:

n = unique pieces of equipment making up production station

N_i = number of item i required for production station

V_i = voltage supplied to item i

A_i = current draw of item i

D_i = duty cycle of item i

This yields the following:

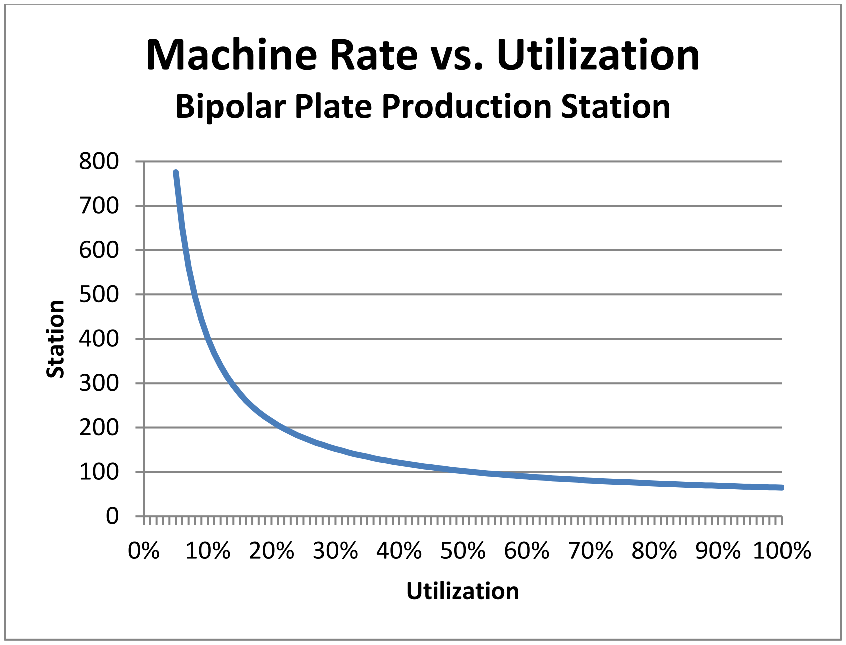
Bipolar Plate Compression Molding	N_i	V_i	A_i	D_i	P
1,000-ton fast-acting press	1	460	150	96%	66.24
Heated platens, 15"x12", 4.5 kW, controller	1	230	20	25%	1.15
Arbor or hand-operated hydraulic pre-mold press	1	0	0	10%	0.00
Electronic scale, industrial, gram resolution	1	120	0.1	100%	0.01
Small industrial oven	1	230	18	20%	0.83
Total					**68.23**

The machine rate is calculated as:

$$R_M = \$638{,}400 * \frac{(1.4 * 0.122656 + 0.06 + 0.12)}{6000 * U} + (0.07 * 68.23) + (45.00 * 0.5) = \frac{\frac{\$37.42}{hour}}{U} + 27.28$$

where: U > 0

Graphically:



Applying the above to the remaining stack production stations yields the following:

LTPEM Production Station	Baseline Cost	Power Cost (/hr)	Labor Cost (/hr)	100% Utilization Machine Rate
Bipolar Plate Compression Molding	$638,400	$1.50	$45.00	$64.70
Platinum Catalyst Preparation	$37,000	$0.01	$9.00	$11.18
Slot Die Coating	$94,892	$0.90	$22.50	$62.20
Decal Transfer	$58,400	$0.74	$22.50	$26.66
MEA Hot Pressing	$289,000	$0.80	$22.50	$52.58
Die Cutting	$125,000	$0.32	$22.50	$30.15
GDL Slit and Cut	$87,700	$0.45	$22.50	$28.09
Seal Injection Molding	$48,000	$0.72	$45.00	$26.04
End Plates	$416,000	$6.50	$90.00	$116.49
Stack Assembly	$1,310	$0.00	$45.00	$45.08
Testing and Conditioning	$300,000	$2.42	$14.85	$17.64

A-1.1 Make vs Buy Decision

As indicated in James et al. (2014)[21], at low utilizations, job shops may make parts at a lower cost by pooling orders. Additional job shop costs include the profit charged by the job shop and any overhead incurred by the manufacturer as a result of contract administration, shipping, and incoming parts

[21] Ibid.

inspection. Assuming a 65% minimum machine utilization and 40% markup for profit plus overhead, the job shop maximum machine rate becomes:

$$R_{Mjs} = 1.4 * \left[C_{CAP} \frac{(F_{Inst} * F_{Cap} + F_{Maint} + F_{Misc})}{6000 * 0.65} + C_P * P + C_L * L \right]$$

Assuming labor, energy, and capital costs are the same, the maximum job shop machine rate for the bipolar plate station above would be:

$$R_{Mjsmax} = 1.4 * \left[\frac{\frac{\$37.42}{hour}}{0.65} + \$27.28 \right] = \$118.83$$

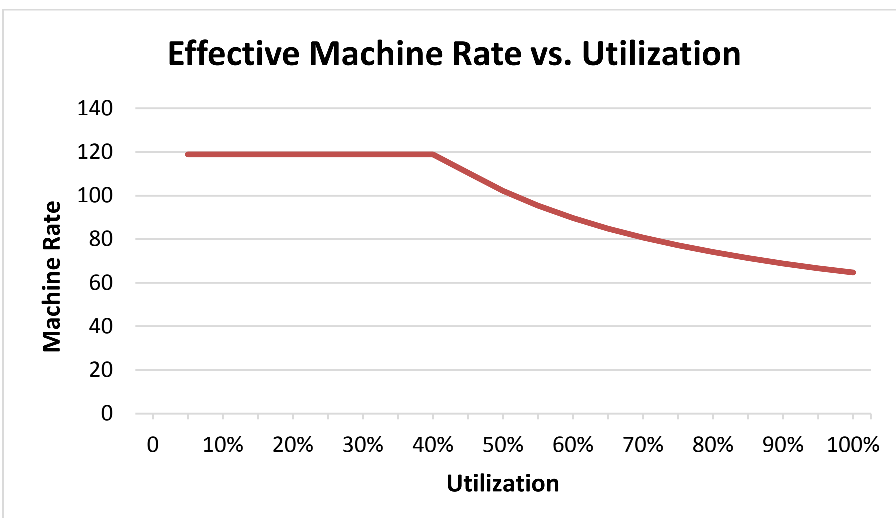
To achieve an equivalent in-house rate, the minimum utilization is:

$$R_{Mih} = \left[\frac{\frac{\$37.42}{hour}}{U} + \$27.31 \right] = \$118.83$$

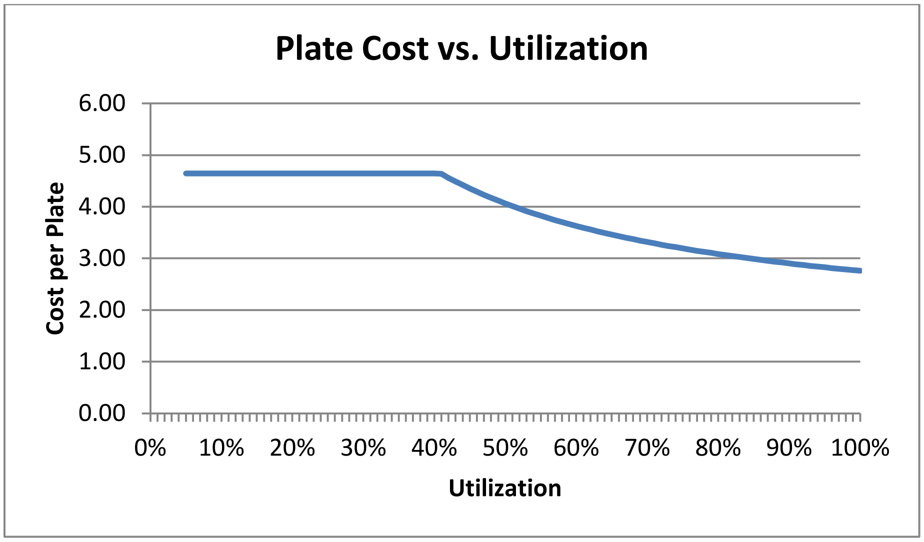
$$U = \frac{\$37.42}{(\$118.83 - \$27.31)} = 0.409$$

In other words, for utilization rates of less than 40.9%, bipolar plate manufacturing should be subcontracted to a job shop instead of incurring the costs of manufacturing the plates in-house.

It should be noted that the make-buy strategy outlined above results in a discontinuity in the machine rate curve (and, by extension, the total cost curve) since the job shop machine rate is unchanged up to the critical utilization rate of 40.9%, as shown below.



This can be further illustrated by estimating the production per unit for bipolar plates. Each anode bipolar plate for an 11.5-kW stack contains 0.244 kilogram (kg) of BMC940 composite. Material cost for a purchase quantity Q is computed using the formula presented in Appendix A-2. The throughput of the process is 90 parts/hour, yielding a maximum annual capacity of 540,000 plates per year, and requires 0.5 operator hour per machine hour. Using the above equations, the bipolar plate unit cost as a function of station utilization is shown below:



Where multiple processes are closely coupled due to timing or handling constraints, the make-buy decision needs to consider the overall cost of the entire process train and not just the cost of individual processes within the train. In cases like these, the entire cost of the process train needs to be computed for both in-house and outsourced manufacturing costs using the following formula:

$$C_m = \sum_{i=1}^{n} R_{m_i} T_{m_i}$$

where:

C_m = process train manufacturing cost

R_{mi} = machine rate for process i

T_{mi} = machine time for process i

n = number of processes

A similar situation arises when a single machine can be used for multiple processes, such as a slot die coater that can be used for both anode and cathode catalyst deposition. In this case, the utilization used in the machine rate calculation is total time required to complete all of the processes divided by the total machine time available:

$$U_m = \frac{\sum_{i=1}^{n} T_{p_i}}{T_R + T_S}$$

where:

U_m = utilization of machine m

T_{pi} = time to complete process i

T_R = total annual run time

T_S = total annual setup time

n = number of processes using machine m

Appendix A-2: Material Cost Learning Curve Calculations Documentation

A-2.1 Background

In general, material cost on a per-unit basis (e.g., per kilogram [kg], per square meter [m^2]) decreases with increasing purchase volumes, due primarily to the manufacturer's ability to produce larger volumes of material from a single production run setup. It has been noted in previous work that material cost estimates at various discrete purchase volumes could be estimated for the intermediate volumes using a learning curve analysis.

From the *Cost Estimator's Reference Manual* (1995),[22] the general learning curve equation is:

$$Y = AX^b$$

where:

Y = time or cost per cycle or unit

A = time or cost for first cycle or unit

X = number of cycles or units

b = log(m)/log(2)
m = slope of learning curve

If the material production is "learned" after 10,000 units (i.e., no substantial discounts are available for higher-volume purchases), then the cost Y in the learning curve equation is the cost of the 10,000th unit.

A-2.2 Preliminary Analysis

Where possible, quotes were obtained from both domestic and international suppliers for the materials. Other material costs were obtained from previous third-party fuel cell manufacturing analysis reports.

Some materials, such as the silicone gasket material, are considered commodity items for which manufacturing processes are well established and supplies are high enough to support most available demand. One supplier provided a quote for liquid silicone material of $7.00 to $7.50 per pound ($15.40 to $16.50 per kilogram) for quantities ranging from 250 to 25,000 pounds.

For these materials, the cost curve is very flat, which means the value of m in the learning curve equation is high. Iteration using the costs above led to a value of m=0.99, which results in:

$$b = \log(0.99)/\log(2) = -0.0154$$

[22] Stewart, R.D., Wyskida, R.M., Johannes, J.D. (eds). 1995. Cost Estimator's Reference Manual, 2nd Ed. Wiley-Interscience, April 1995. 744 p.

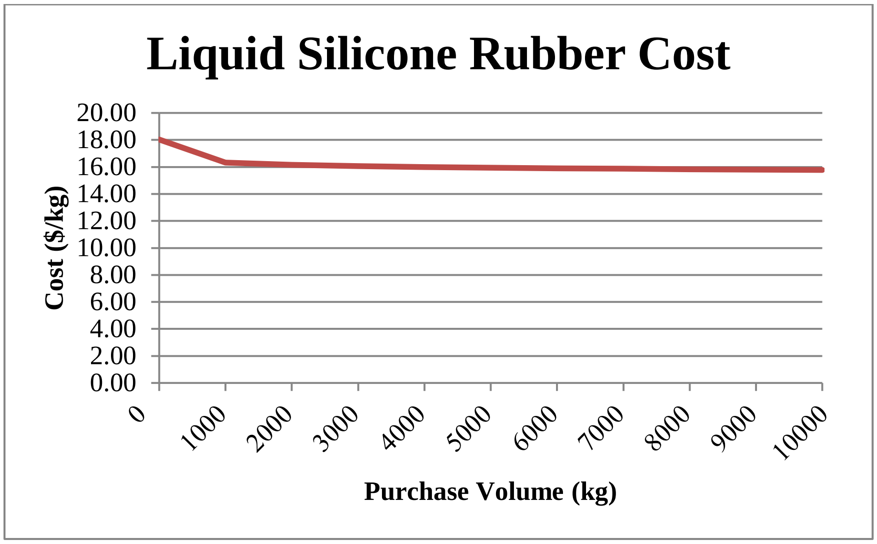
Using a learned cost of \$15.40/kg for a volume of 55,000 kg, then the cost of the first unit is:

$$A = Y / X^b = 15.40 / 55{,}000^{(-0.0145)} = \$18.04$$

For a purchase of 250 kg of material, the calculated cost per unit is:

$$Y = A \times X^b = 18.04 \times 250^{(-0.0145)} = \$16.65$$

The corresponding cost chart would appear as:



For specialty materials, like the polytetrafluoroethylene (PTFE)/ionomer membrane, the cost curve is steeper. One supplier provided low-volume quotes of \$535.63/m^2 for 3 m^2, and \$313.13/m^2 for 45 m^2. Estimates obtained from previous fuel cell manufacturing cost analyses estimated high-volume costs to be in the range of \$50.00/m^2 for volumes up to 150,000 m^2. Iteration using the costs above led to a value of m=0.86, which results in:

$$b = \log(0.86)/\log(2) = -0.21759$$

Using a learned cost of \$56.00/m^2 for a volume of 100,000 m^2, then the cost of the first unit is:

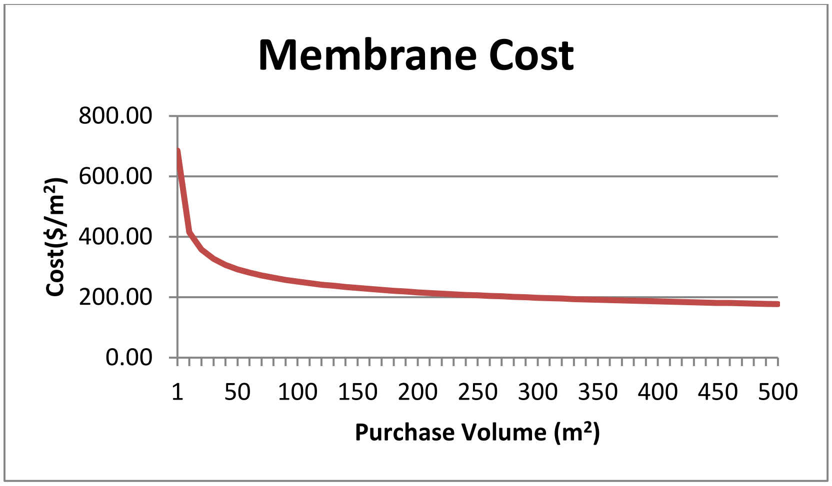
$$A = Y / X^b = 50.00 / 150{,}000^{(-0.21759)} = \$668.72$$

For a purchase of 40 and 100 m^2 of material, the calculated cost per unit is:

$$Y_{40} = A \times X^b = 685.72 \times 3^{(-0.\ 21759)} = \$526.53$$

$$Y_{100} = A \times X^b = 685.72 \times 45^{(-0.\ 21759)} = \$292.09$$

The corresponding cost chart would appear as:



Using the above approach, the following learning curve parameters were used for the cost analysis:

PEM Material	Unit	Y	X	m	b	A
Platinum	kg	$41,602.00	1	1.00	0.0000	$41,602.00
XC-72	kg	$0.90	1,000	0.95	-0.0740	$1.50
DE-521	kg	$90.00	100,000	0.85	-0.2345	$1,338.35
DI Water	kg	$0.10	160	0.85	-0.2345	$0.33
Methanol	kg	$0.55	10,000	0.95	-0.0740	$1.09
Membrane	m^2	$50.00	150,000	0.86	-0.2176	$668.72
Polyester Film	m^2	$0.32	30,000	0.55	-0.8625	$2,289.88
GDL	m^2	$78.00	100,000	0.69	-0.5353	$37,047.02
LSR	kg	$15.40	55,000	0.99	-0.0145	$18.04
BMC 940	kg	$2.43	1,100	0.85	-0.2345	$12.55
A356 Aluminum	kg	$2.50	1,000	0.97	-0.0439	$3.39
Hydrogen	m^3	$5.93	30,000	0.80	-0.3219	$163.82

A-2.3 High-Quantity Purchased Material Cost

For the annual system volumes used, the material purchase volume can be extremely large. For example, to manufacture bipolar plates for 50,000 28.75-kilowatt (kW) stacks requires more than 4,500 metric tons of BMC940 material. According to the learning curve equation, a bulk purchase of this size would cost $0.36/kg—a cost that is most likely unachievable and therefore unrealistic.

