Manufacturing Cost Analysis of PEM Fuel Cell Systems for 5- and 10-kW Backup Power Applications

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Executive Summary

Fuel cell power systems may be used to provide backup power in the event of a grid outage for a variety of applications. Factors such as prevention of injury, loss of revenue or commodity stock, or continuity of security and communication in the event of a power outage drive end users to purchase backup power systems. The telecom industry in particular makes extensive use of backup power systems for cellular towers to ensure that their towers remain operational in the event of a grid outage. Battelle evaluated low-temperature polymer electrolyte membrane (LTPEM) systems for use as a backup power system. The power levels considered for this portion of the project were 5 and 10 kilowatts (kW). Conventional reciprocating gas- or diesel-based generators, battery banks, and fuel cell systems are each capable of providing backup power at this rate; however, fuel cell systems offer many advantages over conventional generators or battery-based systems. Fuel cell systems operating on compressed hydrogen can provide backup power for a significantly longer time than batteries, depending on the amount of on-site hydrogen storage, and provide more reliable backup power than diesel generators. Moreover, compressed hydrogen is more energy-dense than are batteries, and the storage cylinders require no special housing or space conditioning.

Battelle's evaluation included defining representative systems that could serve this market. The representative system concepts were subjected to a detailed cost evaluation based on industry feedback and the application of standard design for manufacturing and assembly analysis methods, including the application of the Boothroyd Dewhurst, Inc. Design for Manufacture and Assembly (DFMA®) software for specific hardware and assembly evaluation. A sensitivity analysis was performed to evaluate the influence of specific high-cost items and components with a high degree of cost uncertainty.

PEM stack costs were less than 50% of overall system cost for all sizes and production volumes considered, and were typically less than 15% at higher production volumes (greater than 10,000 units per year). The DC/DC converter represented the largest cost associated with the balance of plant (BOP), followed by high-pressure regulators to step hydrogen down from its stored pressure to operating pressure for the PEM fuel cell. At the largest annual production volume (50,000 units per year), the overall system cost per kilowatt was found to be $1,875 for a 5-kW system and $1,215 for a 10-kW system.

A sensitivity analysis on some of the major cost contributors shows the potential for further cost reductions. We found the price of platinum to have a minor overall impact on the PEM system. This primarily results from the relatively small quantity of platinum used with this specific cell configuration. We found that major cost drivers included the assumed current density of the fuel cell (here assumed to be 1.5 A/cm^2) and the DC/DC converter as part of the BOP.

A life cycle cost analysis was performed, which evaluated the various non-monetary advantages offered by a PEM fuel cell backup power system. These advantages include the ability to store fuel for long durations without regard to degradation or theft, reduced environmental permitting, elimination of noise and irritating pollutants, and general "good neighbor" characteristics. While the financial incentive is not yet sufficient to choose a fuel cell over a conventional backup power system, these non-monetary advantages need to be considered when selecting a backup power technology.

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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 Technologies Office, will provide an independent assessment of fuel cell manufacturing costs at various volumes and for alternative system designs. This report provides cost estimates for the manufacture of 5- and 10-kilowatt (kW) fuel cell systems for backup power applications. Because backup power must respond quickly to unanticipated events, only direct-hydrogen polymer electrolyte membrane (PEM) fuel cell stacks are considered. This report identifies the manufacturing costs of fuel cell systems using scale-appropriate manufacturing processes at annual production volumes of 100, 1,000, 10,000 and 50,000 units. The manufacturing volumes were defined by DOE and are used for all systems being evaluated within the overall project.

A fuel cell system operating on compressed hydrogen can provide backup power for significantly longer than batteries, depending on the amount of on-site hydrogen storage, and more reliable backup power than diesel generators[1]. Compressed hydrogen has a higher energy density than do batteries, requires no special housing or space conditioning (locating the storage tank outside is acceptable), and is less likely to be stolen than diesel fuel. Diesel fuel is also subject to degradation after extended storage, whereas compressed hydrogen is not. Additionally, diesel engine backup power may be limited to a small number of total run hours per year by environmental regulations. Therefore, a fuel cell system using outside storage for hydrogen offers operational and potential cost advantages over battery and diesel engine backup power. However, to identify the potential life-cycle costs and benefits of a fuel cell backup power system, the entire cost of the competitive systems (including housing and space conditioning) as well as the projected duration of grid outages must be considered. Locations prone to extended outages will benefit most from the unique capability of a fuel cell system to provide extended run times. Locations that experience only occasional short duration outages, on the other hand, are unlikely to derive any economic benefit from a fuel cell system until fuel cell system costs come down significantly. It is the objective of this report to identify the key cost drivers for fuel cell backup power systems and to thereby encourage innovation focused on those drivers, leading to overall lower costs for fuel cell systems.

The system designs that formed the basis of our cost analysis were defined based on Battelle's fuel cell system integration expertise and refined through discussion with industry partners. The report presents our representative design for a PEM system configured for backup power applications, including the basic sizing and configuration design assumptions. Backup power systems necessarily operate without grid support and must be capable of a black start; that is, they must be able to start completely independently. The predominant market application identified for these systems is telecom tower backup. This application has typically used battery banks operating at 48 VDC as the backup system. Hence the primary system configuration considered in this report is a 48-VDC output system as a drop-in replacement for a typical battery bank assembly. For telecom tower backup, 5 kW seems to be a typical power level; however, we anticipate that multi-carrier towers may benefit from higher-power backup systems, hence the inclusion of 10-kW sized systems in this report. Alternate configurations for other applications would be nearly identical except that a DC/AC inverter to output 120/240 VAC would likely be used in place of the DC/DC converter used for 48-VDC output.

[1] http://www.nrel.gov/docs/fy07osti/41572.pdf

Key components of the representative designs were evaluated using manufacturing processes modeled with the Boothroyd Dewhurst, Inc. Design for Manufacture and Assembly (DFMA®) software. Costs of the overall system, subsystem, and specific components were determined by obtaining quotes from candidate manufacturers, and the main cost drivers were identified through a sensitivity analysis. The sensitivity analysis includes the costs of some of the more expensive components, key assumptions, and those components for which the included cost is less certain. A summary of possible opportunities for cost reduction is included. Because fuel cell backup power systems are not currently mass-manufactured, the assumptions for the higher production volumes must be understood to reflect engineering judgement as to the level of cost reduction possible through specific design for mass-manufacturing that would necessarily occur to support the higher volume production rates.

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/Lifecycle Cost Analysis

This approach has been successfully applied to previous cost analyses developed by Battelle.[2,3]

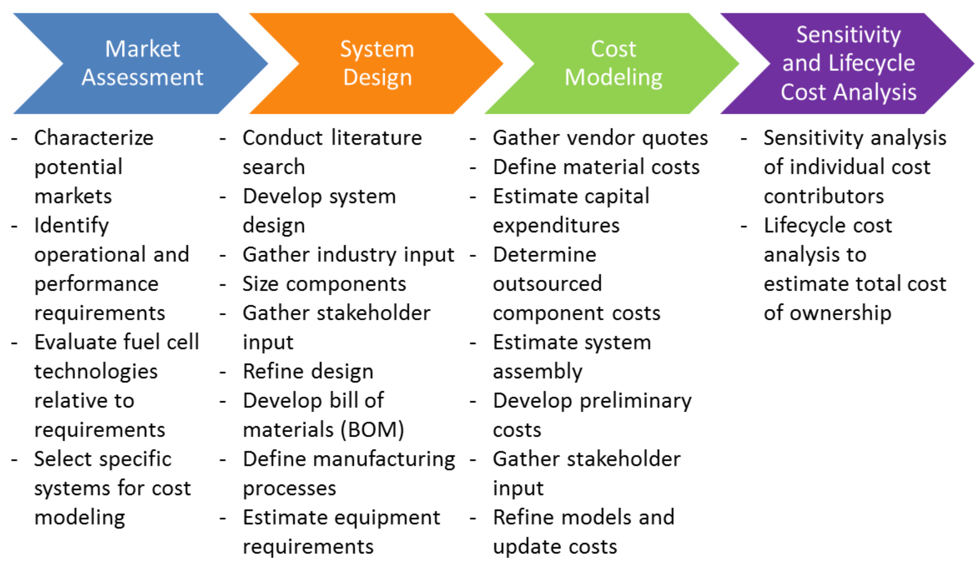


Figure 2-1. Battelle's cost analysis approach

[2] 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.
[3] H. Stone, K. Mahadevan, K. Judd, H. Stein, V. Contini, J. Myers, J. Sanford, J. Amaya, and D. Paul. 2006. Economics of Stationary Proton Exchange Membrane Fuel Cells, Interim Report. Contract No. DE-FC36GO13110.

The first step in our methodology, ***Market Assessment***, assures that we have selected the right fuel cell type and appropriate production volumes to meet market requirements. In this step, Battelle identifies the operational and performance requirements (e.g., hours of operation, frequency, expected lifetime) of the target application and market. Using this information, we define an assessment of the user requirements for a fuel cell product. For this phase of the project Battelle completed a quick survey of the market through dialogue with industry stakeholders to estimate the number of potential units in the market and the expected market growth for backup fuel cell systems in the 5- to 10-kW range. This information formed the basis for selecting the system design and fuel cell types best suited to meet user requirements and the appropriate production volumes to consider in the modeling exercise.

Step 2, ***System Design,*** was a literature review of fuel cell designs for backup power applications including component design and manufacturing processes. Possible improvements in system design and manufacturing were identified and incorporated into the example system. From these results, the basic construction and operational parameters for a fuel cell stack and system were defined, along with potential improvements. The fuel cell system and stack designs did not focus on an individual manufacturer's designs, but were instead representative of a typical design based on the literature and Battelle's engineering expertise. The stack and system design were vetted with industry stakeholders to ensure the feasibility of the design, identify possible improvements, and determine current and alternative manufacturing approaches. The final design and projected improvements were consolidated 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 component costs were estimated through vendor quotes. Mathematic functions for scaling factors were developed to estimate the changes to outsourced components and material costs as a function of production volumes when vendor quotes for higher volumes were not available. These 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 line utilization. These calculated values determined the number of individual process lines required to support various product demand levels. The manufacturing capital cost model is in turn based on the number of process lines required. We 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 (H_2A) model. Total fuel cell system costs including capital expenditures were then estimated for the baseline system and projected improvements. Details of these costing calculations are provided in Appendices A-1 through A-10.

A ***Sensitivity Analysis*** (Step 4) was performed to determine which design parameters or assumptions have the most effect upon the stack and system cost. Single factor sensitivity analyses were performed and helped determine the impact of individual parameters on system costs. Based on these results, Battelle outlined possible design optimization approaches 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 installations of 5- and 10-kW fuel cell power generation systems used solely for backup power. As noted above, the most common application, particularly in overseas markets with poor grid reliability, is telecom tower backup. Additional applications could include emergency power for a wide range of residential, commercial, industrial, and municipal buildings (e.g., fire stations), particularly to support safe egress and critical operational functions. We believe that fuel cell systems used for many of these applications are likely to be primary power or combined heat and power (CHP) systems designed for long-term grid power offset operation in addition to backup power. Because the value propositions and system designs are considerably different for those applications, our previous CHP-primary power evaluation for the 1- to 25-kW size range[4] is more appropriate for those applications.

3. Market Assessment

There are multiple markets for backup power systems such as telecom, residential, light commercial, and health care. With the increasing frequency and severity of storms, residential backup power systems, and particularly natural gas-fueled reciprocating engine/generator sets, are seeing significant market growth[5]. Businesses of all sizes are also moving to provide on-site backup power to assure safe egress, continued security, and effective response to emergency conditions as well as data protection. Some businesses, notably e-commerce and telecom, are highly sensitive to a business operations outage as the cost of an outage can be extremely high in terms of lost revenue and customer dissatisfaction. These businesses typically have the staff and expertise to evaluate a variety of possible options for backup power, whereas residential backup purchase decisions tend to be based on price and company reputation.

The most widely marketed residential backup power systems fall in the 5- to 30-kW range. At 20- to 25-kW ratings, these systems are capable of handling most domestic power loads including some air conditioning and/or cooking tasks. At the 5-kW size, power is generally limited to critical loads (refrigeration, lighting, sump-pump). A 10-kW system might operate some space conditioning systems. Residential systems include a once/month short-cycle run to assure the system is operating correctly. Residential systems are generally sold on price and are not usually considered regulated environmental sources when operating on natural gas. Various news articles and reports suggest that the number of standby generators (as opposed to portable generators) sold may be on the order of 100,000 or more units/year[5,6] in the United States. Hence, this market might be an opportunity for the higher-volume manufacturing levels envisioned by DOE. Although the extreme sensitivity to first cost will limit early

[4] Battelle Memorial Institute. 2015. *Manufacturing Cost Analysis of 1, 5, 10, and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications.*
[5] http://www.nytimes.com/2013/04/25/business/energy-environment/generators-become-must-have-appliances-in-storm-battered-areas.html?_r=0
[6] https://www.cpsc.gov/PageFiles/102941/ecportgen.pdf

penetration, consideration of cost drivers may help define an approach to this market. However, with natural gas remaining relatively inexpensive and reliable even in extreme weather conditions, bottled hydrogen systems are unlikely to be competitive. Consideration of reformer based systems that could provide unlimited run time comparable to the natural gas engine systems was beyond the scope of this report. Battelle's 2015 report[7] provides an analysis of a reformer system that serves both primary and backup power applications for this size range.

Telecom tower backup power probably represents the most likely early-penetration market. Telecom towers are frequently characterized by remote rural locations (subject to frequent and long outages) or urban settings including commercial building rooftops. In urban settings, outages are generally shorter. However, installation of battery or diesel backup systems may require expensive building modifications. In urban settings, noise or environmental ordinances and good-neighbor relationships may discourage or prevent the installation of diesel systems. Under these conditions a fuel cell system may offer a preferred solution if the initial and life cycle costs are reasonable, even if they are higher than the competitive technology.

3.1 Market Requirements and Desired Features

Residential backup power applications represent a large, but highly price sensitive, market. The telecom tower backup power market is more limited in numbers of units but has a high cost of lost business and customer annoyance associated with an outage—particularly an extended outage—associated with each unit. Because of the cost associated with an outage, telecom backup is considered a significant near-term potential market for fuel cell systems. Additionally, residential applications benefit from installed infrastructure (natural gas pipe lines), while telecom towers are more likely to be far from natural gas sources. Given the diversity of the potential markets, we attempted to identify some key characteristics that would be represented in any of these markets; key among the attributes is reliability.

- The system must start the first time, every time without external grid support and preferably without human interaction.
- The system must recognize that a grid (or primary power) outage exists, isolate itself from the grid, and come on line automatically.
- When the grid is restored, the system should drop off line and shut itself down in an organized manner that facilitates rapid start-up at a later time.
- For most applications, it will be necessary for the system to power-up and self-check monthly (or perhaps more often for critical applications).
- Backup power system lifetime requirements are on the order of 500 to 2,000 hours, allowing for some cost savings, compared to the very long life expectancy (~50,000 hours) for primary power systems.
- For most applications, the system would be expected to be skid mounted (except for the fuel bottles) with hook-up performed by trained installers or licensed professional pipefitters and electricians.

[7] Battelle Memorial Institute. 2015. *Manufacturing Cost Analysis of 1, 5, 10, and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications.*

- All applications will be required to manage safety, including hydrogen leak detection and response.

3.2 Technology Selection

Only low-temperature PEM (LTPEM) technology was considered for this application. Solid oxide fuel cell (SOFC) systems require extended start-up time, which is inconsistent with the need for rapid response to a grid outage. Additionally, SOFC systems do not have the cycling capability necessary for the monthly self-check which would introduce at least 12 starts/year to the number of starts required for outage response. Maintaining a SOFC system in hot standby was not considered a reasonable approach for backup power. LTPEM stacks are assumed to operate at 60°C to 70°C, requiring an air cooled radiator to dissipate heat. A potentially lower cost option would be use of domestic or other on-site water for cooling during the relatively rare periods of backup operation. For commercial building installations, the heating, ventilation, and air conditioning (HVAC) cooling water system may be used to avoid the cost of the radiator. For this analysis, we included the radiator and cooling pump to best fit the telecom backup power application.

A DC/DC inverter and lead acid batteries were incorporated with the system to provide 48-VDC output and enable system startup. For stationary backup power systems there is no need for premium battery technology such as lithium-ion technology.

3.3 Market Analysis Conclusion

PEM fuel cell stacks operating on compressed hydrogen were deemed to be the most appropriate technology to meet the core requirements for backup power based on their ability to provide fast and reliable response. Telecom tower backup applications have been identified as a potential early adopter market. Residential and commercial backup power systems will need to experience major cost reductions before significant market penetration can occur; but the potential volumes for these markets are large.

4. System Specifications

This section provides a general description of the systems selected for analysis. As noted above, only compressed-hydrogen LTPEM systems were considered. The systems analyzed are representative of potential system configurations but do not reflect any specific commercial system. They reflect Battelle's judgment on an appropriate balance between efficiency and cost and between proven and developing technology. The basic system schematic is the same for all systems evaluated; the only differences arise in the sizing of components and choices made for fuel cell stack voltage, which affects some BOP hardware.

4.1 General Description

This report concerns backup power applications, or more specifically, stationary systems that provide electrical power during a grid outage. There is an expectation that the system will recognize a grid outage or grid disruption (e.g., low voltage or off-frequency operation) and shift rapidly—usually within a few seconds—to the backup power system. Generally, the switch from grid to backup power includes dropping non-critical loads and some form of phase matching or spin-down for rotating equipment.
A backup power system is not usually designed to manage all possible loads at the site; however, for the primary market identified (telecom backup) the operator's expectation is that the backup power system

will provide for full functionality of the site. Because telecom loads use DC power, phase matching is not required and both connect and disconnect may occur rapidly and randomly. Since the fuel cell may require up to 10 minutes to come to full power and achieve stable temperature and operating status, adequate battery capacity must be provided to support the fuel cell start-up process and carry the system load during the start-up time. Although some battery capacity is required to manage transient load changes, the start-up requirement defines the battery system needed.

4.2 Nominal Metrics

Table 4-1 shows the performance objectives considered as the example designs were being developed. Table 4-2 provides details on the fuel cell stack design for the PEM systems. Tables 4-1 and 4-2 are based on our judgment regarding typical and representative specifications and requirements: they are not based on any specific system nor do they constitute recommendations for specific hardware.

Table 4-1. Backup Power System Nominal Design Basis

Metric/Feature	Objective
Input, Fuel	Compressed hydrogen
	6,000 psig K-cylinder or similar
Input, Air	Ambient air
Input, Other	N/A
Output	48 VDC (AC output optional with external inverter)
Net Power Output	5, 10 kW
System Efficiency LHV hydrogen to electrical power at DC/DC output terminal	50%
System Life	2,000 hours
System Maintenance Interval	1 year
Grid Connection	No – Backup power only
Operate off-grid	Yes, critical load backup
Start off-grid	Yes
Battery run time at full load (minutes)	10
System Run Time	Varies with on-site hydrogen storage

Table 4-2. PEM Fuel Cell Design Parameters

Parameter	5 kW	10 kW
Power Density (W/cm^2)	0.83	
Full Load Current Density (A/cm^2)	1.5	
Full Load Cell Voltage (VDC)	0.55	
Catalyst (Pt) loading (gm/cm^2)	0.15	
Active Area Per Cell (cm^2)	200	400
System Net Power (kW)	5	10
System Gross Power (kW)	6	12
Number of Cells per stack (#)	36	36
Nominal Stack Open Circuit Voltage (VDC)	36	36
Full Load Stack Voltage (VDC)	20	20
DC/DC Converter type	Boost	Boost

4.3 System Sizing and Operation

Grid outage conditions impose some constraints on system design. The system must be able to self-start without grid assistance and it must be able to follow applied power transients while maintaining a regulated voltage output. For our analysis, we assume the system has a 3:1 turndown ratio for power. As noted above, the primary existing market for backup power is for telecom towers. Telecom towers generally experience relatively slow changes in load—typically slow enough for fuel cell response times once the fuel cell is operating. However, other applications, particularly in the larger power range, may see significant variation in load profile, with characteristic transient times shorter than fuel cell response time; compressor starting is an example of one such application. For those applications, energy storage is required to manage transients and for all systems energy storage is required to support fuel cell start-up. For this analysis we assumed that the battery storage system employed would be able to provide 100% of nominal system power for 10 minutes to support fuel cell system start and up to 200% of nominal system power for 30 seconds to support rapid load changes. In the absence of the grid to provide additional power or to accept excess power, the fuel cell system should be sized to cover critical loads but not to over-power the on-site electrical system when power usage drops. For operation at low loads (below 33% of nominal), the fuel cell would be operated intermittently to recharge the batteries, which would provide the backup power. For example, the batteries sized as above would supply 30% load for 30 minutes, then the fuel cell system would be operated at (say) 50% load for ~50 minutes to cover the load and recharge the batteries. Once the batteries reach full charge, the fuel cell is idled for another 30 minutes.

4.4 System Configuration

Figure 4-1 is a high-level schematic of a backup power fuel cell system operating on compressed hydrogen.

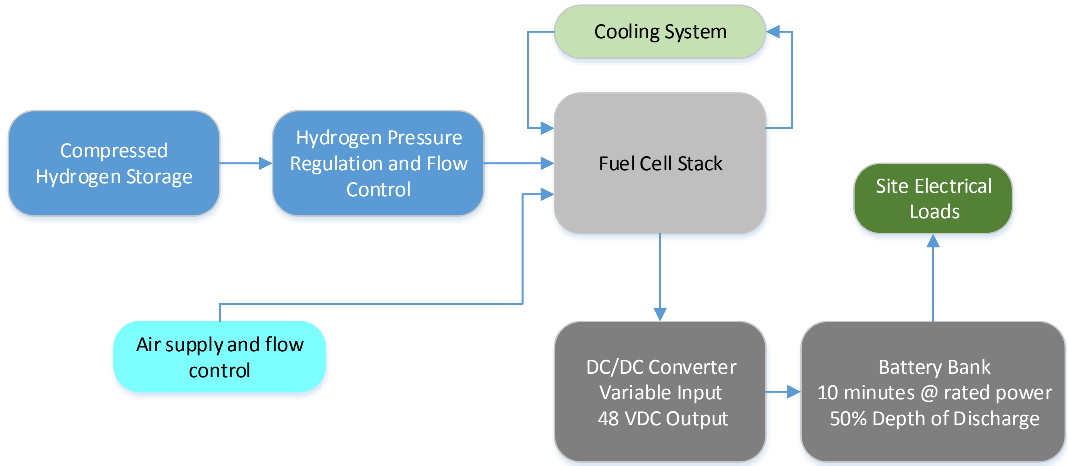


Figure 4-1. High-level fuel cell system schematic

As described above, the fuel cell system can be viewed as a range-extender for a battery system that is otherwise capable of only 10 minutes of system outage. The length of the supported grid outage is determined by the quantity of hydrogen stored on-site. A single 6,000-psig K cylinder provides roughly 3 hours of operation at 5 kW. Unlike batteries, hydrogen cylinders may be stored outside in extreme weather conditions so long as adequate security and safety features are installed.

4.4.1 LTPEM System

A component-level schematic of the LTPEM system configuration used for this costing study is shown in Figure 4-2. The major subassemblies are:

- Fuel supply including compressed hydrogen storage, pressure regulator, and pressure relief devices.
- Air supply including filter, cathode blower and recuperative cathode humidifier. The recuperative humidifier may not be required for some stack configurations.
- Cooling system including coolant pump and radiator. Liquid cooling is assumed for the stack and power electronics. Low-conductivity glycol coolant is required for the LTPEM stack to avoid shorting the stack.
- Electrical system including batteries, DC/DC converter, and system controls.
- Fuel cell stack.