To address this problem, we have elected to assume that any additional volume discounts beyond the bulk pricing represented by the cost Y and quantity X in the above table would be no more than that achieved by doubling the quantity X. Since the learning curve slope (m) represents the amount of reduction in Y when quantity X is doubled, the minimum material price is simply Y×m. Therefore, the material price for a given purchase quantity (q) is calculated as:

$$Y_q = \text{Max}(A \times X^b, Y \times m)$$

For the bipolar plate material, the equation above yields:

$$Y_q = \text{Max}(12.55 \times (4\times10^6)^{-0.2345}, 2.43 \times 0.85) = \text{Max}(0.188, 2.065) = \$2.065$$

A-2.4 Special Cases

Platinum prices are dictated by the precious metals spot markets and are generally not subject to purchase volume reductions. This corresponds to a learning curve slope value of m = 1.

The polyester film would seem to be a material that would have a commodity price profile like that of the silicone sheet. However, price quotes received showed relatively high cost at low purchase volumes of less than 100 m^2, but fell by over 97% at bulk purchase volumes greater than 14,000 m^2.

Appendix A-3: Platinum Catalyst Membrane Coating Process

A-3.1 Model Approach

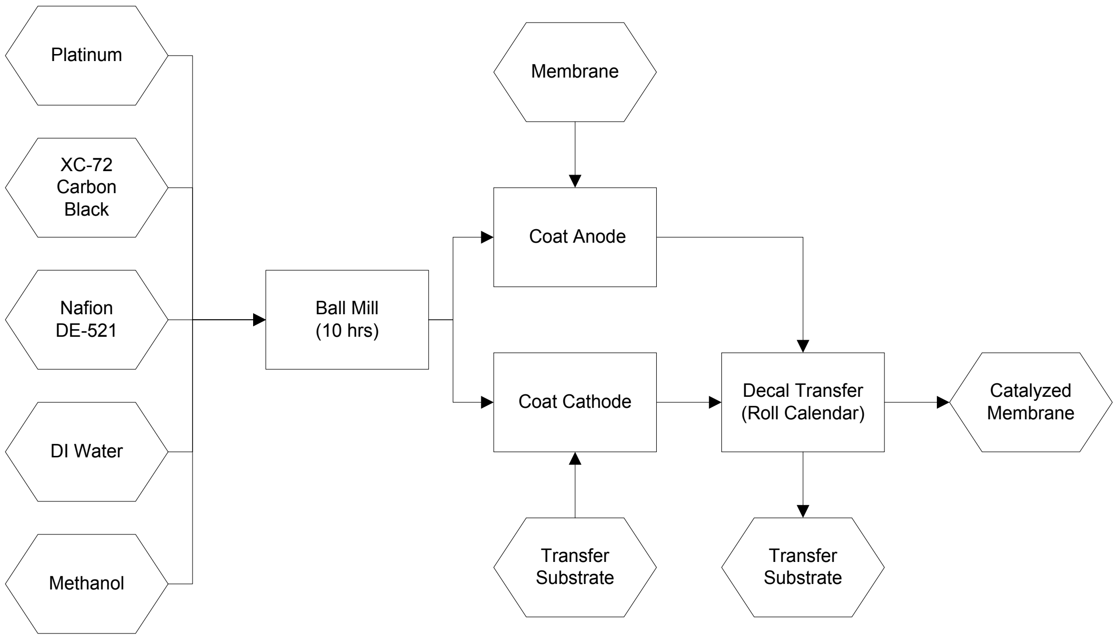
- Catalyst ink preparation operation
  - Compute machine setup labor time based on user input
  - Compute required batch size based on part batch size and catalyst loading
  - Compute catalyst ink material unit cost based on usage
  - Compute catalyst ink processing time and machine utilization

- Anode catalyst ink slot die deposition to membrane operation
  - Compute processing time based on production size and substrate speed
  - Compute number of setups based on purchased roll length
  - Compute setup labor time based on user input and number of setups required
  - Compute material unit cost based on usage
  - Compute required heater area based on drying time and substrate speed
  - Compute total anode ink deposition processing time and machine utilization

- Cathode catalyst ink slot die deposition to transfer substrate operation
  - Compute processing time based on batch size and substrate speed
  - Compute number of setups based on purchased roll length
  - Compute setup labor time based on user input and number of setups required
  - Compute material unit cost based on usage
  - Compute required heater area based on drying time and substrate speed
  - Compute total cathode ink deposition processing time and machine utilization

- Cathode catalyst ink decal transfer calendaring operation
  - Compute processing time based on batch size and substrate speed
  - Compute number of setups based on purchased roll length
  - Compute setup labor time based on user input and number of setups required
  - Compute required heater area based on heating time and substrate speed
  - Compute decal transfer processing time and machine utilization

A-3.2 Process Flow



A-3.3 Background

U.S. patent no. 7,141,270 specified a wet platinum (Pt) catalyst composition of:

- 6 wt% Pt
- 9 wt% Vulcan XC-72 (carbon black)
- 72 wt% Nafion DE-521 solution (5 wt% Nafion)
- 6.5 wt% deionized (DI) water
- 6.5 wt% methanol

Assuming that all solvents are driven off during the drying process, the dry catalyst consists of:

- 48.4 wt% Vulcan XC-72 (carbon black)
- 32.3 wt% Pt
- 19.4 wt% Nafion

Technical literature and conversations with stack manufacturers indicate that ball milling is used as the primary means of grinding and homogenizing the catalyst ink, with milling times reported in the range of 4 hours to “overnight.” U.S. patent no. 6,187,468 details a two-step preparation process of mixing (milling) for 60 to 300 minutes, followed by 30 to 300 minutes in a “three-dimensional vibrating stirrer.” Constant processing in a regular or planetary ball mill for 8 to 10 hours may suffice for both the mixing and stirring parts of the process.

Manufacturers noted that there are significant losses during the ink production process, which tends to occur when handling ink/slurry from one part of the process to the next (e.g., transfer of final composition from mixing vessel to catalyst application method apparatus), but that much of the platinum was subsequently recovered, reducing the platinum scrap rate to 1% or less.

In the past, low-volume catalyst application was performed using screen printing, but the current process is generally done roll to roll. At least one approach involves a two-step process. One catalyst layer is applied directly to the membrane, and the other catalyst layer is applied to a low-cost substrate material. The membrane is then turned over, and the second catalyst layer is applied by hot press decal transfer.

W. L. Gore and Associates, makers of Gore-Tex®, has proposed a three-step membrane electrode assembly (MEA) manufacturing process that involves sequential roll-to-roll coating (see https://www.hydrogen.energy.gov/pdfs/progress14/vi_2_busby_2014.pdf for details). The catalyst ink is applied to a backing material, dried, and re-rolled. The membrane is then applied to the first catalyst layer using a co-extrusion deposition, which is dried and re-rolled. Catalyst ink is then applied to the membrane layer, dried, and re-rolled. The three-layer MEA would then move to the hot-pressing operation to apply the gas diffusion layer (GDL).

The method selected for evaluation involves using a slot-die patch coating process (see www.frontierindustrial.com), where anode catalyst is applied to the membrane and the cathode catalyst is applied to a transfer substrate in rectangular patches sized to the active area. The cathode catalyst patches are then bonded to the membrane using hot press decal transfer, followed by the hot-pressing operation to apply the GDL.

A-3.4 Preliminary Analysis

A-3.4.1 Batch volume

Catalyst batch volume depends on the coated area, catalyst loading, and maximum catalyst batch size.

The cells for this analysis will have an active area size of:

125 millimeter (mm) width $\times$ 160 mm length = 200 square centimeters (cm^2)

Material densities for the catalyst components are as follows:

- $\rho(Pt) = 21.45$ grams per cubic centimeter (g/cm^3)
- $\rho(XC\text{-}72) = 0.264\ g/cm^3$
- $\rho(\text{Nafion DE-521}) = 1.05\ g/cm^3$
- $\rho(\text{DI water}) = 1.0\ g/cm^3$
- $\rho(\text{methanol}) = 0.792\ g/cm^3$

Based on the wet platinum catalyst composition as specified above, 100 grams of wet catalyst contains 6 grams of Pt and has a volume of:

$$v = (6/21.45) + (9/0.264) + (72/1.05) + (6.5/0.792) + (6.5/1) = 117.6\ cm^3$$

Yielding a wet catalyst density of:

$$\rho(\text{wet catalyst}) = (100/117.6) = 0.85\ g/cm^3$$

The Pt content of the wet catalyst is:

$$m(Pt)/\ v(\text{wet catalyst}) = 6/117.6 = 0.051\ g/cm^3 = 51\ mg/cm^3$$

To obtain a loading of 1 mg/cm^2, the depth of the wet catalyst layer is:

$$d(\text{wet catalyst}) = 1/51 = 0.02\ cm = 200\ \text{microns}$$

Based on the dry platinum catalyst composition as specified above, 100 grams of dry catalyst contains 32.3 grams of Pt and has a volume of:

$$v = (32.3/21.45) + (48.4/0.264) + (19.4/1.05) = 203.3\ cm^3$$

Yielding a dry catalyst density of:

$$\rho(\text{dry catalyst}) = (100/203.3) = 0.492\ g/cm^3$$

The Pt content of the dry catalyst is:

$$m(Pt)/v(\text{dry catalyst}) = 32.3/203.3 = 0.166\ g/cm^3 = 159\ mg/cm^3$$

To obtain a loading of 1 mg/cm^2, the depth of the dry catalyst layer is:

$$d(\text{dry catalyst}) = 1/159 = 0.006\ cm = 63\ \text{microns}$$

The total Pt loading for this design is 0.4 milligram per square centimeter (mg/cm^2) with cathode loading in a 2:1 ratio relative to anode loading, making the loadings 0.27 mg/cm^2 and 0.13 mg/cm^2 for the cathode and anode, respectively. This will require wet deposition to depths of 53 and 27 microns, respectively, resulting in dry layer depths of 16 and 9 microns. Therefore, to coat both sides of the membrane with a total loading 0.4 mg/cm^2 will require a total coated depth of 80 microns (0.008 cm):

$$\text{Wet catalyst weight} = 0.85\ g/cm^3 \times (200 \times 0.008)\ cm^3 = 1.36\ g/\text{part}$$

The 11.5-kilowatt (kW) stack requires 106 cells. Based on producing 1,000 stacks per year, the required annual production before scrap is:

$$\text{Annual production} = 106\ \text{parts/stack} \times 1{,}000\ \text{stacks} = 106{,}000\ \text{parts}$$

$$\text{Catalyst batch size} = 106{,}000\ \text{parts} \times 1.36\ g/\text{part} \times 0.001\ kg/g = 144.16\ kg$$

A-3.4.2 Catalyst Ink Material Cost

Material cost of the ink is calculated using the weight percents of the slurry constituents multiplied by the raw material cost to determine a cost per kilogram. Material pricing was obtained from suppliers and supplier web sites in February 2014. Platinum cost is very volatile, with a 3-year monthly range of $1,677/tr.oz. to $832/tr.oz. For this analysis, we will assume a price equal to the 3-year average of $1,294/tr.oz. ($41,602/kg). Bulk costs for DE-521 were estimated at $90/kg at quantities of 100 MT. Bulk costs for XC-72 catalyst-grade carbon black was quoted by WeiKu Information and Technology and others at around $900 per metric ton (MT) ($0.90/kg). Bulk cost for methanol was quoted by Methanex and others at around $550/MT ($0.55/kg). The cost of DI water is based on amortized distillation costs obtained from www.apswater.com.

The weight of each material contained in the catalyst is:

- Platinum: 0.06 × 144.16 kg = 8.65 kg
- Nafion DE-521: 0.72 × 144.16 kg = 103.80 kg
- Vulcan XC-72: 0.09 × 144.16 kg = 12.97 kg
- Methanol: 0.065 × 144.16 kg = 9.37 kg
- DI water: 0.065 × 144.16 kg = 9.37 kg

Using the above quotes, learning curve analysis in accordance with Appendix A-2 was applied to determine the following material costs:

- Platinum = $41,602/kg
- Nafion DE-521 = $447.99/kg
- Vulcan XC-72 = $1.24/kg
- Methanol = $0.920/kg
- DI water = $0.0.191/kg

The cost of the ink is:

Material cost = (0.06 × 41,602) + (0.72 × 447.99) + (0.09 × 1.24) + (0.065 × 0.920) + (0.065 × 0.0.191)

Material cost = $2,897.06/kg = $2.897/g

Total annual catalyst material cost before scrap is:

$2,818.86/kg × 144.16 kg = $406,366

A-3.4.3 Catalyst Ink Processing

The first step is to weigh the materials out and place them in the mill. We will assume a manual process consisting of a measurement step and a material handling step. The Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA®) software contains an analogous operation for off-line precision measurement with a default value of 17.4 seconds for the measurement, and a minimum of 4 seconds for material handling. The catalyst ink is made up of five materials, so total handling time for material preparation can be estimated as:

Material prep time = 5 × 21.4 sec = 107 sec = 1.8 minutes

The primary cost for operating the ball mill is the energy input to the motor running the mill. Some studies have considered the cost of operating large ball mills used for cement and powder metallurgy material processing, where the target parameter is the amount of energy required to process a given amount of material, usually expressed in kilowatt-hours (kW-hr) per ton. The calculations are complex owing to the large number of inputs.