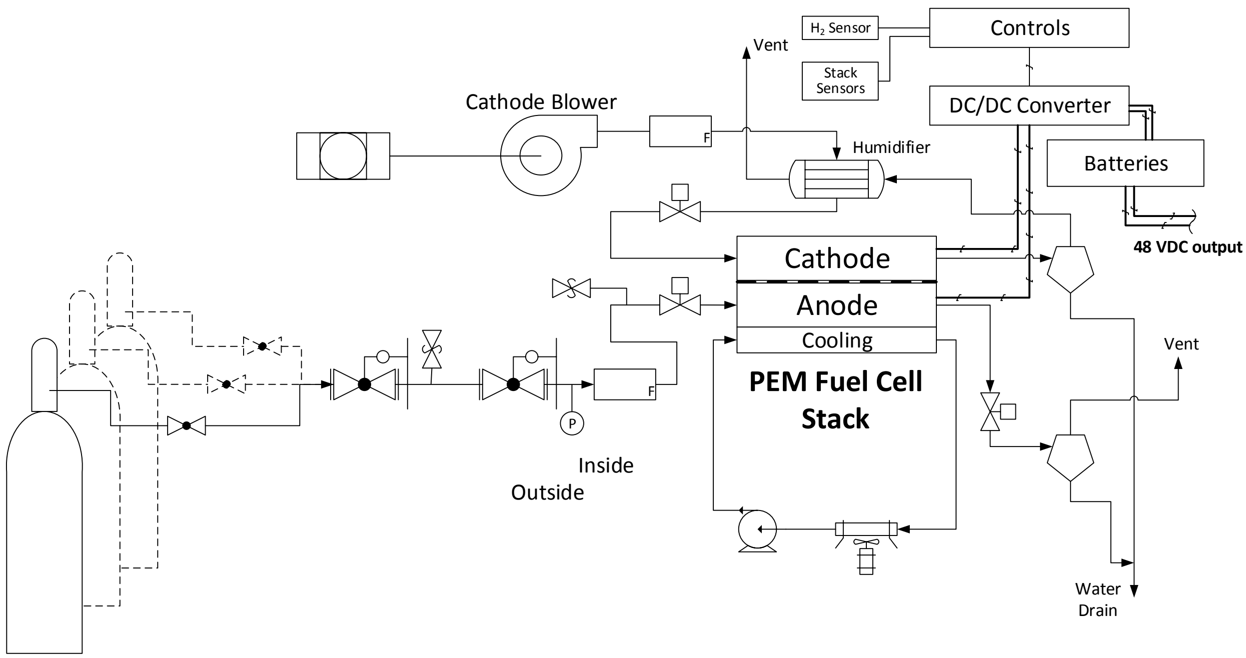


Figure 4-2. Representative LTPEM backup power system

The cathode air entering the stack is humidified by adsorbing water across a membrane (or via enthalpy wheel or some other form of recuperative humidifier) from the stack cathode exhaust. Some stack manufacturers are eliminating the need for cathode humidification through stack design. However, for intermittent and potentially short-time operation there is potential for electrolyte membrane dehydration without direct humidification. The humidifier also reduces the need for precision air flow control, may assist in water management, and reduces the potential for a visible plume of vapor on cold days. An anode purge valve is provided to enable intermittent release of non-reactive gases and water that accumulate on the anode side.

A low-electrical-conductivity glycol/water mixture is used to cool the PEM stack. Coolant enters the stack at about 50°C, with the temperature managed by modulating radiator fan speed. After passing through the stack, the glycol coolant may be directed to the power electronics for cooling before returning to the radiator.

4.5 Electrical System

4.5.1 Overview

The electrical system provides the interface between the fuel cell stack, the batteries, and the local electrical distribution system. The fuel cell backup power system is considered to be a drop-in replacement for a large battery bank system, hence, components downstream of the 48-VDC bus are not included in the cost estimates.

The main challenge in designing a fuel cell system for off-grid operation is matching the stack variable voltage over the desired load range with the battery system. The most straightforward design, and the design used for this analysis, is to have a DC/DC converter between the fuel cell output and the battery bus to manage the battery state of charge, maintain fuel cell system health (prevent excessive current draw), and to sustain system power output. For applications which operate on AC electrical power, a DC/AC inverter would be connected between the battery bus and site loads. The DC/AC inverter is considered to be site-specific hardware and is not included in the cost analysis.

4.5.2 Off-Grid Operation

For off-grid operation (the only operation mode considered in this evaluation), the fuel cell backup power system must start rapidly and respond to transient loads that are usually out of the control of the operator (e.g., contact-closure-based equipment starts and stops that result in near instantaneous electrical load changes). A battery system can respond adequately as long as the current delivery limit of the battery system is not exceeded and the batteries are maintained in an appropriate state of charge. A fuel cell backup power system is slightly different than a battery system in that the fuel cell stack responds within seconds of a major increase or decrease in load, whereas the latter can respond faster, on the order of milliseconds. Generally, a sudden drop in load is not a problem for a fuel cell as hydrogen conversion stops when the terminal voltage increases and the hydrogen pressure regulators maintain the pressure at a safe condition. Short term operation at zero current and open circuit voltage does not damage the fuel cell. A sudden increase in load can be problematic if the current draw exceeds the kinetically limited ability of the hydrogen reaction to provide electrons. Cell voltage reversal can occur and permanent cell damage may result. Therefore, the control system should monitor stack health, primarily cell voltage, as well as limit DC/DC converter current draw from the stack if any cell voltage drops below a predetermined value—typically about 0.5 VDC. This necessary feature, along with the relatively wide voltage range associated with fuel cell operation, adds cost to the DC/DC converter compared to a more passive device.

Deep cycle lead acid batteries are used for energy storage. Lead acid batteries are widely available, relatively inexpensive and well understood. They easily tolerate rapid charge and deep discharge cycles and achieve acceptable lifetimes when properly managed. For lead acid batteries, the battery management system (BMS) can be relatively simple: state of charge is reasonably well represented by battery open-circuit voltage or by a polarization curve of voltage versus current. The BMS is integrated into the overall system control package. The BMS regulates charging rate based on the implied state-of-charge, dropping to a trickle charge (by reducing fuel cell power output) as the battery voltage increases. The BMS also limits the minimum terminal voltage, tripping the system should battery terminal voltage become too low indicating excessively high current draw at the battery state of charge.

Other energy storage options exist. Lithium ion (LI) batteries have a high energy/power density relative to other battery technologies but they cost more than lead acid for equivalent energy storage and require a more sophisticated BMS. For mobile/transportation applications, LI batteries are attractive due to their low weight and small footprint, but for stationary applications the minimal premium for smaller size and weight is not enough to overcome the cost advantage enjoyed by lead-acid batteries, which are historically established as a backup power source. Ultracapacitors are also an option, particularly for high surge power applications. The main drawback of ultracapacitor technology is limited energy density. This can be overcome by hybridizing ultracapacitor technology with either lead acid or LI batteries. For this study we assumed that lead-acid batteries alone would be sufficient to manage the transients; alternative technologies were not considered.

4.5.2.1 DC/DC Converter System

Figure 4-3 shows a basic electrical configuration with a DC/DC converter. Fuel cell output voltage and current are regulated by the DC/DC converter to maintain a relatively constant voltage at the battery terminals. Typically, the battery bus voltage is maintained at a level that yields a relatively high state of charge (90% or greater) on the batteries. However, the DC/DC converter is also managed to prevent it from drawing excessive power from the fuel cell if adequate hydrogen is not available. Limiting the output current of the DC/DC converter causes the batteries to accept additional load as they will attempt to maintain the voltage on the primary bus, though the voltage will decrease as the battery state of charge is decreased.

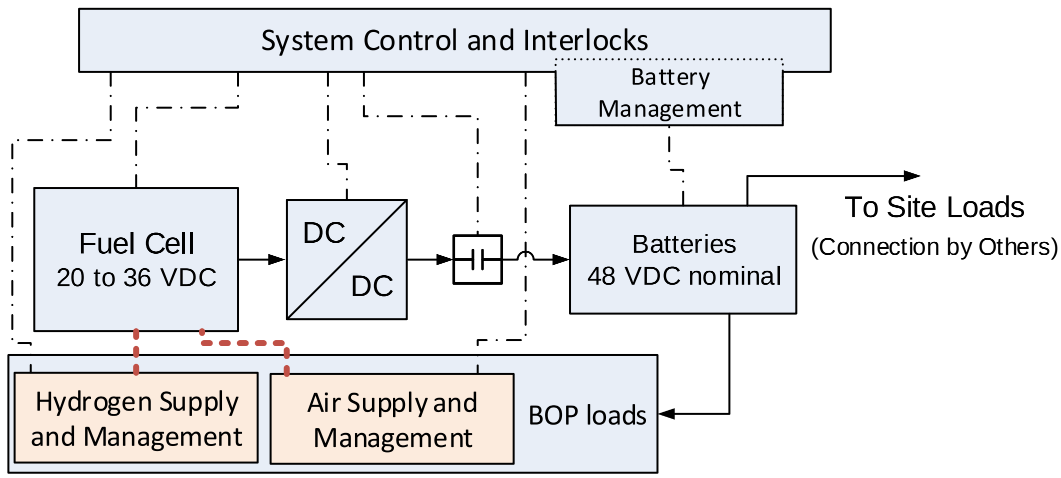


Figure 4-3. Electrical system schematic

Because the output voltage of both the 5- and 10-kW stacks (20 VDC at full load) is below telecom system requirements, a boost converter is used to achieve the 48-VDC nominal output voltage. Boost type DC/DC converters are generally more expensive than buck converters, but are still readily available. Most BOP electrical hardware is expected to operate on 24 VDC; therefore, a small DC/DC converter (generally referred to as a “brick” converter) is required to service the BOP. “Brick” converters have a relatively wide input voltage range and excellent reliability. The system controls circuits operate on the available 48 VDC, but include internal voltage regulation to provide the requisite 5 VDC required by the electronics.

4.5.3 Thermal Management

Most power management electronics are 90% efficient or better—typically on the order of 95%. However, this still represents a significant heat load. We have assumed that, at the power levels evaluated in this study, critical electronic components are supplied with their own air cooling systems for thermal management.

4.5.4 Wiring and Ancillary Components

Wiring, connectors, support hardware, and other minor components of the electrical system were addressed with an addition of 10% of BOP cost.

5. Manufacturing Cost Analysis

5.1 System Cost Scope

As outlined in Section 4, the system cost analysis is focused on backup power for telecom and similar industries which require 48-VDC power and which have historically used battery banks for backup. Therefore, the scope of the analysis is limited to the hardware required to replace a conventional battery bank system. No equipment downstream of the 48-VDC battery bus output terminals is included in the analysis. Hydrogen storage is identified as a separate category within the cost analysis since the necessary run time may vary significantly with application and location. While we have based hydrogen storage costs on K cylinders, alternate storage methods (such as tube trailer or automotive style composite overwrap cylinders) could be substituted where required.

5.2 System Cost Approach

The manufacturing cost analysis approach includes:

- Developing manufacturing models and cost estimates for each component, process, and/or outsourced subassembly.
- Defining 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.
- Evaluating capital costs for the manufacturing facility.

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

Component manufacturing and assembly costs were calculated from both custom models and the DFMA® library of manufacturing process models provided with the Boothroyd Dewhurst software. The specifics of the manufacturing cost calculations are shown in Appendices A-3 through A-7. Cost of purchased components was incorporated into the manufacturing cost models to determine the cost for each component based on stack size and annual production volume.

The output of the manufacturing models included labor time, machine time, tooling cost, and material cost required to produce the components (membrane electrode assemblies [MEAs], bipolar plate) and/or perform the processes (heat treating, stack assembly) required to support annual production levels. Machine/operation time was used to independently calculate the number of individual production stations required to support annual system production levels and to calculate manufacturing equipment utilization for each production station in order to determine machine rates for the various manufacturing processes.

Because of its central role in the system, we have provided the most detail on the stack production process. The overall system production process follows a similar format with parallel and sequential production stations configured to support the required annual production volumes (see Figure 5-1 in Section 5.3). Each station operates independently with required input materials and components assumed to be conveniently available when needed.

Assembly costs were determined by building a structure chart in the DFMA® software that defines the components and processes necessary to build up the assembly. For each structure chart entry, the software computes a process time based on component and process details that are entered in a set of question panels. For components, these include size, weight, handling difficulties (flexible, awkward), alignment difficulties (small clearance, excessive insertion force), etc. Process question panels are specific to the process being performed (fastening, drilling, welding), but generally take into account type of tooling (manual, automatic), handling requirements (one hand, two-person lift), etc. The total time computed by the software is assumed to be for a fully learned process, and is modified for lower volumes using learning curve analysis as described in Appendix A-8.

The final cost of producing the fuel cell systems includes a testing and burn-in sequence for both the individual stacks and the overall system. Machine time and fuel consumption are calculated based on a testing schedule that generally consists of a partial-power warm-up, full-power test, and partial-power cool-down, with power output directed to a multi-input load bank. We assume that the stack and system test sequences are identical, as defined in Appendix A-9.

The manufacturing capital cost model is based on the number of production stations required, and provides the basis for calculating factory floor space and personnel requirements as detailed in Appendix A-10. We assumed that capital equipment expenditures for fuel cell system 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.

5.2.1 System Manufacturing Cost Assumptions

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

Table 5-1. General Process Cost Assumptions

Cost Category	Cost Assumption
Labor	$45.00/hr
Energy	$0.07/kWh
Overall plant efficiency	85%

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)[8]. Appendix A-1 provides details of our machine rate calculations for the various production processes used to manufacture the backup power systems.

For each production station, utilization is calculated as the fraction of the total available time required to produce the components and/or perform the processes necessary to support 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

[8] 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.

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 backup power system manufacturing process.

5.3 PEM Stack Manufacturing Costs

A PEM system, as described in Section 4, includes: the fuel cell stack, hydrogen supply, air supply, controls and sensors, cooling system, electrical equipment, and assembly and support hardware. Section 5.3.1 discusses the stack manufacturing process used to achieve the design specifications in Table 5-2. Section 5.3.2 considers fuel cell support subassemblies created from commercially available hardware. The remaining subsections under Section 5.3 consider the overall system assembly process.

Table 5-2. PEM Fuel Cell Design Parameters

Parameter	5-kW System	10-kW System
Power Density (W/cm²)	0.83	
Current Density (A/cm²)	1.5	
Cell Voltage (VDC)	0.55	
Active Area Per Cell (cm²)	200	400
System Net Power (kW)	5	10
System Gross Power (kW)	6	12
Number of Cells per stack (#)	36	36
Nominal Open Circuit Voltage	36	36
Full Load Stack Voltage (VDC)	20	20
Membrane Base Material	PFSA, 0.05mm thick, PTFE reinforced	
Catalyst Loading	0.15 mg Pt/cm² (total) Cathode is 2:1 relative to Anode	
Catalyst Application	Catalyst ink applied with selective 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	
MEA Construction	Hot press and die cut	
Seals	0.8 mm silicone, injection molded	
Stack Assembly	Hand assembled, machine pressed before tie rod installation	
Bipolar Plates	Graphite composite, compression molded	
End Plates	Die-cast and machined A356 aluminum	

5.3.1 PEM Stack Manufacturing Process

The stack consists of end plates, bipolar plates, seals and MEAs as shown in Figure 5-1, which shows the manufacturing process in flow chart format. The four fabrication processes leading to stack assembly are:

- End plate fabrication
- Bipolar plate fabrication (anode and cathode plates have different channel patterns so appear as separate lines in Figure 5-1. The fabrication process is identical for both plates.)
- Seal fabrication
- MEA fabrication

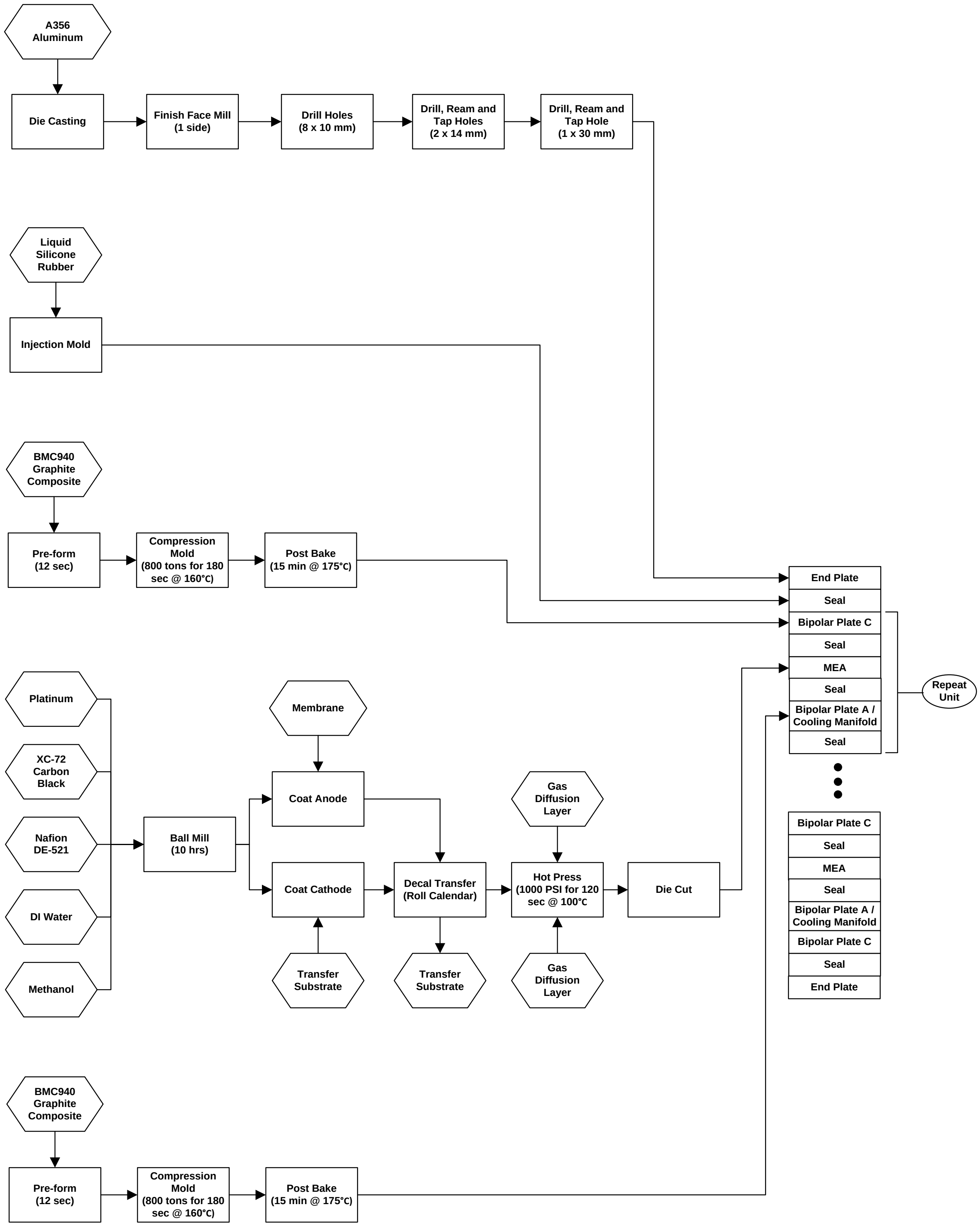


Figure 5-1. PEM fuel cell stack manufacturing process

Only the primary manufacturing and assembly processes are shown. As indicated in Figure 5-1 and Table 5-2, a stack consists of two end plates and the appropriate number of repeat units. Repeat units include:

- One MEA
- One each cathode and anode bipolar plate
    - When stacked, the Anode and Cathode plates are back to back to provide coolant flow channels)
- Seals between each item (three seals each repeat unit)

5.3.1.1 PEM Stack Component Size and MEA Manufacturing Setup

MEA components for the 5-kW system have 200-cm^2 active area. The MEAs for the 10-kW system have a 400-cm^2 active area. Figures 5-2 and 5-3 show these two configurations. Both cell sizes use a 30-mm margin on all sides to allow for gas/cooling manifolds and tie rod holes. The primary dimensions were selected to optimize usage from standard roll material of 610 mm in width.