In “Technical Notes 8, Grinding,” R.P. King develops a relationship based on fundamental physical models of ball mill processing. (see http://www.mineraltech.com/MODSIM/ModsimTraining/Module6/Grinding.pdf). He assumes a 35%

volumetric loading ratio, of which milling balls represents 10% of the total charge volume. Given a mill with diameter *d* and length *l*, the total catalyst charge volume is:

$$\text{Catalyst charge volume} = (\pi \times d^2 / 4) \times l \times 0.35 \times 0.9 = 0.079\ \pi\ d^2 l\ m^3$$

Patterson Industries offers simple torque drive batch ball mills in 42-inch *d* × 48-inch *l* (1.067-meter *d* × 1.219-meter *l*), and 48-inch *d* × 60-inch *l* (1.219-meter *d* × 1.524-meter *l*). These provide maximum catalyst charge volumes of:

$$V = 0.079 \times \pi \times (1.067)^2 \times 1.219 = 295\ kg$$

$$V = 0.079 \times \pi \times (1.219)^2 \times 1.524 = 482\ kg$$

We note that production levels of 1,000 stacks per year will require 144.16 kg of catalyst production per year, or only one batch per year in the smaller mill.

King presents a log-log plot showing that a mill with a diameter of 1 meter will consume about 10 kW of power, where a mill with a diameter of 2 meters consumes about 100 kW. These two values yield the equation:

$$\text{Power} = 10d^{3.32}\ kW$$

To estimate the power required to process a batch of catalyst with a density of 850 kilograms per cubic meter (kg/m^3), we plug the mill diameter into the power equation to obtain:

$$\text{Power} = 10 \times (1.067)^{3.32} = 12.4\ kW$$

Once processing is complete, the catalyst ink will need to be separated from the milling balls and transferred to the coating machine. While we currently have no information about this part of the process, one approach would be the use of a vacuum sieve (e.g., Farleygreene, Ltd. SM950 Sievmaster Vacu-siev) to remove and separate the catalyst ink from the mill, and transfer the ink to a transport container or directly to the coater reservoir.

ShopVac reports a sealed suction of 54 inches of water (in-H_2O) (13.4 kilopascals [kPa]) for its 2-horsepower [HP] (1.5-kW) unit. Using an equivalent vacuum sieve with a 1.5-inch (0.038-meter) diameter hose and 80% transfer efficiency, the flow rate is:

$$\text{Flow rate} = 0.8 \times (\pi \times (0.038)^2 / 4) \times (2 \times 13.4 / 850)^{1/2} = 0.00016 \text{ cubic meters per second } (m^3/sec)$$

Since the catalyst forms 90% of the charge volume, the total charge volume of

$$\text{Charge volume } (m^3) = 1.11 \times (\text{catalyst weight (kg) / catalyst density } (kg/\ m^3))$$

$$\text{Charge volume } (m^3) = 0.0013 \times \text{catalyst weight}$$

Therefore, the optimal time required to remove the charge volume is:

$$\text{Material removal time (sec)} = \text{Charge volume / Flow rate} = 8.1 \times \text{Catalyst weight}$$

The optimal time to remove a full charge of catalyst from the mill would be:

Material removal time = 8.1 $\times$ 144.16 = 1,168 sec = 19.5 minutes

We will estimate the total transfer time to remove the ink from the mill and transfer it to the coater as twice the ink removal time.

The estimated total processing time is calculated as the sum of the setup time, material prep time, milling time, and transfer time, multiplied by the total number of batches processed for annual production of 144.16 kg of catalyst:

Process time = 1 batch $\times$ (10 + 0.5 + (1.8 / 60) + (2 $\times$ (19.5 / 60))) hrs = 11.18 hrs

Given an availability of 6,000 hours per year per machine, the number of mills required is:

Roundup(11.18 / 6,000) = 1 mill

Machine utilization is:

11.18 / 6,000 = 0.19%

Machine rate was determined in accordance with Appendix A-1 as:

In-house rate = $11.18 / 0.0019 = $5,884.21

Job shop rate = 1.4 $\times$ ($11.18 / 0.65) = $24.08

A-3.4.4 Catalyst Ink Deposition

As indicated previously, one approach to catalyst deposition involves a two-step process. The anode catalyst is applied to the membrane and the cathode catalyst applied to a transfer substrate in rectangular patches sized to the active area. The cathode catalyst patches are then bonded to the membrane using hot press decal transfer. Both the membrane application and decal creation are direct deposition processes to a substrate material; one being to the membrane itself, and the other to a carrier substrate, commonly a polyester or polyimide material. The patches will be centered in the full cell size envelope of 185 mm $\times$ 220 mm.

We will assume a roll-to-roll slot die application process. Depending on the roll length and width, multiple machine setups may be required to process the material for an entire production run. The length of material being processed is a function of the batch size and the number of parts that can be produced across the material width. Assuming no cutting margin for rectangular MEAs, the optimal part orientation can be determined based on the fraction of material width left over as waste as:

Number of lengthwise parts = INT(Roll width / Part length)

Lengthwise waste fraction = (Roll width / Part length) - Number of lengthwise parts

A-3.4.4.1 Material Cost

Membrane material is sold in widths of 12 inches (0.305 meter) and 24 inches (0.610 meter) with lengths of 50 or 100 meters. Common thin films (polyimide, polyethylene) used as transfer media tend to be either 0.4 or 0.8 meters, while lengths can be found up to a maximum of about 1,000 meters. GDL material is typically sold in either 0.4- or 0.8-meter widths and is available up to a maximum of 800-meter lengths.

The membrane roll has the smallest standard width, so it will be used to determine the maximum coating width with minimum scrap. Because the 11.5-kW cells are rectangular, orientation is an important issue in terms of minimizing scrap. Three widthwise cells will take up 555 mm of membrane width, while 2 lengthwise cells will take up 440 mm of membrane width, so the widthwise orientation will result in less overall scrap. The material length required will be:

> Material length = (106,000 parts / 3 part widths/part length) × 220 mm part length / 1,000 = 7,773.3 meters

The total material area required before scrap is:

> Membrane area = 7,773.3 meters (m) × 0.610 m = 4,741.7 m^2
>
> Transfer substrate area = 7,773.3 m × 0.8 m = 6,218.64 m^2

Using learning curve analysis in accordance with Appendix A-2, the material cost before scrap can be estimated as:

> Membrane cost = \$105.44/m^3
>
> Transfer substrate cost = \$1.20/m^3

Slot die coating machine setup consists of loading and threading the substrate, and loading the catalyst ink into the reservoir. For costing purposes, we will take the setup time as a user input and assume a value of 0.5 hour. Bulk roll stock is available in 100-meter length for the membrane, and 1,000-meter length for the transfer substrate, so the number of setups required to run 42,000 parts is:

> Number of setups = Roundup(Carrier length (m) / Roll length (m))
>
> Membrane: Number of setups = Roundup (7,773.3 / 100) = 78
>
> Transfer substrate: Number of setups = Roundup (7,773.3 / 1,000) = 8

A-3.4.4.2 Slot Die Coating

Slot die coating is capable of very thin coating thicknesses. The coated material passes through the slot die at a speed determined by the rheology of the coating material and the thickness of the application. While the precise rheology of the catalyst ink is not known, we can estimate the substrate speed using the tape casting estimating formula as follows:

> Maximum coating speed = 157.18 × 0.987$^{\text{coating thickness (µm)}}$ mm/sec

The wet coating thickness was calculated above as 200 microns per 1 mg/cm^2 of platinum loading. The cathode/anode coating ratio is assumed to be 2:1. For a total loading of 0.4 mg/cm^2 of platinum, the anode will be coated to a depth of 27 microns, while the cathode will be coated to a depth of 53 microns, making the maximum coating speeds:

Anode maximum coating speed = 157.18 × 0.987^{27} = 110.40 mm/sec = 6.624 meters per minute (m/min)

Cathode maximum coating speed = 157.18 × 0.987^{53} = 78.56 mm/sec = 4.714 m/min

Part throughput is calculated as:

Throughput (parts/hour) = Coating speed (m/min) × Parts per part length (parts) / Part length (m) × 60 min/hour

Anode: Throughput = 6.624 × 3 / (220 / 1,000) × 60 = 5,419.6 parts/hour

Cathode: Throughput = 4.714 × 3 / (220 / 1,000) × 60 = 3,856.9 parts/hour

Total machine time to set up and produce 106,000 parts is:

Anode machine time = (78 setups × 0.5 hour/setup) + (106,000 parts / 5,419.6 parts/hour) = 58.56 hours

Cathode machine time = (8 setups × 0.5 hour/setup) + (106,000 parts / 3,856.9 parts/hour) = 31.48 hours

Given an availability of 6,000 hours per year per machine, the number of coating systems required is:

Roundup ((58.56 + 31.48) / 6,000) = 1 coater

Machine utilization is:

(58.56 + 31.48) / 6,000 = 1.5%

Machine rate was determined in accordance with Appendix A-1 as:

In-house rate = $62.20 / 0.015 = $4,146.67

Job shop rate = 1.4 × ($62.20 / 0.65) = $133.97

A-3.4.4.3 Tooling Cost

Slot dies are precision machined and assembled to provide uniform coating thickness. The cost can vary widely depending on the coating fluid properties and die size. Frontier Industries estimates a stainless steel fixed die cost of $14,000. The slot die can deliver approximately 100,000 parts before refurbishment, which costs around $3,500. Assuming four refurbishments before scrapping, and amortizing over a 5-year production life, the total annual tooling cost is:

$$\text{Annual tooling cost} = \frac{1}{5}(\text{Tooling cost} \times \text{Number of tools purchased})$$

where:

Number of tools purchased = Roundup(Total production / Tool life)
Total production = Annual production × 5

Anode annual tooling cost = $\frac{1}{5}$ ((\$14,000 + (4 × \$3,500)) × Roundup((106,000 parts/year × 5 years) / 500,000 parts/tool)) = \$11,200

Cathode annual tooling cost = $\frac{1}{5}$ ((\$14,000 + (4 × \$3,500)) × Roundup((106,000 parts/year × 5 years) / 500,000 parts/tool)) = \$11,200

A-3.4.5 Catalyst Ink Drying

Following deposition, the catalyst ink is dried, usually by a tunnel dryer positioned directly after the deposition step. The drying can be done by either radiant or convective heating. For the cost analysis, we will assume radiant (infrared) heating and compute the cost of drying by determining the required heater area based on the substrate speed and the drying time.

Infrared (IR) heating panels are generally sold in standard-sized units with various energy watt densities and are assembled to provide the necessary heating area. Using the Casso-Solar Type FB as an example, standard watt densities are 15 and 25 watts per square inch (W/in^2) (23 and 39 kW/m^2) with standard width of 12 inches (0.305 meter) and lengths in 12-inch increments up to 60 inches (1.524 meters). Casso-Solar notes that 25 W/in^2 corresponds to an emitter temperature of 880°C, and that the conversion efficiency of electrical power to usable radiant energy is up to 80%.

Drying time is a function of the evaporation rate of the solvent and is inversely and exponentially proportional to the coating thickness. Experiments conducted by Mistler et al. (1978)[23] indicate drying rates of 1.35×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 2 liters/min, and 2.22×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 75 liters/min.

The change in density from wet to dry catalyst is 0.335 g/cm^3, making the liquid removed per unit area a function of coating thickness as follows:

Anode liquid removed per area = 0.335 g/cm^3 × 0.0027 cm = 0.0009 g/cm^2

Cathode liquid removed per area = 0.335 g/cm^3 × 0.0053 cm = 0.0018 g/cm^2

For costing purposes, we will take drying time as an input and use the substrate speed and part width to compute the theoretical required heater area.

Heater area = Drying time (min) × Substrate speed (m/min) × (Part width (mm) / 1,000) × Parts across width

[23] Mistler, R.E., Shanefield, D.J., Runk, R.B. 1978. Tape casting of ceramics, in *Ceramic Processing Before Firing*, Onoda, G.Y. Jr. and Hench, L.L. (eds). John Wiley and Sons, New York.

At a rate of 2.0×10^{-5} g/cm^2-sec drying rate, the estimated drying time is:

Anode drying time = 0.0009 g/cm^2 / 2.0×10^{-5} g/cm^2-sec = 45 sec = 0.75 min

Cathode drying time = 0.0018 g/cm^2 / 2.0×10^{-5} g/cm^2-sec = 90 sec = 1.50 min

The required dryer length is:

Anode dryer length = 0.75 min × 6.624 m/min = 4.97 m

Cathode dryer length = 1.50 min × 4.714 m/min = 7.07 m

Sizing for the maximum dryer length, and assuming 12-inch × 36-inch panels fitted two across the drying conveyor, we require 14 total IR panels.

A-3.4.6 Catalyst Layer Decal Transfer

The roll-to-roll decal transfer operation can be either a semi-continuous process, where the material is indexed into a standard heated platen press (see James et al. [2010], Section 4.4.6.1),[24] or a calendaring process, where the material is preheated and passed through heated rollers. For the preliminary analysis, we will assume a calendaring process.

A-3.4.6.1 Setup

Decal transfer setup consists of loading, threading, and aligning the anode and cathode into the calendaring rollers. For costing purposes, we will take the setup time as a user input and assume a value of 0.5 hour. The number of setups is a function of the shortest roll stock length, so that the number of setups to run 42,000 parts is the same as the number of setups for the anode slot die coating:

Number of setups = 78

A-3.4.6.2 Calendaring

The calendaring process consists of two main steps: preheating and rolling. We will assume that the coated membrane and decal catalyst layers are brought together and passed through an IR tunnel oven for preheating. If the two layers need to reach 100°C (and noting that 1 W = 1 joule per second [J/sec]), we can estimate the oven dwell time as:

Oven dwell time = Part weight (g) × Part specific heat (J/g-°C) × Temperature rise (°C) / Energy input (W)

If we assume that the same IR heaters used for drying are used for preheating, the energy rate impinging on the part is:

Energy input = Heater watt density (W/cm^2) × Part area (cm^2) × Energy transfer efficiency

Energy input = 2.3 W/cm^2 × 200 cm^2 × 0.80 = 368 W/part

[24] James, B.D., Kalinoski, J.A., and Baum, K.N. 2010. *Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications: 2010 Update.* NREL Report No. SR-5600-49933. Directed Technologies, Inc. Available at https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/dti_80kwW_fc_system_cost_analysis_report_2010.pdf

Common polymers (polytetrafluoroethylene [PTFE], polyester, polyimide) have specific heats (in joules per gram) in the range of 1.1 to 1.3 J/g-°C and densities around 2.2 g/cm^3. Specific heat capacities of the dry catalyst constituents are:

- Nafion: 4.2 J/g-°C
- Pt: 0.13 J/g-°C
- Carbon black: 4.18 J/g-°C

The specific heat of the catalyst is:

Catalyst specific heat = (0.194 × 4.2) + (0.323 × 0.13) + (0.484 × 4.18) = 2.88 J/g-°C

The volumes of dry catalyst for the anode and cathode per part are:

Anode dry catalyst volume = 200 cm^2 × 0.0009 cm = 0.18 cm^3

Cathode dry catalyst volume = 200 cm^2 × 0.0016 cm = 0.320 cm^3

The volume of substrate material (75-micron thickness) per part is:

Membrane volume = 200 cm^2 × 0.0075 cm = 1.50 cm^3

The heating dwell time for each is then (dry catalyst density = 0.492 g/cm^3):

Anode oven dwell time = ((2.2 g/cm^3 × 1.50 cm^3 × 1.2 J/g-°C) + (0.492 g/cm^3 × 0.18 cm^3 × 2.88 J/g-°C)) × 75°C / 368 W = 0.856 sec/part

Cathode oven dwell time = ((2.2 g/cm^3 × 1.50 cm^3 × 1.2 J/g-°C) + (0.492 g/cm^3 × 0.32 cm^3 × 2.88 J/g-°C)) × 75°C / 368 W = 0.366 sec/part

For the calendaring process, the layers will be moving together, so the worst-case heating time of 0.856 second is used to determine the required oven length. At a substrate speed of 5 meters per minute (m/min) (8.33 cm/sec), the required heating length is about 0.071 meter, which can be accomplished using four 12-inch by 24-inch IR panels (two for each layer).