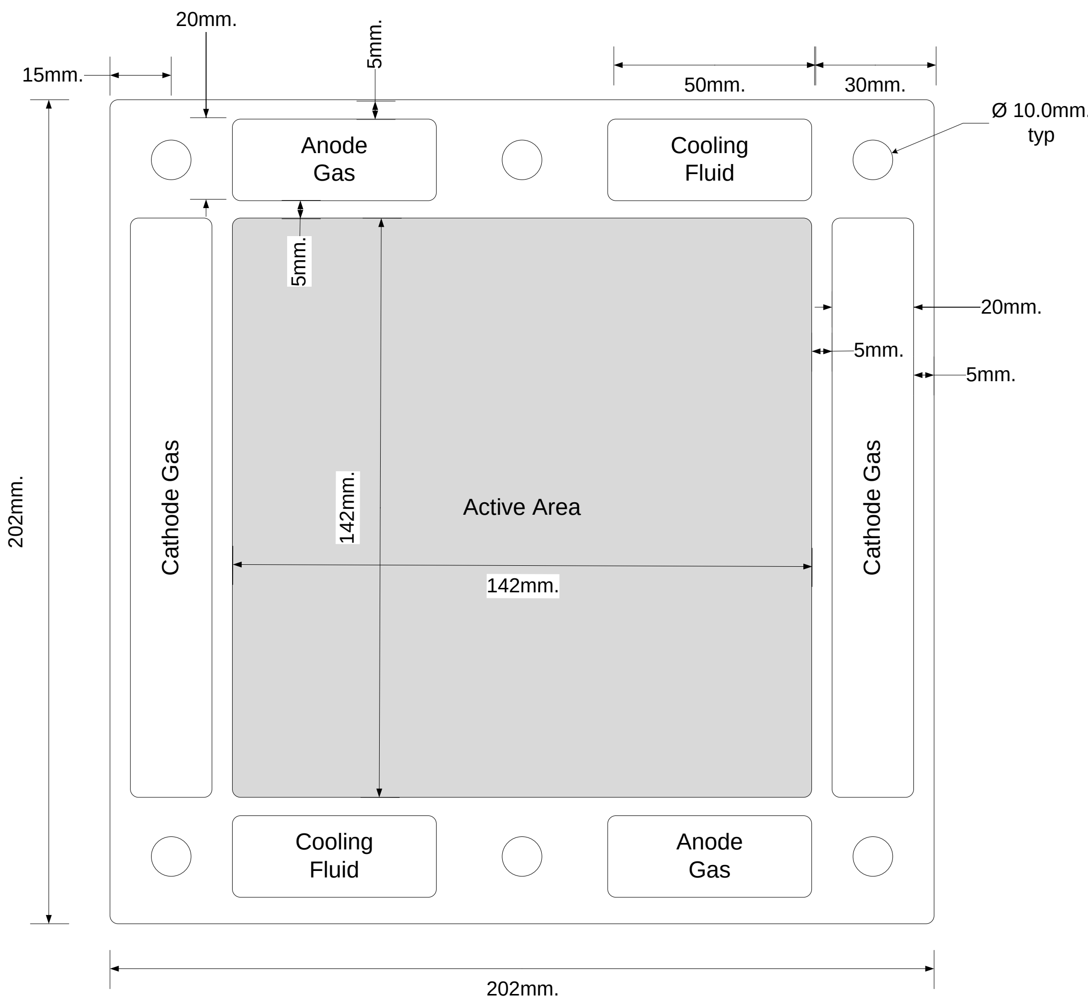


Figure 5-2. PEM MEA configuration for 200-cm^2 active area

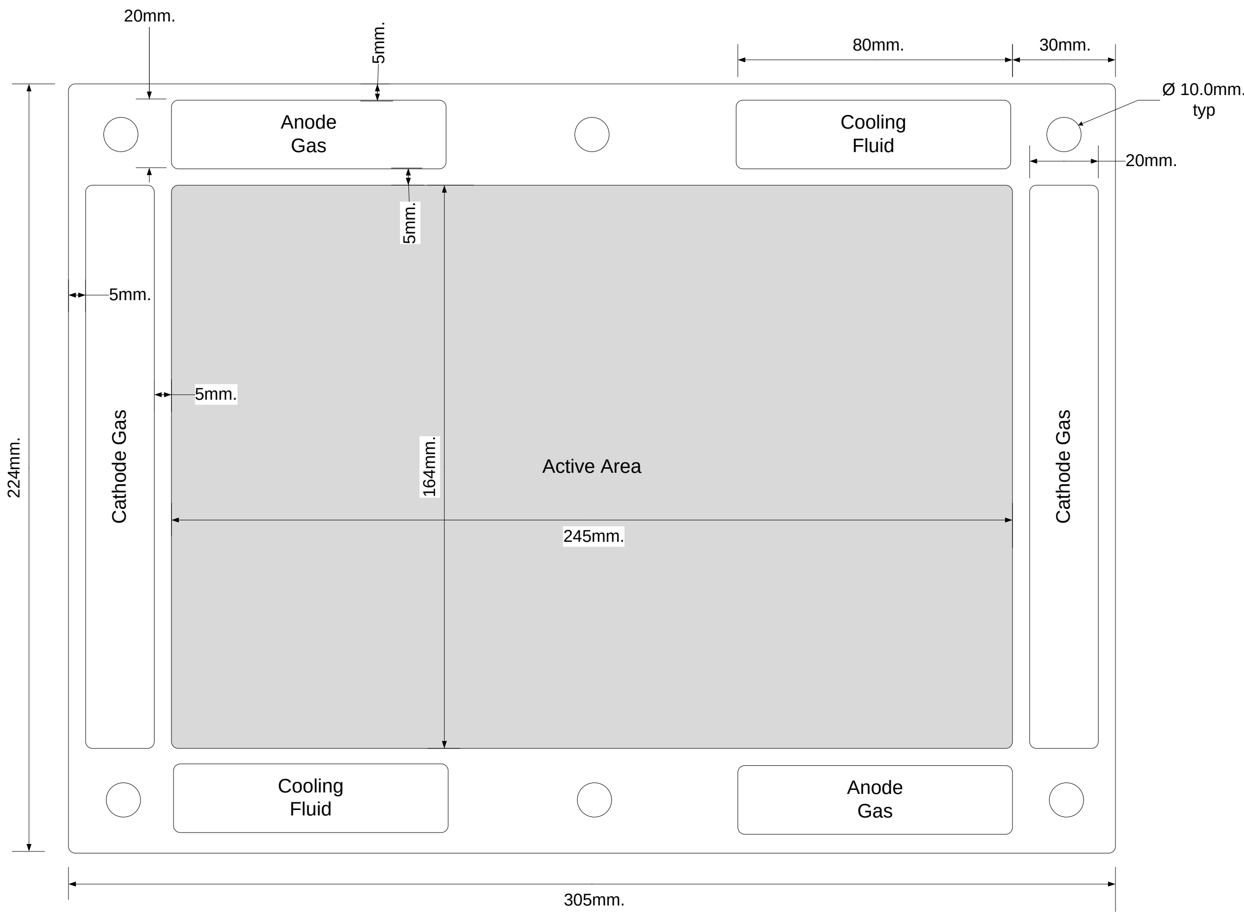


Figure 5-3. PEM MEA configuration for 400-cm² active area

5.3.1.2 PEM Membrane Electrode Assembly (MEA)

The MEA is built up in layers starting with the hydrated membrane. The components of the catalyst ink are ball-milled into a uniform suspension. The anode layer is selective slot die coated directly on the hydrated membrane and dried. Meanwhile, the cathode layer is slot die coated onto a transfer substrate and dried. The coated membrane and transfer substrate layers are heated and roll pressed, then the transfer substrate is peeled away from the cathode layer following pressing. The catalyzed membrane is finally hot pressed between two gas diffusion layers (GDLs) and die cut to final cell dimensions. The catalysts and GDLs are only applied to the active area. The die cutting process includes cutouts for the manifolds as shown in Figures 5-2 and 5-3. Details of the process calculations are shown in Appendices A-3 (catalyst application) and A-4 (GDL application). 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. The MEA material cost summary is provided in Table 5-3 and production cost summary is provided in Table 5-4.

Table 5-3. PEM MEA Material Cost Summary—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Catalyst	$1.79	$1.59	$1.48	$1.43	$3.42	$3.09	$2.90	$2.81
Membrane	$5.43	$3.29	$1.99	$1.41	$8.09	$4.90	$2.97	$2.09
GDL	$118.15	$34.44	$10.04	$4.24	$149.66	$43.63	$12.72	$6.96
Transfer Substrate	$1.32	$0.18	$0.02	$0.01	$1.41	$0.19	$0.03	$0.02
Total Material Cost	**$127**	**$40**	**$14**	**$7**	**$163**	**$52**	**$19**	**$12**

Note that the GDL is the principal cost driver at all volumes, representing over 55% of the MEA cost at 50,000 units/year and over 90% of the cost at low volumes; identifying alternate materials for the GDL could significantly impact cell, stack, and system cost. Because of the precious metal content in the catalyst, its cost does not reduce as quickly with production volume as do the other materials. A potential concern is that platinum availability may be reduced as other fuel cell systems (automotive) are commercialized, and that this could further drive up catalyst cost. A robust recycling program to reclaim the catalyst from retired fuel cells would significantly reduce this concern. Such a program is in place for automotive catalytic converters and would probably be even easier to implement for PEM fuel cells.

Table 5-4. PEM MEA Cost Summary—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$126.69	$39.51	$13.54	$7.08	$162.59	$51.81	$18.61	$11.88
Labor	$0.33	$0.27	$0.27	$0.27	$0.56	$0.49	$0.49	$0.49
Machine	$0.51	$0.42	$0.41	$0.26	$0.88	$0.78	$0.77	$0.52
Scrap	$0.83	$0.31	$0.15	$0.10	$1.10	$0.45	$0.23	$0.18
Tooling	$4.10	$0.41	$0.11	$0.09	$4.27	$0.43	$0.13	$0.11
Part Total	**$132.44**	**$40.92**	**$14.48**	**$7.80**	**$169.40**	**$53.96**	**$20.23**	**$13.17**
# per Stack	36	36	36	36	36	36	36	36
Stack Total	**$4,768**	**$1,473**	**$521**	**$281**	**$6,098**	**$1,943**	**$728**	**$474**

5.3.1.3 PEM 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 assembly to provide alignment (note 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.

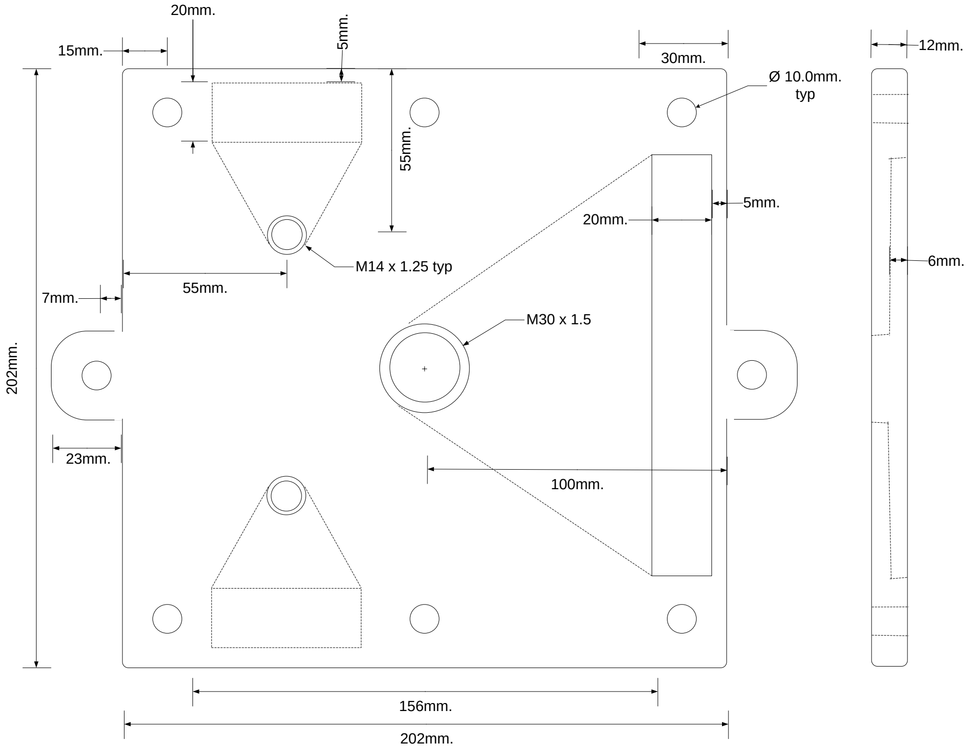


Figure 5-4. PEM 5-kW end plate size

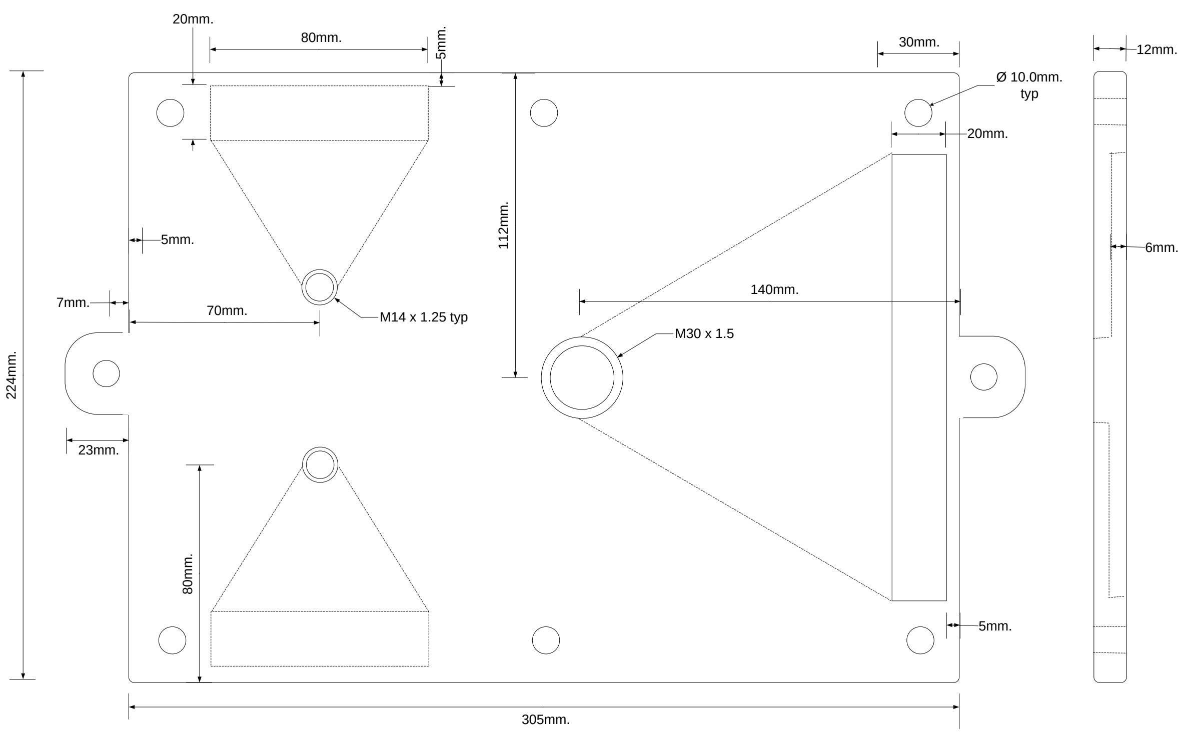


Figure 5-5. PEM 10-kW end plate size

The process selected to produce the end plates was near net shape die 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 5-5.

Table 5-5. PEM End Plate Cost Summary—5- and 10-kW Systems

Category	6 kW Stack				12 kW Stack			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$3.34	$3.05	$3.05	$3.05	$5.58	$5.21	$5.21	$5.21
Labor	$4.85	$3.03	$2.84	$2.83	$5.08	$3.26	$3.08	$3.06
Machine	$17.34	$10.82	$10.17	$2.57	$18.18	$11.66	$11.01	$2.10
Scrap	$0.13	$0.08	$0.08	$0.04	$0.14	$0.10	$0.10	$0.05
Tooling	$26.17	$2.62	$0.26	$0.26	$37.29	$3.73	$0.37	$0.37
Part Total	**$51.83**	**$19.60**	**$16.41**	**$8.75**	**$66.27**	**$23.97**	**$19.77**	**$10.80**
# per Stack	2	2	2	2	2	2	2	2
Stack Total	**$104**	**$39**	**$33**	**$18**	**$133**	**$48**	**$40**	**$22**

5.3.1.4 PEM 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 four 400-cm^2 plates can be formed during each machine cycle. The anode plate includes the cooling channels (two-sided plate) and is roughly twice 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 bipolar plate cost summary is provided in Tables 5-6 and 5-7.

Table 5-6. PEM Anode Bipolar Plate Cost Summary—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.56	$0.52	$0.52	$0.52	$0.87	$0.87	$0.87	$0.87
Labor	$0.42	$0.34	$0.33	$0.33	$0.73	$0.66	$0.65	$0.65
Machine	$1.87	$1.74	$0.90	$0.66	$3.51	$3.38	$1.82	$1.33
Scrap	$0.07	$0.07	$0.04	$0.04	$0.13	$0.13	$0.09	$0.07
Tooling	$8.33	$0.83	$0.25	$0.24	$8.44	$0.84	$0.49	$0.49
Part Total	**$11.25**	**$3.50**	**$2.04**	**$1.79**	**$13.68**	**$5.87**	**$3.91**	**$3.40**
# per Stack	37	37	37	37	37	37	37	37
Stack Total	**$416**	**$129**	**$76**	**$66**	**$506**	**$217**	**$145**	**$126**

Table 5-7. PEM Cathode Bipolar Plate Cost Summary—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.37	$0.34	$0.34	$0.34	$0.58	$0.58	$0.58	$0.58
Labor	$0.42	$0.34	$0.33	$0.33	$0.73	$0.66	$0.65	$0.65
Machine	$1.87	$1.74	$0.90	$0.66	$3.51	$3.38	$1.82	$1.33
Scrap	$0.07	$0.06	$0.04	$0.03	$0.12	$0.12	$0.08	$0.07
Tooling	$3.75	$0.38	$0.10	$0.10	$3.12	$0.31	$0.17	$0.17
Part Total	**$6.49**	**$2.86**	**$1.72**	**$1.47**	**$8.07**	**$5.04**	**$3.30**	**$2.79**
# per Stack	37	37	37	37	37	37	37	37
Stack Total	**$240**	**$106**	**$64**	**$54**	**$299**	**$187**	**$122**	**$103**

5.3.1.5 PEM 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 seal cost summary is provided in Tables 5-8 and 5-9. With the configuration shown in Figure 5-2, the seal between 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 5-8. PEM Anode and Cooling Seal Cost Summary—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.19	$0.18	$0.17	$0.17	$0.25	$0.24	$0.24	$0.23
Labor	$0.08	$0.07	$0.07	$0.07	$0.08	$0.07	$0.07	$0.07
Machine	$0.11	$0.11	$0.10	$0.03	$0.11	$0.11	$0.10	$0.03
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$1.66	$0.17	$0.07	$0.06	$2.40	$0.24	$0.10	$0.09
Part Total	**$2.04**	**$0.53**	**$0.41**	**$0.33**	**$2.84**	**$0.66**	**$0.51**	**$0.42**
# per Stack	72	72	72	72	72	72	72	72
Stack Total	**$147**	**$38**	**$30**	**$24**	**$205**	**$48**	**$36**	**$30**

Table 5-9. PEM Cathode Seal Cost Summary—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.17	$0.16	$0.16	$0.15	$0.24	$0.23	$0.22	$0.22
Labor	$0.08	$0.07	$0.07	$0.07	$0.08	$0.07	$0.07	$0.07
Machine	$0.12	$0.10	$0.09	$0.03	$0.11	$0.10	$0.09	$0.03
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$2.64	$0.26	$0.05	$0.05	$3.57	$0.36	$0.07	$0.07
Part Total	**$3.00**	**$0.60**	**$0.37**	**$0.30**	**$4.00**	**$0.75**	**$0.45**	**$0.38**
# per Stack	38	38	38	38	38	38	38	38
Stack Total	**$114**	**$23**	**$14**	**$12**	**$152**	**$29**	**$17**	**$15**

5.3.1.6 PEM Stack Assembly

The stack components are assembled as defined 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 $9.28 per stack and gas fittings were estimated to be $5.62 per stack before applying learning curve analysis. Stack 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 $45.00/hour, the average stack assembly costs were calculated as shown in Table 5-10. Details of the process calculations are provided in Appendix A-8.

Table 5-10. PEM Stack Assembly Costs—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$48.15	$45.03	$42.11	$40.18	$48.15	$45.03	$42.11	$40.18
Labor	$35.31	$28.20	$27.49	$27.43	$35.60	$28.43	$27.71	$27.65
Total Assembly Cost	**$83**	**$73**	**$70**	**$68**	**$84**	**$73**	**$70**	**$68**

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 fairly 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 5-11. 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 have to assume that the rate does not change with production volume. There is a sharp drop in machine cost per stack as production volumes change from 100 to 1,000 units/year that 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 5-11. PEM Stack Testing and Conditioning Cost Summary—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$30.52	$13.38	$6.11	$3.60	$46.59	$20.79	$9.62	$5.79
Labor	$74.31	$73.56	$73.48	$73.48	$74.34	$73.58	$73.51	$73.50
Machine	$2,412.45	$213.73	$42.72	$42.72	$2,412.45	$213.73	$42.72	$42.72
Scrap	$132.49	$15.82	$6.44	$6.30	$133.34	$16.22	$6.62	$6.42
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	**$2,649.76**	**$316.48**	**$128.75**	**$126.09**	**$2,666.71**	**$324.32**	**$132.47**	**$128.43**
# per Stack	1	1	1	1	1	1	1	1
Stack Total	**$2,6450**	**$316**	**$129**	**$126**	**$2,667**	**$324**	**$132**	**$128**

5.3.1.8 PEM Stack Cost Summary

Total stack manufacturing costs are summarized in Tables 5-12 and 5-13. Breakdowns of stack cost volume trends are shown in Figures 5-6 and 5-7.

Table 5-12. PEM Stack Component Cost Summary—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
MEA	$4,767.90	$1,473.27	$521.31	$280.83	$6,098.41	$1,942.58	$728.30	$474.17
Anode / Cooling Gasket	$146.55	$37.86	$29.72	$24.01	$204.67	$47.85	$36.43	$30.38
Cathode Gasket	$114.06	$22.72	$14.17	$11.58	$151.94	$28.61	$17.18	$14.57
Anode Bipolar Plate	$416.42	$129.35	$75.57	$66.16	$506.18	$217.27	$144.81	$125.96
Cathode Bipolar Plate	$239.98	$105.86	$63.73	$54.27	$298.65	$186.65	$121.93	$103.06
End plates	$103.66	$39.20	$32.81	$17.50	$132.55	$47.93	$39.54	$21.60
Assembly hardware	$48.15	$45.03	$42.11	$40.18	$48.15	$45.03	$42.11	$40.18
Assembly labor	$35.31	$28.20	$27.49	$27.43	$35.60	$28.43	$27.71	$27.65
Test and conditioning	$2,649.76	$316.48	$128.75	$126.09	$2,666.71	$324.32	$132.47	$128.43
Total	**$8,522**	**$2,198**	**$936**	**$648**	**$10,143**	**$2,869**	**$1,290**	**$966**

Table 5-13. PEM Stack Manufacturing Cost Summary—5- and 10-kW Systems

Category	5-kW System				10-kW System			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$4,700.53	$1,537.83	$592.10	$354.90	$6,039.61	$2,021.26	$810.95	$562.20
Labor	$170.38	$150.53	$148.52	$148.35	$202.96	$182.52	$180.51	$180.33
Machine	$2,616.56	$390.78	$155.43	$109.11	$2,753.03	$526.73	$237.98	$167.15
Scrap	$167.91	$32.20	$15.32	$12.92	$183.07	$41.75	$21.44	$18.18
Tooling	$866.42	$86.64	$24.29	$22.76	$964.19	$96.42	$39.61	$38.12
Part Total	**$8,522**	**$2,198**	**$936**	**$648**	**$10,143**	**$2,869**	**$1,290**	**$966**

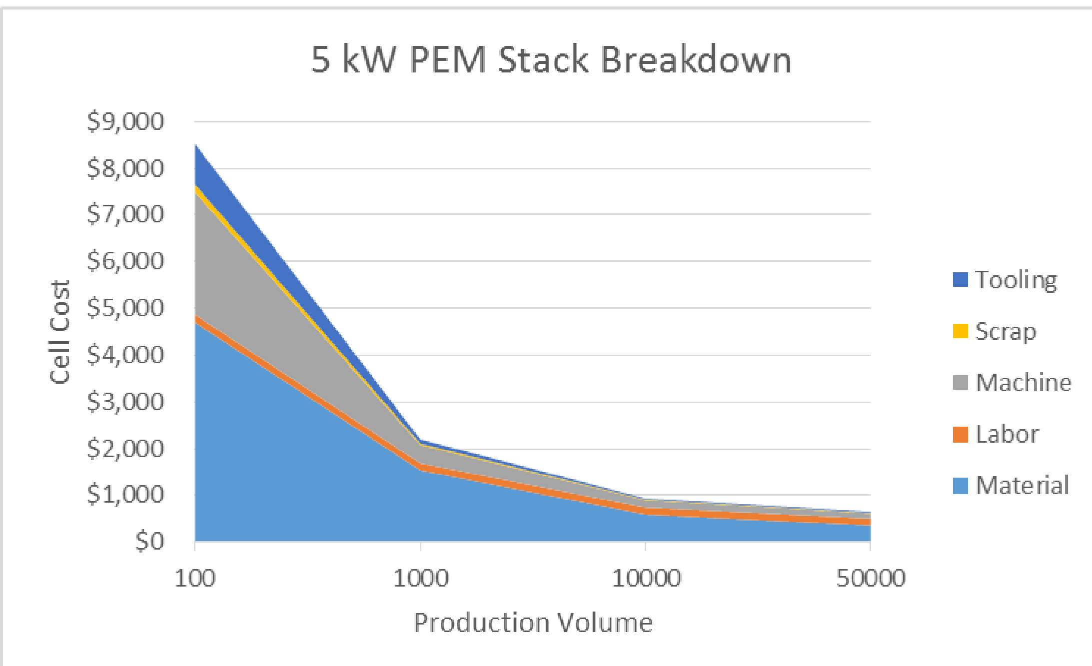


Figure 5-6. Breakdown of 5-kW system fuel cell costs and production volume trends