At 5 m/min (300 m/hour), part throughput is:

Parts per hour = 300 m/hour / 0.220 m × 3 parts per width = 4,090.9 parts/hour

Once the material layers are preheated, they are compressed between steel rollers that bond the catalyst decal layer to the membrane. The decal substrate is then peeled away from the decal layer and collected on a roll or in a bin. Total machine time to set up and produce 42,000 parts is:

Decal transfer machine time = (78 setups × 0.5 hour/setup) + (106,000 parts / 4,090.9 parts/hour) = 64.91 hours

Given an availability of 6,000 hours per year per machine, the number of coating systems required is:

Roundup(64.91 / 6,000) = 1 calendar machine

Machine utilization is:

64.91 / 6,000 = 1.08%

Machine rate was determined in accordance with Appendix A-1 as:

In-house rate = \$26.66 / 0.0108 = \$2,468.52

Job shop rate = 1.4 × (\$26.66 / 0.65) = \$57.42

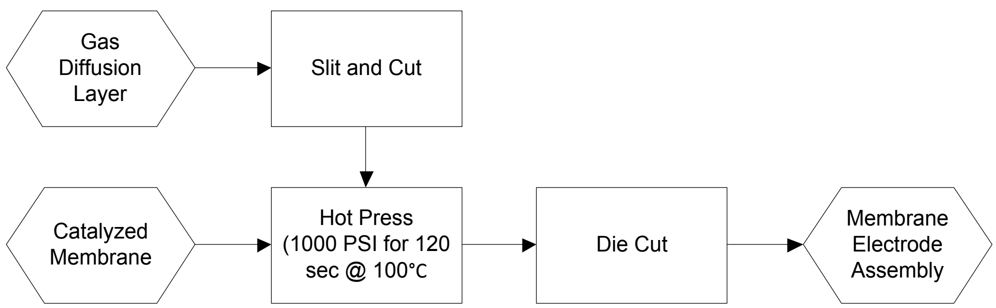
Appendix A-4: Membrane Electrode Assembly (MEA) Hot Process

A-4.1 Model Approach

- GDL Slit and Cut
  - Machine setup labor cost based on number of setups required to process material and input labor time; default = 0.5 hours
  - Slit and cut in single machine operation
  - Operation cost based on parts per cutting operation and cutter cycle time

- Hot press operation
  - Machine setup labor cost based on number of setups required to process material and input labor time; default = 0.5 hours
  - Tooling cost based on input platen cost and life
  - Press cost based on part size, cycle time, platen energy, and standard machine rate

A-4.2 Process Flow



A-4.3 Background

Directed Technologies, Inc. (James et al., 2010)[25] reported hot pressing conditions for MEA fabrication as 160°C for 90 seconds using heated platens of 0.5 m wide by 1.5 m long for processing 0.5-m-wide roll materials. They estimated a reset period of 3 seconds to open the press, index the materials, and re-close the press.

Therdthianwong et al. (2007)[26] found that the most suitable hot pressing conditions for MEA fabrication to be 100°C and 1,000 psi (70 kg/cm^2) for 2 minutes, stating that these conditions "…provided the highest

[25] James B.D., Kalinoski J.A., and Baum K.N. 2010. *Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications: 2010 Update.* NREL Report No. SR-5600-49933. Directed Technologies, Inc. Available at https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/dti_80kwW_fc_system_cost_analysis_report_2010.pdf.
[26] Therdthianwong A, Manamayidthidarn P., and Therdthianwong S. 2007. Investigation of membrane electrode assembly (MEA) hot-pressing parameters for proton exchange membrane fuel cell. *Energy*, 32(12): 2401–2411.

maximum power density from the MEA and the best contact at the interfaces between the gas diffusion layer, the active layer, and the electrolyte membrane."

A-4.4 Preliminary Analysis

The 11.5-kW stack cells for this analysis will have a total active area of:

125.0 mm width × 160.0 mm length = 200.0 cm^2

The 11.5-kW stack cells for have a total MEA area of:

185.0 mm width × 220.0 mm length = 407.0 cm^2

The parts for this analysis were coated three across the 185-mm width for a total width of 555 mm.

A-4.4.1 Material

GDL material is typically sold in either 0.4- or 0.8-meter widths and will be cut to the size of the active area plus a 2.5-mm margin on all sides, making the final dimensions 130 mm wide by 165 mm long. Six widthwise cells will take up 780 mm of GDL width, while four lengthwise cells will take up 660 mm of width, so the widthwise orientation will result in less overall scrap. Assuming two GDL layers per MEA, the material length required will be:

Material length = ((2 × 106,000 parts) / 6 part widths/part length) × 165 mm part length / 1,000 = 5,830.0 meters

The GDL material usage is calculated as:

Material usage = 0.8 m × 5,830.0 m = 4,664.0 m^2

The cost of the membrane is accounted for in a previous process step, and is not included as part of the hot pressing operation. GDL material cost is computed in accordance with Appendix A-2 as:

Material cost = \$395.98/m^2

A-4.4.2 Setup

GDL material is available up to a maximum of 800 meter lengths, so that the number of setups required to run 212,000 parts is:

Number of setups = Roundup(Carrier length (m) / Roll length (m))

Number of setups = Roundup (5,830 / 800) = 8

A-4.4.3 GDL Slit and Cut

The GDL is cut to shape by slitting the 800-mm-wide bulk roll into strips of the predetermined width of 130 mm, then cutting the strips to the required length of 165 mm. We assume a single machine operation with one full-time operator. The limiting rate is the shearing operation, which is estimated to be

50 cuts/minute, or 3,000 cuts per hour. Each shearing operation produces six parts, making the total number of required operations:

Number of cuts = Roundup((2 × 106,000 parts) / 6 parts/operation) = 35,334 cuts

At a rate of 3,000 cuts/hour, the total slitting and cutting time is:

Total operation time = 35,334 cuts / 3,000 cuts/hour = 11.79 hours

Given an availability of 6,000 hours per year per machine, the number of cutting stations required is:

Roundup(11.79 / 6,000) = 1 machine

Machine utilization is:

11.79 / 6,000 = 0.20%

Machine rate was determined in accordance with Appendix A-1 as:

In-house rate = \$28.09 / 0.002 = \$14,045.00

Job shop rate = 1.4 × (\$28.09 / 0.65) = \$60.50

A-4.4.4 MEA Hot Press Tooling

Tooling consists of the heated platens, which generally consist of 2-inch to 2.5-inch-thick aluminum plates loaded with electric cartridge heaters spaced 3 inches (7.6 cm) apart. In 2010, DTI obtained a quote from Custom Engineering Co. (http://www.customeng.com/platens/) for heated platens used for compression molding of bipolar plates. The quote estimated the cost at approximately \$13,500/m^2 of platen area and included platen, base plate, and heater control electronics, estimated to be approximately \$15,650 in 2015 dollars. Standard platen widths are in 0.5-meter increments based on standard cartridge heater sizes. For the size and orientation of the parts, the platen width will be 1 meter. Due to the indexing and alignment required for the patch-coated MEAs, the die length should be at least 1 meter long, and as close to a multiple of 202 mm as possible while allowing for proper cartridge heater spacing. Fifteen cells arranged three widthwise by five lengthwise take up 110 cm of length. The number of heaters is calculated as:

Number of heaters = Roundup(Required length / Heater spacing) =
Roundup(110 cm / 7.6 cm) = 15

The overall die length is:

Die length = Number of heaters × Heater spacing = 15 × 7.6 cm = 114 cm = 1.14 m

An engineering estimate for tool life based on heater life would be around 100,000 cycles. Using \$15,600/m^2 as a basis, and amortizing over a 5 year production life, the total annual tooling cost is:

Annual tooling cost = $\frac{1}{5}$(Tooling cost × Number of tools purchased)

where:

Number of tools purchased = Roundup(Total production / Tool life)

Total production = Annual production × 5

Annual tooling cost = $\frac{1}{5}$ ((\$15,600/m^2 × 1.14 m^2) × Roundup(((212,000 parts/year / 15 parts/cycle) × 5 years) / 100,000 cycles/tool)) = \$3,556.80

A-4.4.5 MEA Hot Press

The hot press occurs in two steps: the material is moved into the press (handling time) and the press operation (clamp time). The material handling time is computed using an empirical formula developed by Boothroyd Dewhurst, Inc. for automated handling with 2.8-second minimum as follows:

Handling time = Layers placed × Max((0.012 × (Platen length (cm) + Platen width (cm)) + 1.6), 2.8)

Handling time = 3 layers × Max((0.012 × (114 + 100) + 1.6), 2.8) = 12.50 sec

Omega (http://www.omega.com/prodinfo/cartridgeheaters.html) estimates 0.5-inch cartridge heaters to have a watt density of 50 W per inch of heater length (about 20 W per centimeter length). Calculating the total input heater power for the platen:

Platen power input = Number of heaters × (Platen width (cm) × 20 (W/cm))

Platen power input = 15 heaters × (100 cm × 20 W/cm) = 30 kW

The heated platens need to maintain a temperature during pressing of about 100°C. A study conducted by the food service industry indicates that 3-foot electric griddles with rated energy inputs of 8 to 16 kW demonstrate a 25% duty cycle in actual use.

Platen sizing allows for processing 15 parts per press cycle (3 parts wide × 5 parts long). Throughput can be computed as:

Parts/hour = 15 parts/cycle / ((124 + 12.5) / 3,600) hours/cycle = 395.6 parts/hour

The total machine time for processing and setup is:

Machine processing time = (106,000 parts / 395.6 parts/hour) + (78 setups × 0.5 hrs/setup) = 306.95 hours

Total machine labor time for processing and setup:

Machine labor time = 1 operator/machine × 306.95 hours = 121.67 hours

Machine utilization is:

306.95 / 6,000 = 5.12%

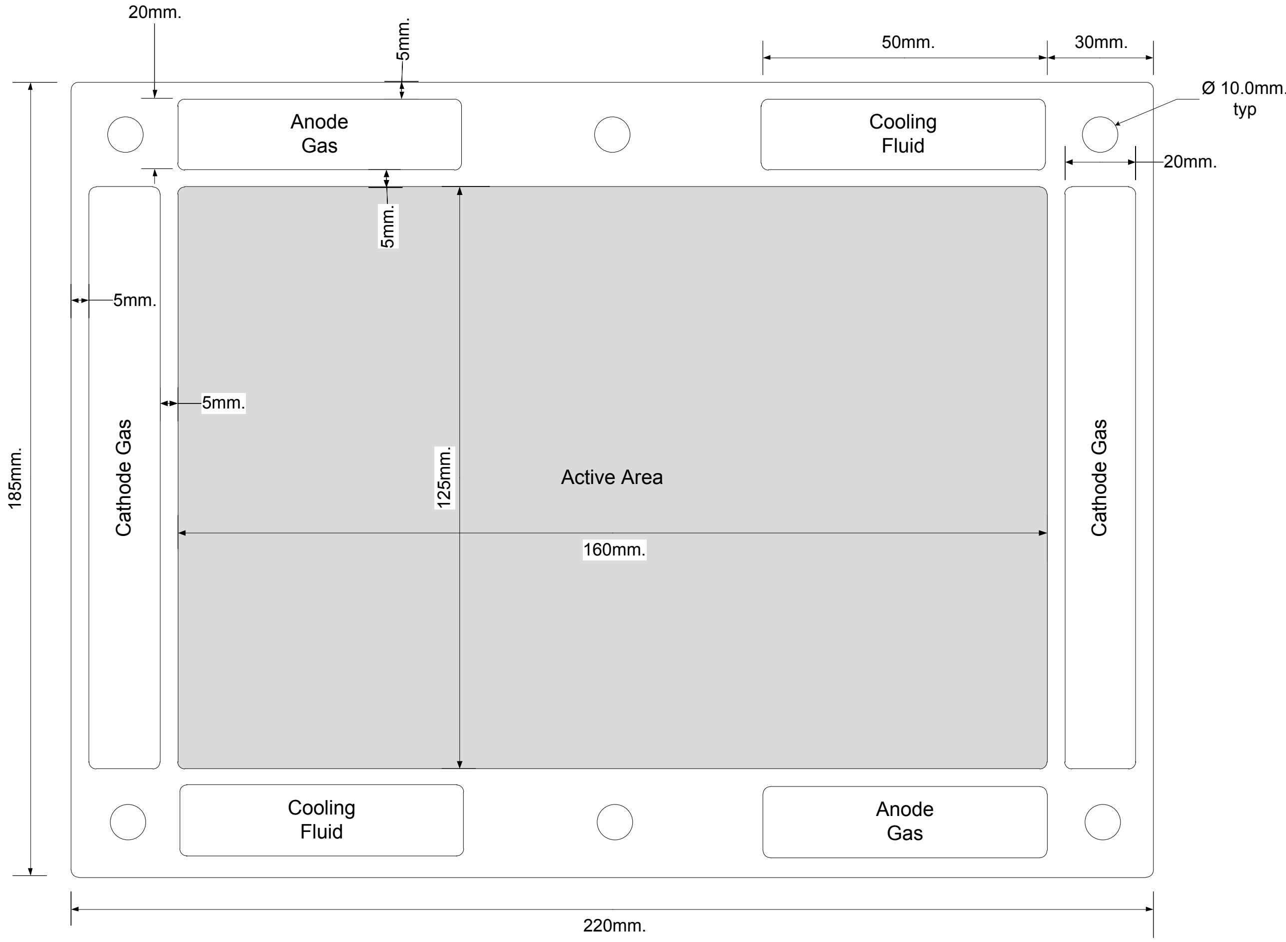
Machine rate was determined in accordance with Appendix A-1 as:

In-house rate = \$52.58 / 0.0512 = \$1,026.95

Job shop rate = 1.4 × (\$52.58 / 0.65) = \$113.25

A-4.4.6 MEA Die Cutting

Following hot pressing, the MEA is die cut to final shape as shown:



A-4.4.7 Tooling

The primary factor contributing to steel rule die cost is the total cutting length of the die. Assuming a platen size equal to that of the hot pressing operation, the total number of cavities is 15 (3 widthwise by 5 lengthwise). The outer cell perimeters will require a total length of:

$$\text{Outer perimeter length} = 2 \times (3 \times 185) + 2 \times (5 \times 220) = 3{,}310.0 \text{ mm}$$

The inner perimeters are shared and will require a total length of:

$$\text{Inner perimeter length} = 4 \times (3 \times 185) + 2 \times (5 \times 220) = 4{,}420.0 \text{ mm}$$

Internal features are unique to each cell cavity and include the fluid and gas openings and the tie rod holes, which require a total die length of:

$$\text{Feature length} = 4 \times (2 \times (50 + 20)) + 2 \times (2 \times (125 + 20)) + 6 \times (\pi \times 10) = 1{,}396.5 \text{ mm}$$

Therefore, the total die cutting length is:

$$\text{Die cutting length (mm)} = 3{,}310.0 + 4{,}420.0 + (15 \times 1{,}396.5) = 28{,}677.4 \text{ mm}$$

A rough quote of approximately $230 was obtained from steel-rule-dies.com for a two-cavity die with a similar configuration.

$$\text{Tooling rate} = \$230 / (2 \times 2{,}706) \text{ mm} = \$0.04/\text{mm}$$

Information obtained from Mag-Knight (www.mag-knight.com/diecutting/Steel_Rule_Dies.htm) indicates that dies used to cut softer materials have an expected life of about 30,000 hits. For a 6 cavity die (6 parts per cycle) and amortizing over a 5 year production life, the total annual tooling cost is:

$$\text{Annual tooling cost} = \tfrac{1}{5}(\text{Tooling cost} \times \text{Number of tools purchased})$$

where:

$$\text{Number of tools purchased} = \text{Roundup}(\text{Total production} / \text{Tool life})$$
$$\text{Total production} = \text{Annual production} \times 5$$

$$\text{Annual tooling cost} = (28{,}677.4 \text{ mm/die} \times \$0.04/\text{mm}) / 5 \text{ years}) \times \text{Roundup}(((42{,}000 \text{ parts/year} / 15 \text{ parts/cycle}) \times 5 \text{ years}) / 30{,}000 \text{ cycles/tool}) = \$229.42$$

A-4.4.8 Setup

The total number of setup operations will be dictated by the length of the membrane at 100 meters. As shown above, the number of roll setups is 78. Assuming 0.5 hours per setup, the total setup time is:

$$\text{Setup time} = 78 \times 0.5 \text{ hrs.} = 39 \text{ hrs}$$

A-4.4.9 Die Cutting

The primary energy input to run the press is hydraulic pump motor power. The total force required to cut the material is the total shear area (cutting length × material thickness) multiplied by the material shear strength. Shear strength data for Nafion is not readily available, but polymer-based materials typically range from 8,000 to 11,000 pounds per square inch (psi) (55 to 76 newtons per square millimeter [N/mm^2]). Assuming the worst-case shear strength, and using the material thickness of 0.7 mm, the total required press force per part is calculated as:

Press force = Die cutting length (mm) × Material thickness (mm) × Shear strength (N/mm^2)

Press force = 28,677.4 mm/die × 0.7 mm × 76 N/mm^2 = 1,526 kilonewton (kN)

A survey of 15- to 100-ton (150- to 1,000-kN) fast-acting die cutting presses found that the motor power required to operate the press fell in the range of 0.015 to 0.025 kW/kN. Assuming a 50% capacity margin and using the upper end of the motor power rating, the maximum required press energy input is:

Press energy = 1,526 kN × 1.5 × 0.025 kW/kN = 57.2 kW

Typical die cutting press speed ranges from 30 to 60 cycles/minute (1,800 to 3,600 cycles/hour). Assuming the slower speed, the time to process a batch of parts is calculated as

Processing time = 106,000 parts / 15 parts/cycle / 1,800 cycles/hour = 3.9 hours

The total machine time for processing and setup is:

Machine processing time = 39 + 3.93 = 42.9 hours

Given an availability of 6,000 hours per year per machine, the number of presses required is:

Roundup(42.9 / 6,000) = 1 machine

Machine utilization is:

42.9 / 6,000 = 0.72%

Machine rate was determined in accordance with Appendix A-1 as:

In-house rate = $30.15 / 0.0072 = $4,187.50

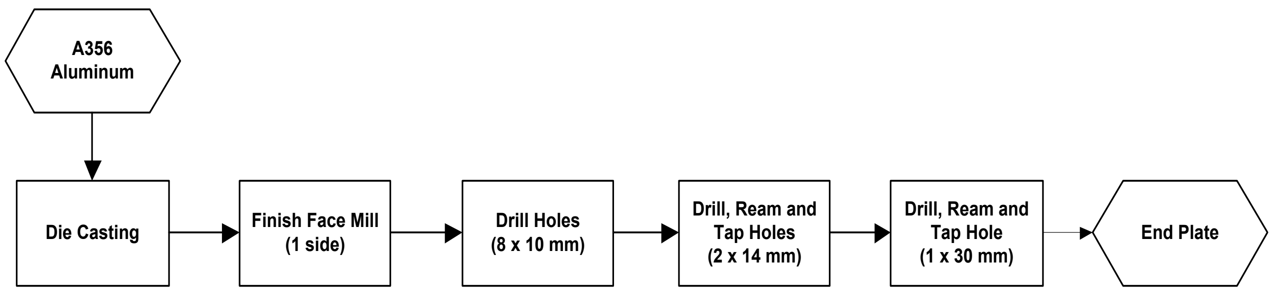
Job shop rate = 1.4 × ($30.15 / 0.65) = $64.94

Appendix A-5: PEM End Plate Manufacturing Process

A-5.1 Model Approach

- Use standard Boothroyd Dewhurst, Inc. (BDI) Design for Manufacturing and Assembly (DFMA®) cell machining cost analysis
  - Near net shape workpiece
  - Face mill bottom
  - Ream, and tap gas connector mounting holes

A-5.2 Process Flow

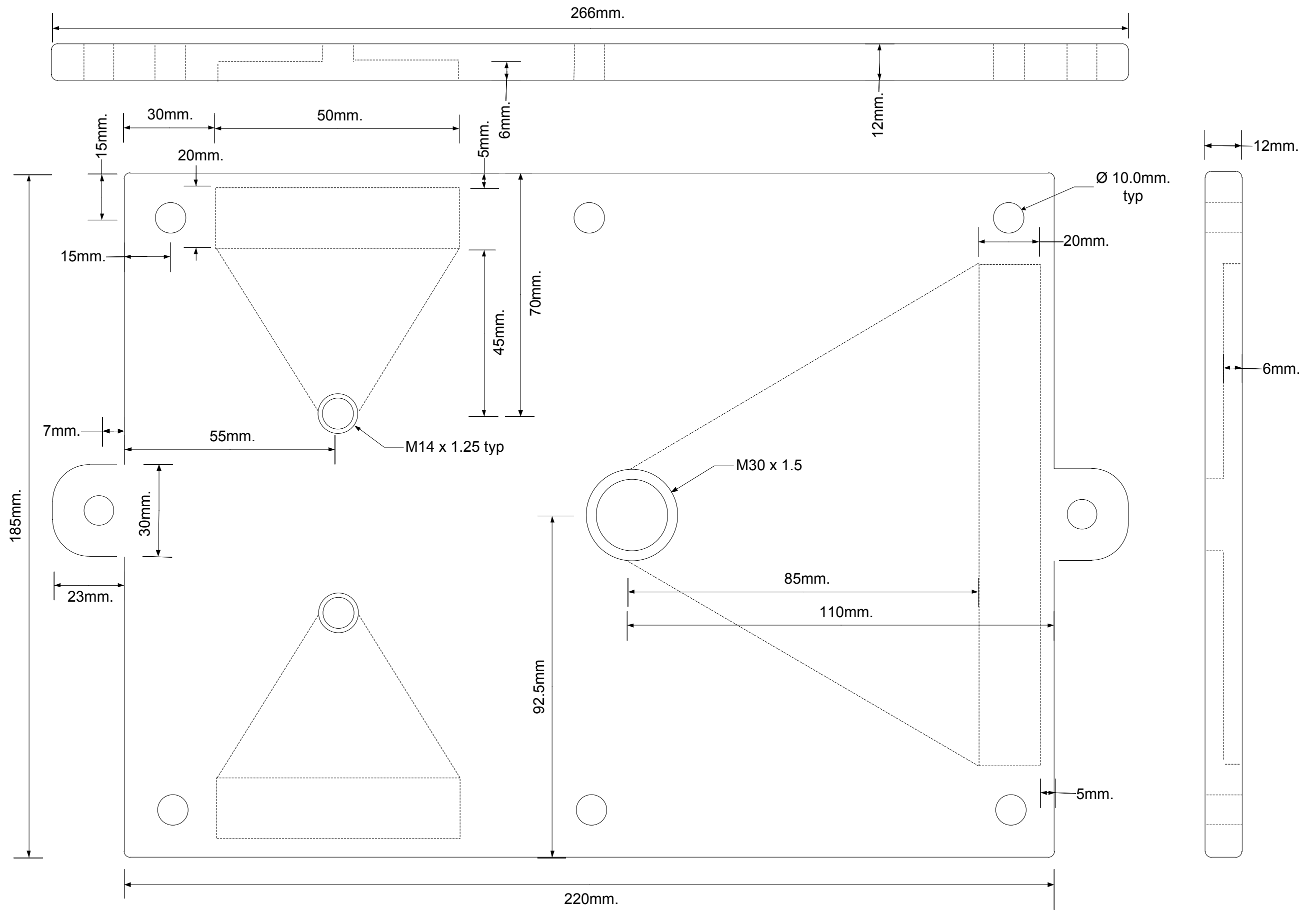


A-5.3 Background

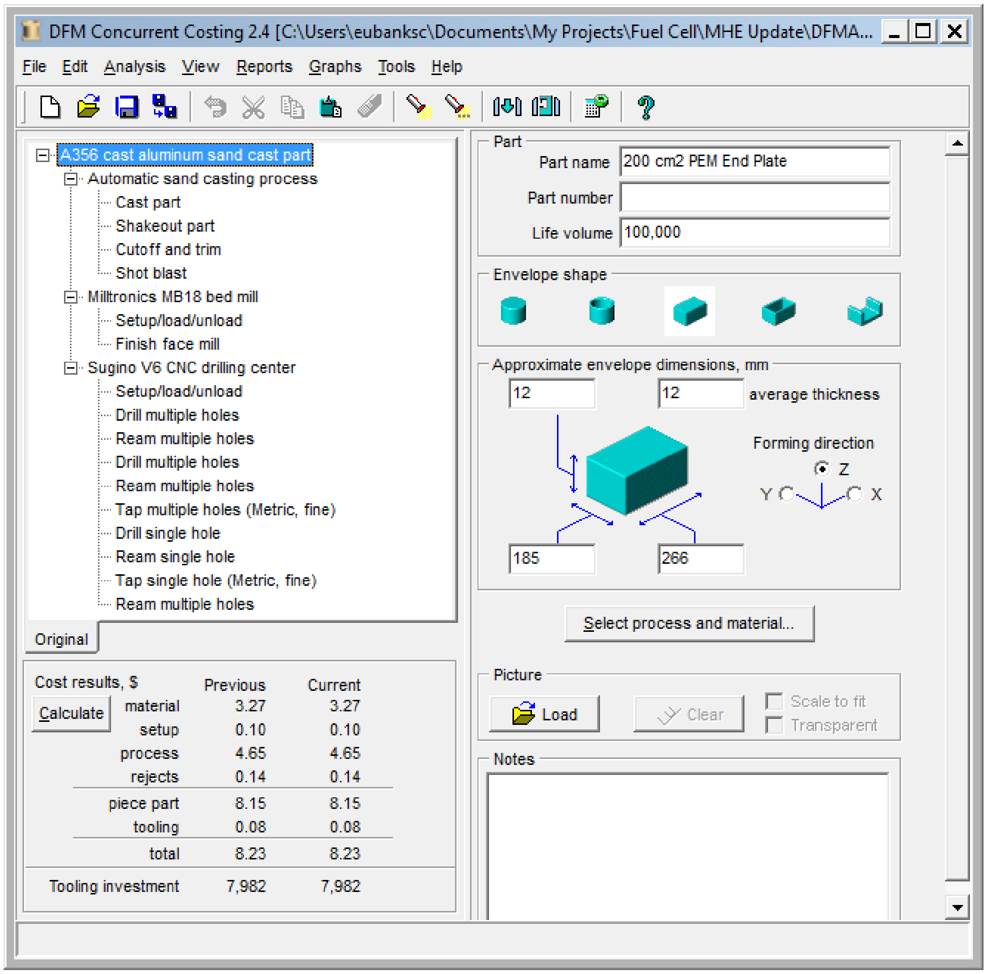
The BDI DFMA® software provides preprogrammed cost models for the casting and cell machining operations used to manufacture the fuel cell stack end plates. The end plates need to be rigid to apply even pressure across the face of the stack. The process selection for the low temperature polymer electrolyte membrane (PEM) end plate was sand casting of A356 cast aluminum to near net shape, followed by finish machining of the stack contact face, and reaming and tapping of the holes for fuel, exhaust, and cooling flows.

A-5.4 Preliminary Analysis

The 11.5-kW stack end plate features and dimensions are shown below for reference:



A-5.5 DFMA® Software Analysis



A-5.5.1 End Plate

The DFMA® software estimates a 17.78-hour machine setup time and calculates the total manufacturing time for the end plates as 352 seconds (sec), making the total machine time for annual production of 1,000 11.5-kW stacks:

$$\text{Machine time} = (352 \text{ sec/part} / 3{,}600) \times 2{,}000 \text{ parts} + 17.78 = 213.3 \text{ hours}$$

Machine utilization is:

$$\text{Utilization} = 213.3 / 6{,}000 = 3.6\%$$

Assuming two full-time operators (one for casting, one for machining) per station, the total machine labor time is equal to twice the machine time = 426.6 hours.

Material cost was determined in accordance with Appendix A-2 as:

$$\text{Material cost} = \$2.425/\text{kg}$$

Tooling cost is $7,982 and is assumed to be capable of producing 100,000 parts. Amortizing over a 5-year production life, the total annual tooling cost is:

$$\text{Annual tooling cost} = \frac{1}{5}(\text{Tooling cost} \times \text{Number of tools purchased})$$

where:

$$\text{Number of tools purchased} = \text{Roundup}(\text{Total production} / \text{Tool life})$$
$$\text{Total production} = \text{Annual production} \times 5$$

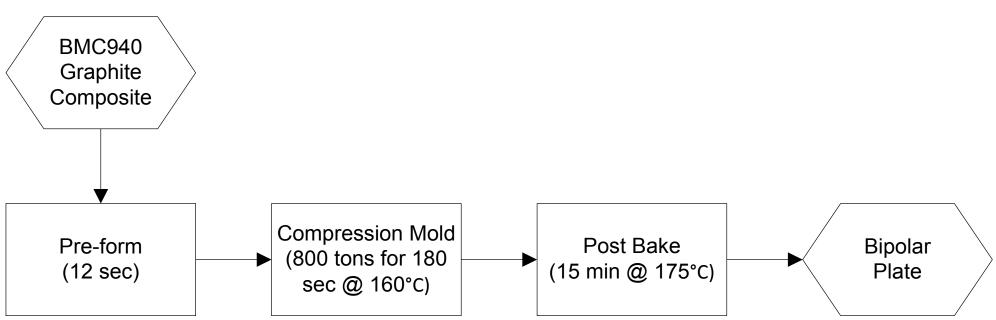
Annual tooling cost = ($7,982 / 5 years) × Roundup((2,000 parts/year × 5 years) / 100,000 parts/tool) = $1,596.40

Appendix A-6: Bipolar Plate Compression Molding Process

A-6.1 Model Approach

- Setup operation
  - Machine setup labor time based on user input
  - Tooling cost based on input insert and platen cost and life
- Pre-form operation
  - Measure and pre-form labor time based on user input labor time
  - Part material unit cost based on usage
- Compression mold
  - Part handling time based on part size per Boothroyd Dewhurst, Inc. (BDI) Design for Manufacturing and Assembly (DFMA®) formula; 4-second (sec) minimum
  - Press processing time based on part size and cycle time
  - Compute machine utilization
- Post bake
  - Part handling time based on part size per BDI DFMA® formula and throughput; 4-sec minimum

A-6.2 Process Flow



A-6.3 Background

A supplier of composite bipolar plates for polymer electrolyte membrane (PEM) fuel cell stacks provided the following information regarding its process:

- Process requires a special press
  - High speed – 30 inches per second (ips)

  - High tonnage – 800-ton capacity to produce 1 part per cycle
  - Cure time in the press is 120 to 230 sec
  - Allow 5% material overage

- Tooling costs
  - Inserts: $45K-$50K produces about 100,000 parts
  - Base: $50K (reusable)

- Molding material supplied by Bulk Molding Compounds (BMC)
  - Has a consistency like sand
  - From BMC940 specification sheet
    - Cure time: 30 to 60 seconds
    - Mold temp: 300 to 320°F (149 to 160°C)
    - Recommended tonnage: >40 megapascals (MPa) on projected part area
    - Press close speed: <2 sec after material begins flowing
    - Post-mold bake at 350°F for 15 minutes

A-6.4 Preliminary Analysis

Unlike injection molding, compression molding requires that a premeasured, usually preformed, and generally preheated amount of material be loaded into a mold insert prior to pressing. Given the stated consistency of the material, we will assume a manual weighing process followed by a manual packing process to get the material into the rough rectangular shape of the plate. No material pre-heating was mentioned by the manufacturer or the material spec sheet.