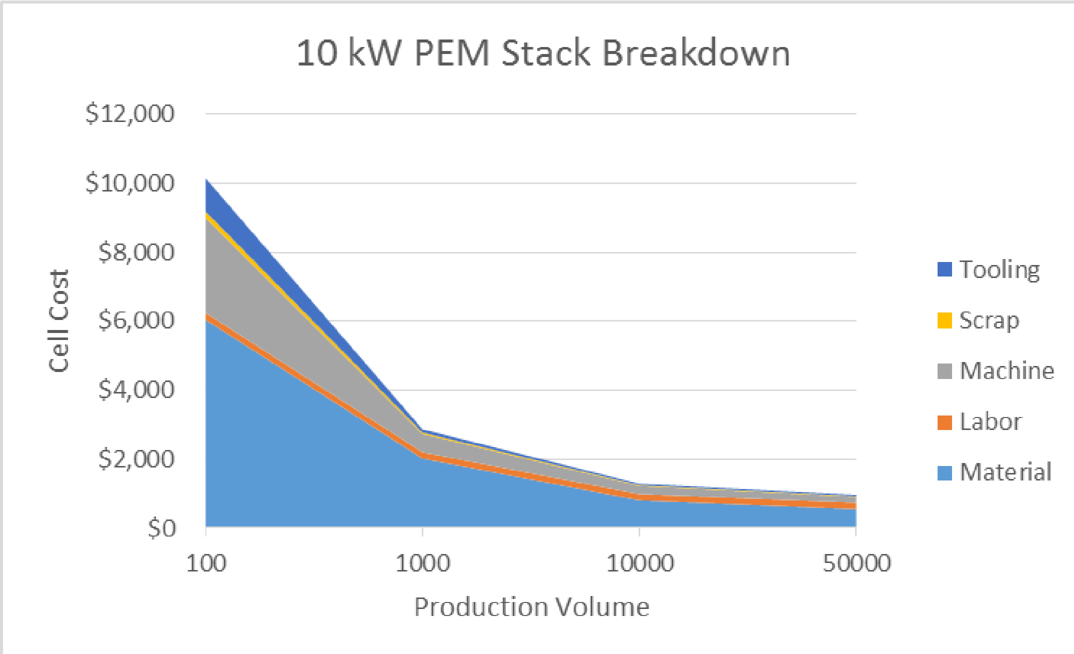


Figure 5-7. Breakdown of 10-kW system fuel cell costs and production volume trends

5.3.2 PEM Systems BOP Manufacturing Cost Assessment

The BOP for backup power systems consists of hardware to manage the hydrogen, air, and coolant flows as well as sensors and controls necessary for system operation. All components shown in Figure 4-3, other than the stack, are considered to be BOP components. A significant component of the support hardware is the DC/DC converter that interfaces the fuel cell with the batteries. All of the components for the BOP with the possible exception of the DC/DC converter are available as commercial off-the-shelf (COTS) items, though some are in limited production.

As noted in Section 4, some PEM stack manufacturers are providing stacks that do not require external humidification. However, for backup power applications we expect monthly test runs to assure the system will be ready when needed. These test runs will be short duration and may therefore tend to dehydrate the membrane, hence the inclusion of a recuperative humidifier to assist with humidification as well as cathode air preheating during cold weather.

5.3.3 PEM BOP Cost Assumptions

The costs associated with the BOP components are tabulated in Table 5-14. Figures 5-8 through 5-11 compare component costs at a subcategory level. At a production rate of 1,000 systems a year, the BOP hardware is estimated to cost in excess of $10,300 for each 5-kW system. The cost increases to over $13,200 for a 10-kW system at the same production volume. The BOP costs are ~ $2,060/kW and ~$1,320/kW respectively. This compares to $509/kW and $322/kW for the fuel cell stacks for these systems. System overall cost is more sensitive to the assumptions applied to the BOP components than those applied to the stack. Many component costs, including most sensors and regulators, remain the same regardless of system size, and are therefore similar to costs presented in the FY14 Primary Power and CHP study.[9] Furthermore, these costs do not vary significantly with system size.

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 and a 10% buffer to all remaining hardware.

Table 5-14. PEM BOP Cost Summary—5- and 10-kW Systems

System	Component Description	Annual Production of 5kW PEM Systems				Annual Production of 10 kW PEM Systems			
		(100)	(1,000)	(10,000)	(50,000)	(100)	(1,000)	(10,000)	(50,000)
Hydrogen Supply	High pressure regulator	$ 1,295	$ 1,101	$ 881	$ 837	$ 1,295	$ 1,101	$ 881	$ 837
	Mid-pressure PRD	$ 155	$ 150	$ 150	$ 150	$ 155	$ 150	$ 150	$ 150
	Low Pressure regulator	$ 113	$ 102	$ 90	$ 86	$ 113	$ 102	$ 90	$ 86
	Lower Presure PRD	$ 155	$ 150	$ 150	$ 150	$ 155	$ 150	$ 150	$ 150
	Anode shutoff valve	$ 71	$ 65	$ 63	$ 60	$ 71	$ 65	$ 63	$ 60
	Anode purge valve	$ 92	$ 78	$ 72	$ 68	$ 92	$ 78	$ 72	$ 68
Air Supply	Chemical/particulate filter	$ 347	$ 333	$ 320	$ 307	$ 347	$ 333	$ 320	$ 307
	Cathode Blower	$ 360	$ 324	$ 291	$ 282	$ 360	$ 324	$ 291	$ 282
	Recuperative humidifer	$ 420	$ 290	$ 200	$ 165	$ 840	$ 580	$ 400	$ 330
	Cathode isolation valve	$ 466	$ 440	$ 414	$ 414	$ 466	$ 440	$ 414	$ 414
Cooling	Radiator	$ 683	$ 614	$ 546	$ 519	$ 625	$ 500	$ 425	$ 404
	Coolant Pump	$ 303	$ 242	$ 206	$ 196	$ 240	$ 195	$ 190	$ 181
	Deionization polisher	$ 43	$ 39	$ 35	$ 31	$ 43	$ 39	$ 35	$ 31
Controls and instrumentation	Control Module	$ 500	$ 300	$ 175	$ 166	$ 500	$ 300	$ 175	$ 166
	Temperature sensors	$ 95	$ 55	$ 40	$ 38	$ 95	$ 55	$ 40	$ 38
	Pressure Sensor	$ 710	$ 638	$ 574	$ 556	$ 710	$ 638	$ 574	$ 556
	Flow Meter (cathode)	$ 128	$ 115	$ 103	$ 97	$ 128	$ 115	$ 103	$ 97
	Voltage sensor (DC/DC input)	$ 50	$ 43	$ 39	$ 37	$ 50	$ 43	$ 39	$ 37
	Voltage sensor (DC/DC output)	$ 50	$ 43	$ 39	$ 37	$ 50	$ 43	$ 39	$ 37
	Hydrogen Sensor (leak sensor)	$ 132	$ 106	$ 97	$ 92	$ 132	$ 106	$ 97	$ 92
Electrical	DC/DC Converter	$ 3,735	$ 2,538	$ 2,209	$ 1,780	$ 5,070	$ 4,100	$ 3,350	$ 3,016
	Contactors	$ 72	$ 64	$ 60	$ 54	$ 72	$ 64	$ 60	$ 54
	Batteries	$ 669	$ 643	$ 620	$ 595	$ 1,384	$ 1,329	$ 1,282	$ 1,231
Assembly Comp	Assorted Plumbing/Fittings	$ 580	$ 525	$ 475	$ 430	$ 590	$ 535	$ 480	$ 430
	Assembly Hardware	$ 60	$ 55	$ 50	$ 45	$ 60	$ 55	$ 50	$ 45
	Frame and Housing	$ 180	$ 165	$ 150	$ 135	$ 180	$ 165	$ 150	$ 135
+	Additional Work Estimate	$ 1,285	$ 1,170	$ 1,055	$ 950	$ 1,800	$ 1,635	$ 1,470	$ 1,325
	TOTAL BOP COST	$ 12,748	$ 10,388	$ 9,105	$ 8,278	$ 15,623	$ 13,240	$ 11,391	$ 10,560

[9] Battelle Memorial Institute. 2015. *Manufacturing Cost Analysis of 1, 5, 10, and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications*.