The bipolar plates for this analysis will be:

185 millimeter (mm) width × 220 mm length = 407 square centimeters (cm^2)

Process values will be calculated based on annual production of 1,000 11.5-kilowatt (kW) stacks per year. The 11.5-kW stack requires 107 anode bipolar plates and 104 cathode bipolar plates, requiring annual production of 107,000 of each type of plate.

A-6.4.1 Setup

We will assume one full setup per run of parts. This would include such things as platen and die installation, die alignment, work station setup, and maintenance and operational checks. An analogous setup operation in the BDI DFMA® software is for a powder metallurgy compaction press, for which the default value is 4 hours.

A-6.4.2 Material cost

Flow channels cut into the plates are generally 1 mm deep. The cathode bipolar plate has flow channels cut into one side of the plate, indicating a plate depth of around 2 mm. The anode bipolar plate has flow channels cut into both sides of the plate to accommodate anode gas flow on one side, and cooling fluid flow on the other, indicating a plate depth of around 3 mm. Given a material density of 1.9 grams per cubic centimeter (g/cm^3) (BMC940 spec sheet) and 5% overage allowance, the total annual material required before scrap is:

> Cathode plate material required = 1.9 g/ cm^3 × 0.001 kilograms per gram (kg/g) × (407 × 0.2) cm^3 × 1.05 × 107,000 parts = 17,376 kg

> Anode plate material required = 1.9 g/ cm^3 × 0.001 kg/g × (407 × 0.3) cm^3 × 1.05 × 107,000 parts = 26,064 kg

Based on quotes from BMC, the material cost can be estimated in accordance with Appendix A-2 as:

> Material cost = \$2.066/kg

A-6.4.3 Compression molding press time

The material specification recommends molding pressure in excess of 40 MPa (0.4 ton/cm^2) on the projected part area:

> Tonnage = 0.4 ton/cm^2 × 407 cm^2 = 162.8 tons

Discussions with a bipolar plate manufacturer indicate the use of a special fast-acting 800-ton press. Moving the capacity up to 1,000 tons, it is feasible to mold six plates per cycle (977 tons).

The primary energy input to run the press is hydraulic motor power. Surveying press manufacturers Wabash, Beckwood, and Karunanand, the hydraulic motor size for 800-ton presses appears as either 30 or 50 horsepower (HP), but lists pressing speeds of only 20 inches per minute (ipm) (0.3 ips). Cylinder bore sizes are listed as 26- to 30-inch diameter. To move a 30-inch diameter cylinder at 30 ips requires a pump delivery of:

> Flow rate = $(30")^2 \times (\pi / 4) \times 30"/sec \times 60$ sec/min × 0.004 gal/in^3 = 5,089 gallons per minute (gpm)

This is beyond the practical limit of most high-performance hydraulic gear pumps, which tend to have maximum flow rates of 90 gpm at 100-HP input power and 2,500 psi working output pressure (reference Commercial Intertech P365 series hydraulic pumps).

To supply 1,000 tons of force using a 30-inch cylinder requires a delivery pressure of:

> Pressure = 1,000 tons × 2,240 lbs/long ton / $((30")^2 \times (\pi / 4))$ = 3,169 psi

For this analysis, we will assume two 100-HP (75-kW) pumps feeding a set of staged cylinders; e.g., two smaller-diameter cylinders to provide the necessary pressing speed, and one larger cylinder to develop the required pressure. To provide some limited scalability, we assume that 150 kW of input power is required to mold six 407-cm^2 bipolar plates, giving a factor of approximately 0.062 kW/cm^2 of plate area.

Total press cycle time is the sum of part handling time, press actuation time, and press dwell time. An empirical formula developed by BDI calculates a quantity called part girth, then calculates a theoretical total handling time (both load and unload) with a minimum value of 4 sec, as follows:

Part girth = Part length + Part width + Part depth

Handling time = Max((0.60714 × (Part girth / 25.4) - 4.57143), 4)

Cathode plate handling time = Max((0.60714 × ((185 + 220 + 2) / 25.4) - 4.57143), 4) = 5.16 sec

Anode plate handling time = Max((0.60714 × ((185 + 220 + 3) / 25.4) - 4.57143), 4) = 5.18 sec

For an actuation time of 10 sec, dwell time of 230 sec, and handling times shown above, the total cycle time is:

Cathode plate cycle time = ((6 × 5.16) + 230 + 10) = 270.9 sec/cycle = 0.0752 hour/cycle

Anode plate cycle time = ((6 × 5.18) + 230 + 10) = 271.1 sec/cycle = 0.0753 hour/cycle

Throughput is calculated as:

Parts per hour = 6 parts/cycle / 0.0753 hour/cycle = 79.7 parts/hour

Since throughput for each type of plate is essentially the same, we can calculate the total time required to process both sets of plates (214,000 parts) as:

Press machine time = 214,000 parts / 79.7 parts/hour + (2 × 4) hour setup = 2,693 hours

Given an availability of 6,000 hours per year per machine, the number of presses required is:

Roundup(2,693 / 6,000) = 1 machine

Machine utilization is:

2,693 / 6,000 = 44.9%

Machine rate was determined in accordance with Appendix A-1 as:

In-house rate = $64.70 / 0.449 = $144.10

Job shop rate = 1.4 × ($64.70 / 0.65) = $139.35

A-6.4.4 Tooling cost

Tooling consists of the mold inserts and the heated platens. Contact with Custom Engineering Co. (http://www.customeng.com/platens/) indicates that platens in the size range required will generally consist of 2-inch to -2.5-inch-thick aluminum plates loaded with electric cartridge heaters spaced 3 inches (7.6 cm) apart. Costs will be in the range of $10,000 for a 7,500-$cm^2$ platen ($1.333/ cm^2), and $3,500 for the controller. No life was provided for the platens. An engineering estimate based on heater life would be around 500,000 cycles.

Assuming six plates per cycle with 50-mm margin between and around each plate, the total platen area is:

> Platen width = ((2 × 220 mm) + (3 × 50 mm)) = 590 mm
>
> Platen length = ((3 × 185 mm) + (4 × 50 mm)) = 755 mm
>
> Platen area = 590 mm × 755mm = 4,455 cm^2
>
> Platen cost = (4,455 cm^2 × \$1.333/ cm^2) + \$3,500 = \$9,439

Using the BDI DFMA® software, the die cost was estimated at \$10,000 per part (\$24.50/cm^2) with a 100,000 cycle life. Amortizing over a 5-year production life, the total annual tooling cost is:

> Annual tooling cost = $\frac{1}{5}$(Tooling cost × Number of tools purchased)

where:

> Number of tools purchased = Roundup(Total production / Tool life)
> Total production = Annual production × 5
>
> Annual insert tooling cost = $\frac{1}{5}$ ((\$24.50 × 4,455 cm^2) × Roundup((214,000 parts/year / 6 parts/cycle × 5 years) / 100,000 parts/tool)) = \$21,830
>
> Annual platen tooling cost = $\frac{1}{5}$ ((\$9,439) × Roundup((214,000 parts/year / 6 parts/cycle × 5 years) / 500,000 parts/tool)) = \$1,888

A-6.4.5 Heated platen energy

Omega (http://www.omega.com/prodinfo/cartridgeheaters.html) estimates 0.5-inch cartridge heaters to have a watt (W) density of 50 W per inch of heater length (about 20 W per centimeter length). Calculating the total input heater power for the platen based on 3-inch (7.6-cm) heater spacing:

> Number of heaters = Ceiling(Platen width (cm) / 7.6
>
> Platen power input = Number of heaters × (Platen length (cm) × 20 (W/cm))
>
> Number of heaters = Ceiling (59.0 cm / 7.6 cm) = 8
>
> Platen power input = 8 heaters × (75.5 cm × 20 W/cm) = 12.1 kW

The mold insert will be attached to heated platens that can maintain the proper mold temperature of up to 160°C. A study conducted by the food service industry indicates that 3-foot (ft) electric griddles with rated energy inputs of 8 to 16 kW demonstrate a 25% duty cycle in actual use. Given that the surface areas, power densities, and manual work flow are comparable, we will assume a similar usage profile.

A-6.4.6 Post-bake cycle

The BMC940 material spec sheet calls for a post bake at 350°F (177°C) for 15 minutes after the part reaches temperature. For a batch-type oven, the strategy is to rack parts in quantities that permit racks to be interchanged in 15-minute intervals. Given a throughput of 27.32 parts/hour and that we are molding parts in pairs, we can expect a rack size of:

Parts per bake cycle = (79.7 parts/hr $\times$ 0.25 hr) = 19.93 parts per bake cycle $\cong$ 20 parts/rack

For this level of production, we will assume that an industrial bench oven will provide sufficient capacity. One example is the Grieve NBS-400 with 4-kW heating capacity capable of reaching 400°F (204°C), 28 inches $\times$ 24 inches $\times$ 18 inches (0.2 m^3) working volume with seven-shelf capacity, and 2-inch (5-cm) rockwool insulation (k = 0.045 W/m°C) on 304 stainless steel construction. A study conducted by the food service industry indicates that “deck ovens” demonstrate a 20% duty cycle in actual use. Given that the usage scenarios are comparable, we will assume a similar usage profile.

For the post-bake step, we assume that parts will be racked to facilitate swapping parts at intervals equal to the bake time in order to minimize oven heat loss. A rack of two parts will fit onto one shelf. Assuming a rack depth of 10 mm and 50-mm part margin, an estimate of the rack handling time is:

Rack girth = (Parts along width $\times$ (Part width (mm) + 50)) + (Parts along length $\times$ (Part length(mm) + 50)) + 10

Rack girth = (5 $\times$ (185 + 50)) + (4 $\times$ (220 + 50)) + 10 = 2,265

Rack handling time = Max((0.60714 $\times$ ((2,265) / 25.4) - 4.57143), 4) = 49.6 sec

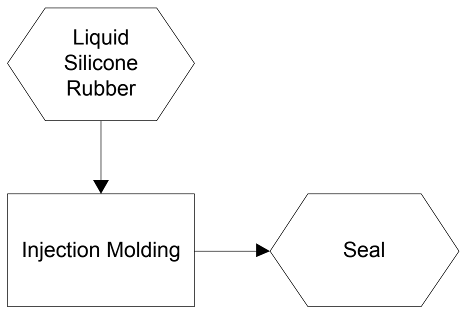
Given that the rack handling time is about 20% of the press dwell time, no additional labor time is incurred by the press operator to complete the tasks associated with the post-bake operation.

Appendix A-7: PEM Seal Injection Molding Process

A-7.1 Model Approach

- Use standard Boothroyd-Dewhurst (BDI) injection molding cost analysis

A-7.2 Process Flow



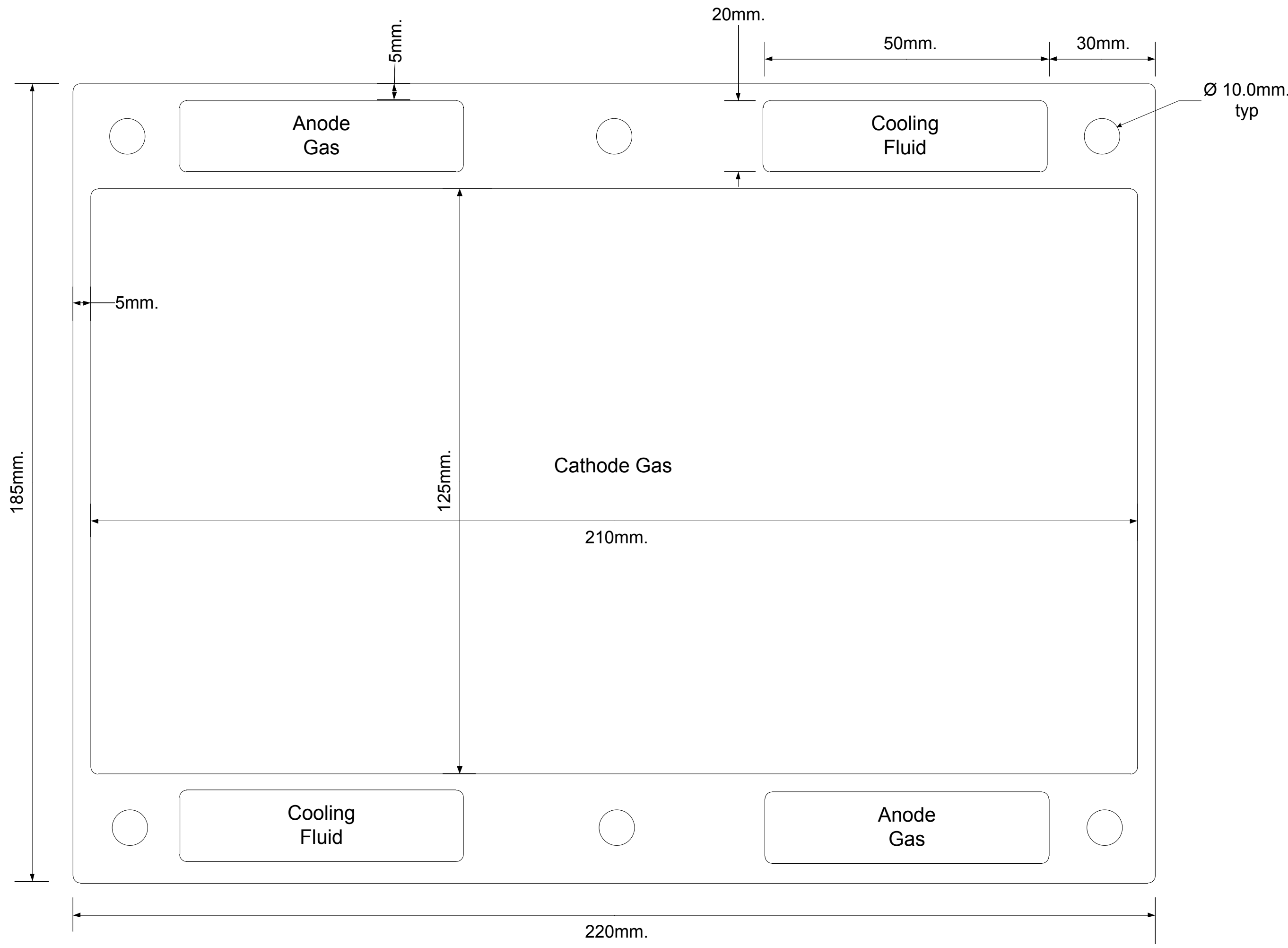
A-7.3 Background

The BDI software provides preprogrammed cost models for the injection molding process used to manufacture the fuel cell stack coolant seals. The process selection was liquid silicon injection molding.

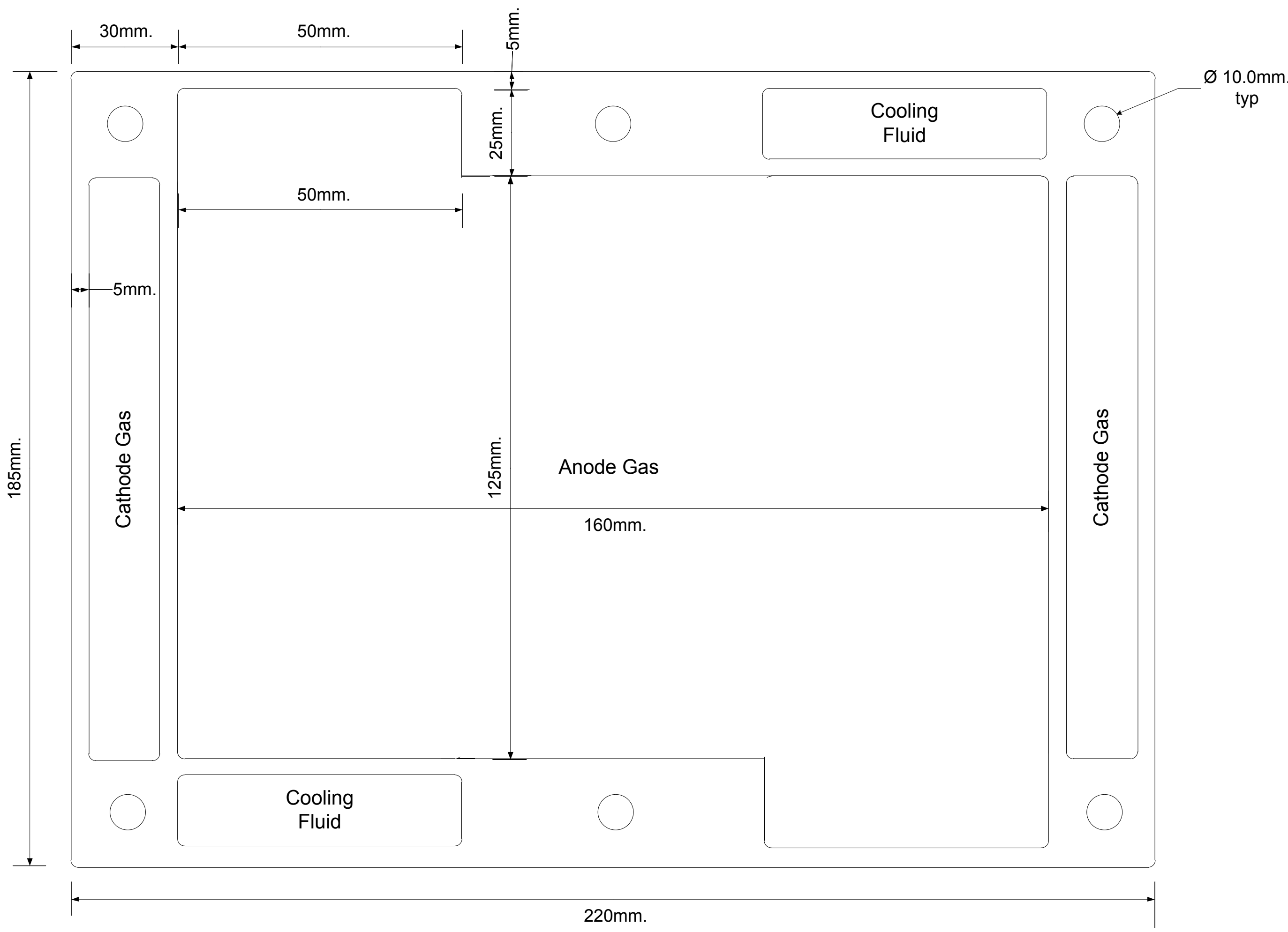
A-7.4 Preliminary Analysis

The stack requires three seals (cathode, anode and cooling) per cell plus two cathode seals on each end of the stack. To manufacture 1,000 11.5-kW stacks consisting of 106 cells each requires a total of 106,000 each anode and cooling seals, and 108,000 cathode seals. The seal features and dimensions are shown below for reference:

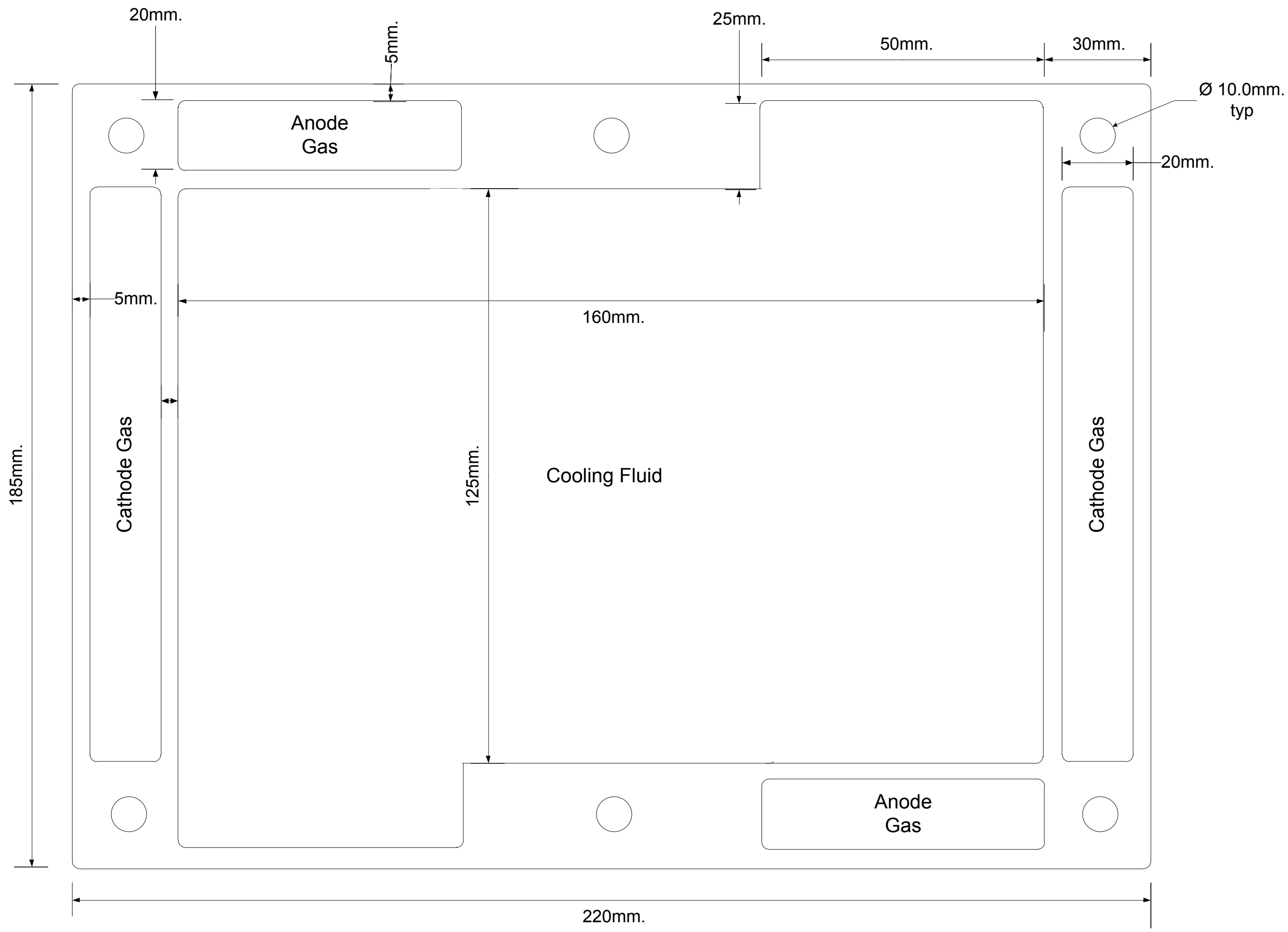
A-7.4.1 Cathode Seal



A-7.4.2 Anode Seal

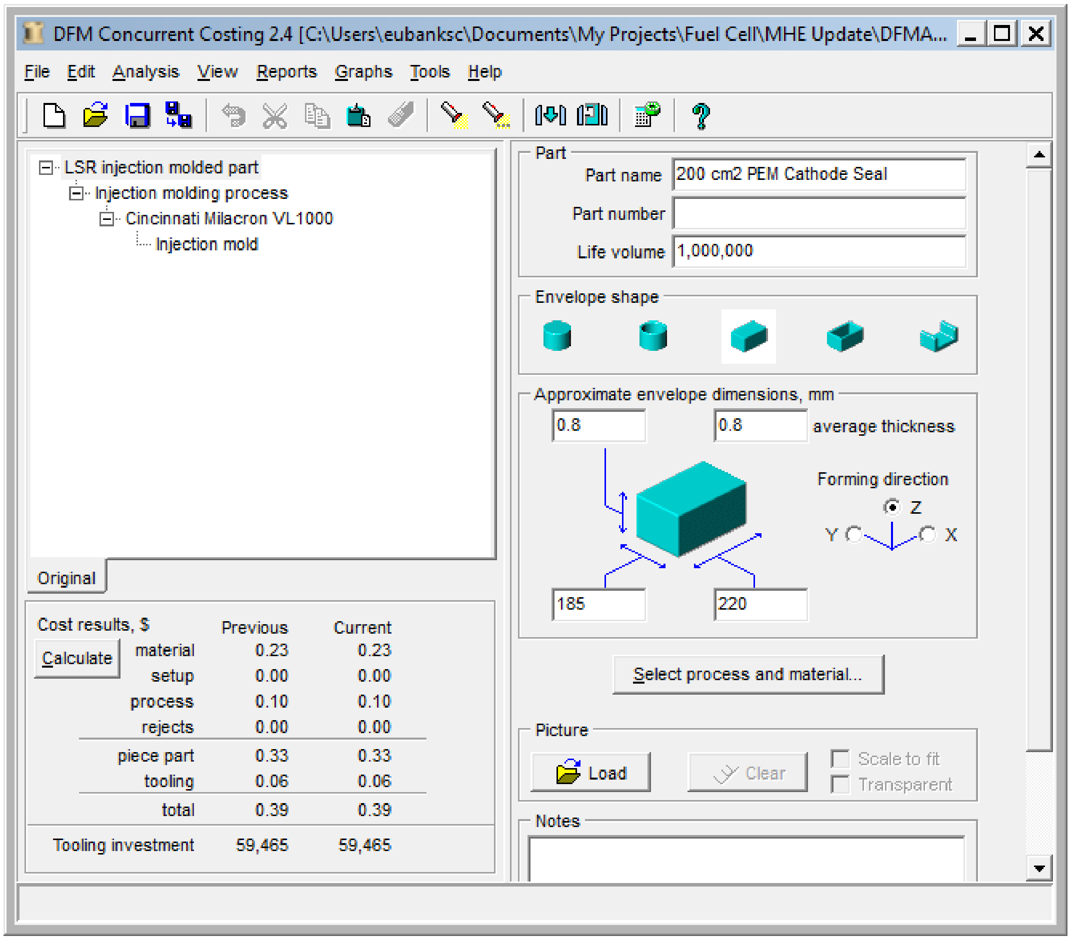


A-7.4.3 Cooling Seal



A-7.5 DFM Software Analysis

A-7.5.1 Cathode Seal



The BDI estimate for the 11.5-kW cathode seal is a 2-hour machine setup time, and calculates the total manufacturing cycle time as 9.66 sec for a four-cavity mold, making the total machine time for annual production of 1,000 stacks:

Machine time = (9.66 sec/cycle / 4 parts/cycle / 3,600) × 108,000 parts + 2 = 74.5 hours

Assuming 1 full-time operator per two molding machines, the total machine labor time is equal to half the machine time = 37.3 hours.

The BDI estimate for material weight per part is 0.010 kg, making total annual material usage:

Material usage = 0.010 kg/part × 108,000 parts = 1,080 kg

Tooling cost is $59,465 and is assumed to be capable of producing 1,000,000 parts. Amortizing over a 5-year production life, the total annual tooling cost is:

$$\text{Annual tooling cost} = \tfrac{1}{5}(\text{Tooling cost} \times \text{Number of tools purchased})$$

where:

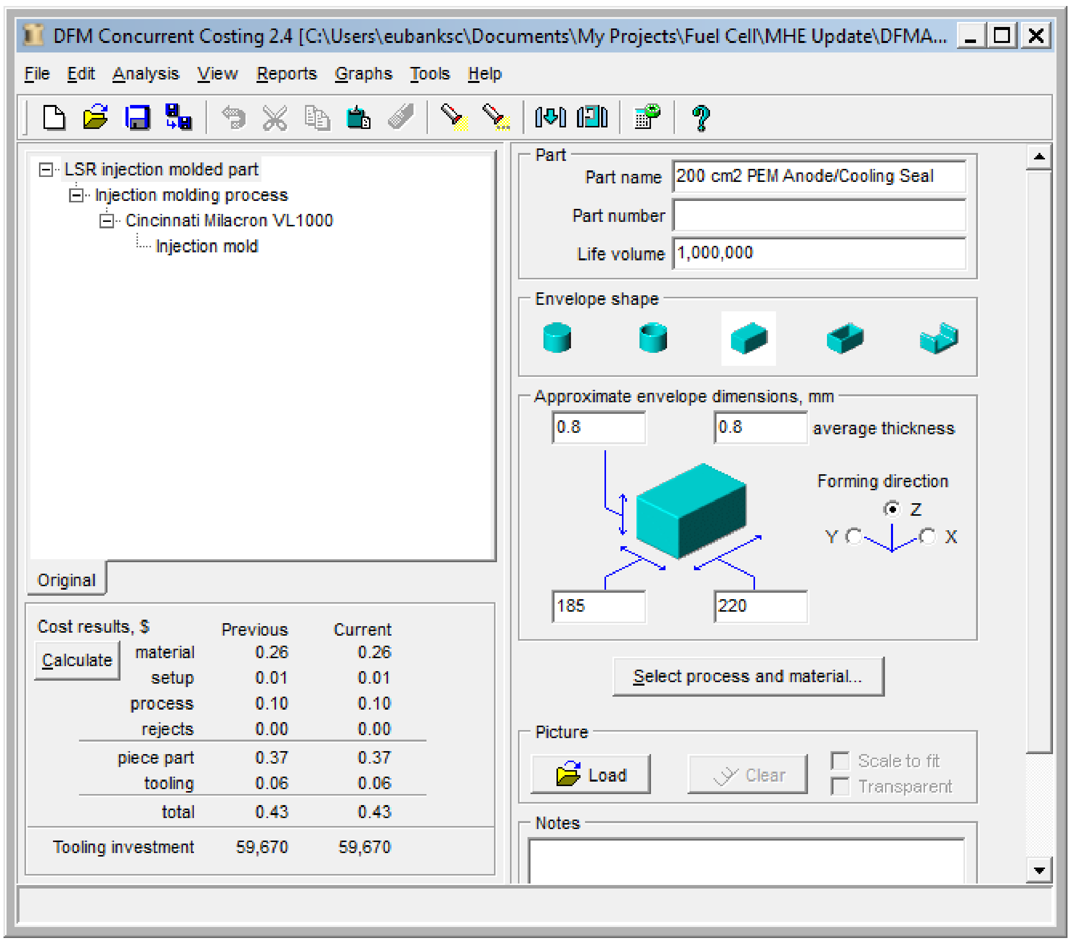
$$\text{Number of tools purchased} = \text{Roundup}(\text{Total production} / \text{Tool life})$$

$$\text{Total production} = \text{Annual production} \times 5$$

$$\text{Annual tooling cost} = \tfrac{1}{5}\,(\$59{,}465 \times \text{Roundup}((108{,}000\ \text{parts/year} \times 5\ \text{years}) / 1{,}000{,}000\ \text{parts/tool})) = \$11{,}893$$

A-7.5.2 Anode/Cooling Seal

Note that the anode and cooling seals are the same design but are installed by flipping along the vertical center axis and are therefore analyzed by the DFM software as the same seal, as shown below:



The BDI estimate for the anode/cooling seal is a 2-hour machine setup time and calculates the total manufacturing cycle time as 9.66 sec for a four-cavity mold, making the total machine time for annual production of 1,000 stacks:

Machine time = (9.66 sec/cycle / 4 parts/cycle / 3,600) $\times$ 212,000 parts + 2 = 144.2 hours

Tooling cost for the anode/cooling seal is $59,670 and is assumed to be capable of producing 1,000,000 parts. Amortizing over a 5-year production life, the total annual tooling cost is:

Annual tooling cost = $\frac{1}{5}$(Tooling cost $\times$ Number of tools purchased)

where:

Number of tools purchased = Roundup(Total production / Tool life)
Total production = Annual production $\times$ 5

Annual tooling cost = $\frac{1}{5}$ (($59,670) $\times$ Roundup((212,000 parts/year $\times$ 5 years) / 1,000,000 parts/tool)) = $23,868.00

Total machine time to mold the three gaskets is 218.7 hours, making the machine utilization:

Utilization = 218.7 / 6,000 = 3.6%

Machine rate was determined in accordance with Appendix A-1 as:

In-house rate = $26.04 / 0.036 = $723.33.00

Job shop rate = 1.4 $\times$ ($26.04 / 0.65) = $56.09

Assuming one full-time operator per two molding machines, the total machine labor time is equal to half the machine time = 109.4 hours.

The BDI estimate for the anode/cooling seal material weight per part is 0.012 kg, making total annual material usage:

Material usage = 0.012 kg/part $\times$ 212,000 parts = 2,544 kg

The three gaskets require a total of 3,624 kg of material. The material cost was determined in accordance with Appendix A-2 as:

Material cost = $16.02/kg

Appendix A-8: Assembly Cost Learning Curve Calculations

A-8.1 Background

The Boothroyd Dewhurst, Inc. (BDI) Design for Manufacturing and Assembly (DFMA®) software produces assembly times based on hand assembly at its most efficient. Using the 11.5-kilowatt (kW) stack as an example, the assembly time was estimated to be 1.01 hour.

The learning curve analysis essentially backs that number up to a time when bugs are still being worked out of the assembly process.

From the *Cost Estimator's Reference Manual* (1995),[27] the general learning curve equation is:

$$Y = AX^b$$

where:

Y = time or cost per cycle or unit

A = time or cost for first cycle or unit

X = number of cycles or units

b = log(m)/log(2)
m = slope of learning curve

A-8.2 Analysis

For stack assembly time, if we assume that m = 0.85 (typical for aerospace processes), then:

$$b = \log(0.85)/\log(2) = -0.23447$$

If the stack assembly process is "learned" after 100 units, and the assembly time for the X = 100th stack is the BDI DFMA® time, then the time to assemble the first unit is:

$$A = Y / X^b = 1.01 / 100^{(-0.23447)} = 2.973 \text{ hrs}$$

The average time to assemble the first 100 units ($\overline{C}_{100}$) is calculated as:

$$\overline{C}_{100} = \frac{\left(\sum_{i=1}^{100} 1.524 * \mathrm{i}^{(-0.23447)}\right)}{100} = 1.297\ hrs$$

Therefore, the average time to assemble n units (n > 100) is calculated as:

$$\overline{C}_{n} = \frac{\left(\bar{C}_{100} + \left(Y_{100} * (n - 100)\right)\right)}{n}$$

[27] Stewart, R.D., Wyskida, R.M., Johannes, J.D. (eds). 1995. Cost Estimator's Reference Manual, 2nd Ed. Wiley-Interscience, April 1995. 744 p.

Using the above equations, the average stack assembly times are:

1st Year Average Assembly Time (hrs)				
Type of stack	No. of stacks per year			
	100	1,000	10,000	50,000
1.5-kW PEM Stack	0.306	0.244	0.238	0.237
5.75-kW PEM Stack	0.726	0.580	0.565	0.564
11.5-kW PEM Stack	1.297	1.036	1.010	1.008
28.75-kW PEM Stack	1.510	1.206	1.176	1.173

The average system assembly times are:

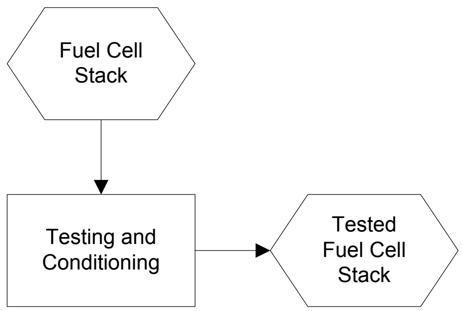
1st Year Average Assembly Time (hrs)				
Type of system	No. of systems per year			
	100	1,000	10,000	50,000
PEM MHE System	1.416	1.131	1.102	1.100

Appendix A-9: PEM Stack Testing and Conditioning Process

A-9.1 Model Approach

- Test and condition fuel cell stack

A-9.2 Process Flow



A-9.3 Background

Following assembly, the polymer electrolyte membrane (PEM) stack is tested and conditioned to determine its fitness for installation into the system. The total test time is assumed to be 2.5 hours. Total hydrogen gas (H_2) consumption at full power is determined from the equation:

H_2 consumption mol/sec = (current $\times$ cells) / (2 $\times$ H_2 cal/mol)

For a 11.5-kilowatt (kW) stack current of 160 amperes (A) and cell count of 106 cells, we have:

H_2 consumption grams per second (g/sec) = 160 A $\times$ 106 cells / (2 $\times$ 96,485 cal/mol) = 0.088 mol/sec

Converting to liters per minute (L/min):

H_2 consumption L/min = 1.2 $\times$ 0.088 mol/sec $\times$ 60 $\times$ 2.016 / 0.0899 = 141.9 L/min

Air is supplied in a stoichiometric ratio of 1.2:2, resulting in required air flow of:

Air flow L/min: (2 / 1.2) $\times$ 141.9 L/min = 236.5 L/min

A-9.4 Preliminary Analysis

Assuming setup and teardown of the stack test stand requires 0.5 hour for one operator per run, the setup time per production run of 1,000 stacks is:

Setup labor time = 0.5 hour/stack × 1,000 stacks = 500 hrs

The Fuel Cell and Hydrogen Energy Association placed the 2010 nationwide average cost of hydrogen in bulk liquid form at about $7.83/kg for usage levels of 700 to 1,400 kilograms (kg) per month. Internet quotes indicate a price of about $5.93/kg for bulk purchases of 30,000 kg or more. The mass of 1 mole H_2 = 2 grams, so the mass of 22.4 L (stp) of H_2 is 2 grams (g).

1 kg of H_2 = (1,000 / 2) × 22.4 L = 11,200 L = 11.2 cubic meters (m^3)

At 100% rated power, the total material usage of the hydrogen is:

Full power material usage = ((141.9 L/min / 1,000 l/m^3) / 11.2 m^3/kg) × 60 min/hr = 0.755 kg/hr

During the 2.5-hour test, we assume a conditioning and test regimen as follows:

25% rated power for 1 hour

100% rated power for 0.5 hour

25% rated power for 1 hour

Therefore, the total material usage of the H_2 is:

H_2 usage = 0.755 kg/hr × ((0.25 × 1.0 hr) + (1.0 × 0.5 hr) + (0.25 × 1.0 hr)) × 1,000 stacks = 755 kg

The material cost before scrap can be estimated in accordance with Appendix A-2 as:

Material cost = $19.04/kg

We will assume that one test station (150-kW load bank) is capable of supporting two stacks during testing, making the total machine time for setup and test:

Testing machine time = ((2.5 hrs/stack / 2) + (0.5 hrs/stack)) × 1,000 stacks = 1,750 hrs

We will assume that one operator can cover three testing stations, making the total labor time:

Testing labor time = (2.5 hrs/stack / 3) × 1,000 stacks = 833.3 hrs

The testing process is subject to a failure rate estimated at around 5%. Stacks failing test are reworked by disassembling the stack, replacing the defective part (assumed to be a membrane electrode assembly [MEA]), and reassembling the stack. Using the Boothroyd Dewhurst, Inc. (BDI) Design for Manufacturing and Assembly (DFMA®) software, the 11.5-kW stack assembly labor time was estimated to be 1.01 hour.

The formula for scrap value is based on the total amount of additional production necessary to make up for the value of the scrapped items as:

Scrap value = (Unit value / (1 – Scrap rate)) – Unit value

Assuming a scrap rate of 5%, the total loss associated with disassembly and reassembly labor is:

Scrap labor time = (((2 × 1.01 hrs/stack) / (1-0.05)) - (2 × 1.01 hrs/stack)) × 1,000 stacks = 106.3 hours

Assuming that the part requiring replacement is a MEA, the total loss associated with replacement parts is:

Scrap value ($) = (($19.36/stack / (1-0.05)) - $19.36/stack) × 1,000 stacks = $1,019

Appendix A-10: PEM Production Facility Estimation

The production facility estimation is based on the floor area required for production equipment, equipment operators, and support personnel. Primary space allowance guidelines used for this analysis were developed by Prof. Jose Ventura at Pennsylvania State University and were downloaded on 10/18/2013 from http://www.personal.psu.edu/jav1/.

A-10.1 Equipment Footprint

Station utilization calculations provide the equipment count for a particular production station. Using the bipolar plate production as an example, each station consists of four pieces of equipment: the 1,000-ton fast acting press, the post-bake oven, the hydraulic pre-mold press, and the electronic material scale, which have the following footprint dimensions in inches:

- Compression molding press: 60 inches x 70 inches
- Post-bake oven: 40 inches x 40 inches
- Pre-mold press: 18 inches x 12 inches
- Material scale: 12 inches x 12 inches

Allowing a 3-foot (36-inch) margin on all sides for maintenance access makes the total machine footprints in square feet (ft^2):

Compression molding press: $(60 + (2 \times 36)) \times (70 + (2 \times 36)) / 144\ in^2/ft^2 = 130\ ft^2$

Post-bake oven: $(40 + (2 \times 36)) \times (40 + (2 \times 36)) / 144\ in^2/ft^2 = 87\ ft^2$

Pre-mold press: $(18 + (2 \times 36)) \times (18 + (2 \times 36)) / 144\ in^2/ft^2 = 53\ ft^2$

Material scale: $(12 + (2 \times 36)) \times (12 + (2 \times 36)) / 144\ in^2/ft^2 = 49\ ft^2$

Three additional space allowances are made for each station for material, personnel, and aisles. The production stations will require space for material receiving and part pickup, typically done using pallets. We will assume one standard 40-inch by 48-inch pallet for receiving and pickup, adding to the required area by:

Material allowance $= 2 \times (40 \times 48) / 144 = 27\ ft^2$

Ventura recommends personnel space of 20 ft^2 per person to allow for movement within the work station during equipment operation. The bipolar plate pressing requires a single operator, adding:

Personnel allowance $= 1 \times 20\ ft^2 = 20\ ft^2$

Aisle allowance is based on the largest transported load. Because we intend to transport material and finished parts on standard pallets, our anticipated load size is 27 ft^2, for which Ventura recommends a 30% to 40% allowance for the net area required, which includes personnel and material. Using a value of 35% makes the aisle allowance for the bipolar plate station:

Aisle allowance: $(130 + 87 + 53 + 49 + 27 + 20) \times 0.35 = 128\ ft^2$

The total floor space allocation for the bipolar plate station is:

Floor space allocation = 130 + 87 + 53 + 49 + 27 + 20 + 128 = 494 ft^2

The fuel cell stack production was broken up into 12 primary work stations with total floor space allocations calculated using the above formulas as:

Production Station	Floor Space Allocation (ft^2)
Catalyst	262
Slot die coating	759
Decal transfer	551
Hot press	426
Die cutting	178
Bipolar plate	494
End plate	1,261
Seal injection molding	178
Stack assembly	522
Stack test and conditioning	439
System assembly	356
System test	439

In addition to equipment, industrial facility space must be allocated for offices, food service, restrooms, and parking, all of which depend on the number of people present during operation. For most automated or semi-automated production equipment, one operator can cover multiple machines. In addition, some operations have long periods of unsupervised operation (e.g.. the 10-hour milling time in catalyst production). Ventura estimates the number of required machine operators using the formula:

$$n' = (a + t) / (a + b)$$

where

a = machine-operator concurrent activity time (load, unload)

b = independent operator activity time (inspect, package)

t = independent machine activity time

n′ = maximum number of machines per operator

The reciprocal of *n′* would represent the minimum number of operators per machine. Using time data (in seconds) extracted from the Boothroyd Dewhurst, Inc. (BDI) Design for Manufacturing and Assembly (DFMA®) process analyses for *a* and *t*, and estimating time for *b*, resulted in the following:

PEM Production Station	a	b	t	n′	1/n′
	(sec)				
Catalyst	1,907	600	36,000	15.12	0.07
Slot die coating	1,800	600	2,666	1.86	0.54
Decal transfer	1,800	600	2,933	1.97	0.51
Hot press	1,800	600	10,547	5.14	0.19
Die cutting	1,800	600	1,316	1.30	0.77
Bipolar plate	20	84	240	2.50	0.40
End plate	60	60	306	3.05	0.33
Seal injection molding	1,800	60	1,480	1.76	0.57
Stack assembly	3,477	0	0	1.00	1.00
Stack test and conditioning	1,800	600	9,000	4.50	0.22
System assembly	3,957	0	0	1.00	1.00
System test	1,800	600	9,000	4.50	0.22

In general, we assume that a single operator can operate a maximum of three machines in a cell arrangement. We also assume that stations requiring multiple operators can utilize a floating operator working between three machines. The exception is catalyst production: we assume that the 10-hour milling time per catalyst batch permits one operator to operate five machines.

To obtain a rough estimate of the number of operators required during any one shift, multiply the required number of operators per station (combinations of either 1.0, 0.5, 0.33) by the number of stations required to produce an annual volume and the station utilization (assuming a single operator is trained to perform multiple tasks). Using the station utilization numbers for 10,000 11.5-kilowatt (kW) stacks per year, we have:

PEM Production Station	Stations	Utilization	Operators per station	Operators per shift
Catalyst	1	0.009	0.20	0.00
Slot die coating	1	0.150	0.50	0.08
Decal transfer	1	0.108	0.50	0.05
Hot press	1	0.511	0.50	0.26
Die cutting	1	0.071	1.00	0.07
Bipolar plate	5	0.895	0.50	2.24
End Plate	1	0.329	2.00	0.66
Seal injection molding	1	0.358	0.50	0.18
Stack assembly	2	0.842	1.00	1.68
Stack test and conditioning	3	0.741	0.33	0.73
System assembly	2	0.919	1.00	1.84
System test	4	0.764	0.33	1.01
Total				**8.80**

Rounding up to nine machine operators per shift, and assuming approximately one support staff per four station operators for purchasing, quality control, and maintenance, the facility needs to support a total of twelve employees. Ventura estimates the following additional facilities:

Food service: 15 ft^2 per employee

Restrooms: two toilets + two sinks per 15 employees (estimated at 25 ft^2 per fixture)

Parking: 276 ft^2 per employee

In addition, office space for support personnel is estimated at 72 ft^2 per employee based on the State of Wisconsin Facility Design Standard. Therefore, additional space requirements are:

Facility	Space Required (ft^2)
Food service	135
Restrooms	100
Parking	2,484
Office	216

Total factory building floor space can be estimated as:

Equipment + Food service + Restrooms + Office = 7,872 ft^2

Assuming a construction cost of $250/$ft^2$, the estimated cost of factory construction is approximately $1,968,000.

Total real estate required can be estimated as building floor space plus parking and building setback (distance from building to streets and other structures). Assuming a 30-foot setback on all sides of a reasonably square facility gives a total real estate requirement of:

$((\text{Factory space} + \text{Parking space})^{1/2} + 60)^2 = 26{,}168\ ft^2 = 0.60\ \text{acre}$

Assuming a real estate cost of $125,000/acre, the estimated total real estate cost is approximately $75,091.