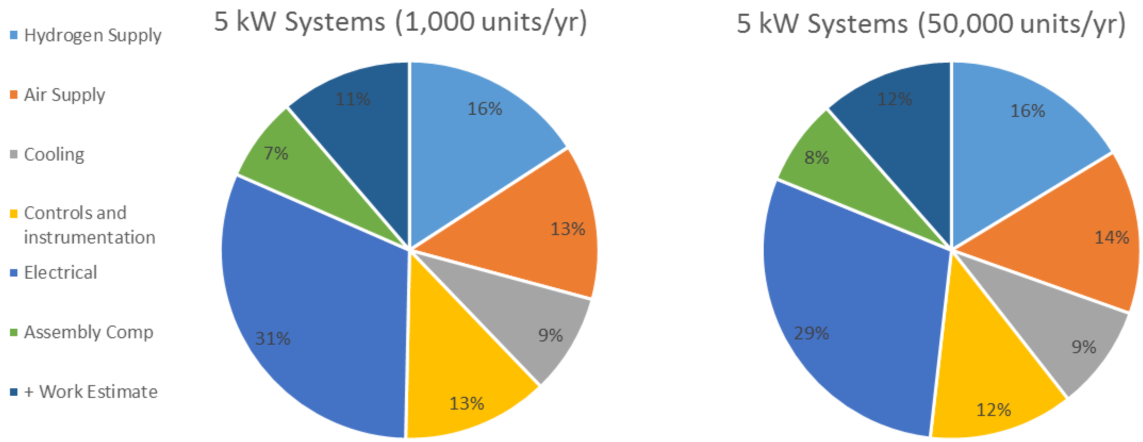


Figure 5-8. 5-kW PEM BOP cost distribution

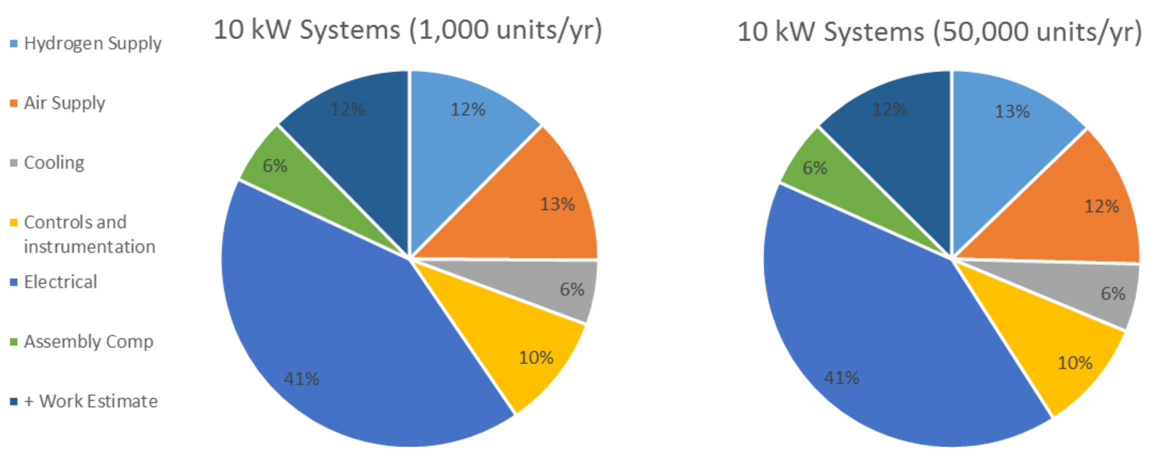


Figure 5-9. 10-kW PEM BOP cost distribution

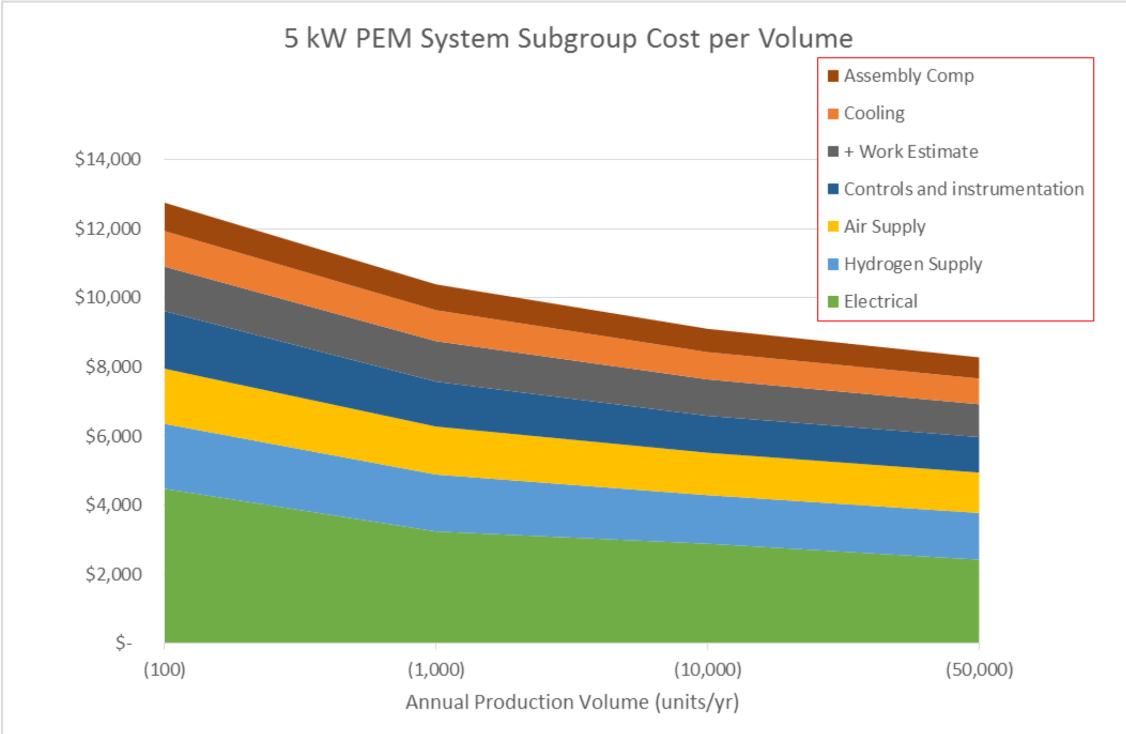


Figure 5-10. 5-kW PEM BOP cost volume trends

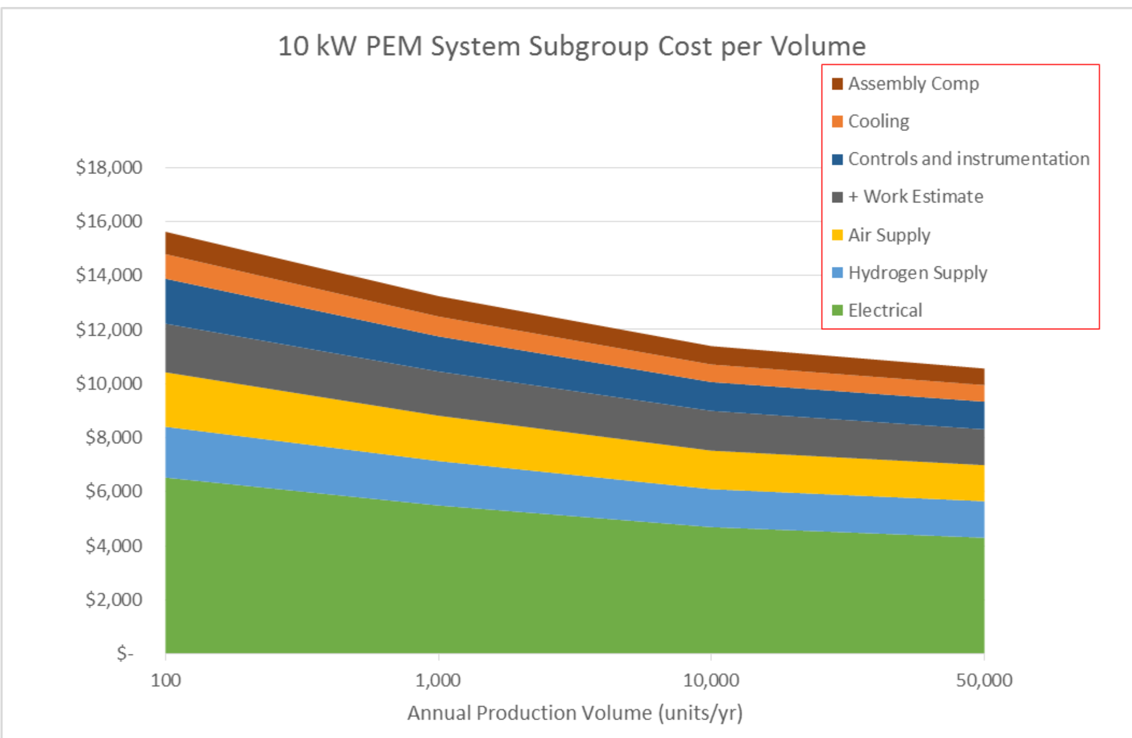


Figure 5-11. 10-kW PEM BOP cost volume trends

5.3.4 PEM System Assembly and Learning Curve Assumptions

The system assembly hardware costs are accounted for in the BOP cost calculations, while 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 $45.00/hour, the average system assembly costs were calculated as shown in Table 5-15. Details of the learning curve analysis are provided in Appendix A-8.

Table 5-15. PEM System Assembly Costs—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor	$74.96	$59.87	$58.36	$58.23	$74.96	$59.87	$58.36	$58.23
Total Assembly Cost	**$75**	**$60**	**$58**	**$58**	**$75**	**$60**	**$58**	**$58**

5.3.5 PEM Backup Power System Testing

Following assembly, the backup power system is tested and conditioned to determine its fitness for installation in the field. The total test time is assumed to be 2.5 hours. Systems failing test are reworked by disassembly, replacement of the defective part and reassembly. The failure rate is assumed to be 3%. The failure cost is 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 process calculations are the same as stack testing and conditioning as shown in Appendix A-9. The system testing costs were calculated as shown in Table 5-16. There is a sharp drop in machine cost per system as production volumes change from 100 to 1,000 units/year that reflects the low utilization rate in the case of the 100-unit volumes as well as the assumption that all system testing is performed in-house.

Table 5-16. PEM System Testing Cost Summary—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$166.60	$166.60	$166.60	$166.60	$333.19	$333.19	$333.19	$333.19
Labor	$105.88	$105.88	$105.88	$105.88	$105.88	$105.88	$105.88	$105.88
Machine	$2,373.14	$174.42	$101.13	$96.24	$2,373.14	$174.42	$101.13	$96.24
Scrap	$81.82	$13.82	$11.55	$11.40	$86.98	$18.97	$16.71	$16.56
Tooling	$0	$0	$0	$0	$0	$0	$0	$0
Part Total	**$2,727**	**$461**	**$385**	**$380**	**$2,899**	**$632**	**$557**	**$552**

5.3.6 PEM Capital Cost Assumptions

Table 5-17 summarizes the cost assumptions for the components that make up the total PEM capital cost.

Table 5-17. Summary of PEM Capital Cost Assumptions

Capital Cost	Unit Cost	Assumption/Reference
Construction Cost	$250/ft^2	Includes Electrical Costs ($50/sq. ft.). Total plant area based on line footprint plus 1.5x line space for working space, offices, shipping, etc. Varies with anticipated annual production volumes
Expected lifetime of capital equipment	20 years	
Discount Rate	7.0%	Guidance for gov't 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 line use was estimated to determine the number of individual process lines required to support various product demand levels. This information, along with equipment cost quotes, was used to determine production line 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 Penn State University, and are detailed in Appendix A-10. Capital cost summaries are presented in Table 5-18.

The number of "Production Lines" refers to the equipment needed to produce a subcomponent or to assemble an entire system from components produced on support production lines. For example, bipolar plate production requires a hot press and a post-press heat treating oven. Because each pair (press and oven) can only produce ~27 parts/hour, a significant number of bipolar plate production lines are required (e.g., 16 bipolar plate production lines to produce 50,000 of the 10-kW systems/year.)

Table 5-18. PEM Capital Cost Summary—5- and 10-kW Systems

Category	6-kW Stack (5-kW System)				12-kW Stack (10-kW System)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Production Lines	4	4	16	78	4	4	18	87
Factory Total Construction Cost	$375,063	$375,063	$1,285,713	$6,768,925	$375,063	$375,063	$1,558,113	$7,903,450
Forklifts	$12,000	$12,000	$48,000	$234,000	$12,000	$12,000	$54,000	$261,000
Cranes	$14,700	$14,700	$58,800	$286,650	$14,700	$14,700	$66,150	$319,725
Real Estate	$45,032	$45,032	$63,621	$207,480	$45,032	$45,032	$81,386	$224,151
Contingency	$44,679	$44,679	$145,613	$749,706	$44,679	$44,679	$175,965	$870,833
Total Capital Cost	**$491,474**	**$491,474**	**$1,601,747**	**$8,246,761**	**$491,474**	**$491,474**	**$1,935,614**	**$9,579,158**
Equivalent annual capital cost	$46,392	$46,392	$151,194	$778,436	$46,392	$46,392	$182,708	$904,205
Annual Capital Cost per Stack	**$464**	**$46**	**$15**	**$16**	**$464**	**$46**	**$18**	**$18**

5.4 Electrical System Cost Assumptions

The cost for the electrical system is primarily driven by the power electronics (DC/DC converter). For some applications a DC/AC inverter and grid-to-backup transfer switch would be needed. However, we have limited this analysis to backup power systems that are drop-in replacements for battery bank systems. Any grid interface hardware is assumed to be already in place. Furthermore, the cost of an inverter can be significant and may be unnecessarily redundant with the DC/DC converter for some applications (see FY14 Primary Power and CHP study[10]). While an inverter can be less expensive for backup power than for CHP and primary power applications, it will still represent a significant expense if needed and should not be overlooked if considering backup for AC power systems. The system controller and sensors comprise the next largest portion of the cost. Protective devices and interconnecting components complete the remainder of the electrical system cost.

5.4.1 DC/DC Power Electronics

Most of the commercially available DC/DC converters rated for continuous use are suitable for fuel cell applications assuming appropriate control interface features to allow the converter to be used to assist with system management. Specifically, the converter is typically coordinated with the fuel system (compressed hydrogen in this case) through the control system to limit current draw in the case of hydrogen depletion resulting in low pressure and reduced output. Since most converters include some form of control interface, no cost was assumed to be associated with this feature. The input to the converters was required to accommodate the range of voltage for the specific fuel cell stack being served: stack output voltage is variable with stack current and number of cells. For the selected design, stack output voltage varies from ~20 VDC at full load to ~36 VDC at open circuit for both the 5- and 10-kW systems; therefore, a boost type DC/DC converter is required for the 5- and 10-kW systems to reach 48 VDC. The 10-kW system was specifically configured to assure that a buck-boost converter would not be required as that type of converter is more expensive than either of the pure versions. The converters are based on 120% of the nominal output of the system size (matching the stack nominal power) to allow for parasitic loads. For example, for the 10-kW system a 12 kW power converter was selected. Table 5-19 includes the converter cost breakdown at increasing production volumes for both 5- and 10-kW systems on a $/kW basis.

Table 5-19. DC/DC Converter Costs per Watt

Category	100 units	1,000 units	10,000 units	50,000 units
Power (W)	($/W)	($/W)	($/W)	($/W)
5,000	$0.62	$0.42	$0.37	$0.30
10,000	$0.42	$0..34	$0.28	$0.25

[10] Battelle Memorial Institute. 2015. *Manufacturing Cost Analysis of 1, 5, 10, and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications.*

5.4.2 Controller and Sensors

The system controller cost was estimated based on previous efforts completed at Battelle and on original equipment manufacturer (OEM) automotive Electronic Control Unit (ECU) costs. We assumed that the system controller is a custom circuit card assembly built around a micro-controller that handles the specific needs of the system. Because of the similarity to an automotive ECU, the system controller would probably have some of the same features as an automotive ECU and as such the cost of OEM ECUs was used to estimate the higher quantity cost of the controller. The current sensor and voltage sensor circuitry are readily available, so the cost for those components could be identified via the internet. The costs are summarized in Table 5-20.

Table 5-20. Controller and Sensors Cost

Component	Cost per System ($)							
	5-kW System (Annual Production)				10-kW System (Annual Production)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Control Module	$500	$300	$175	$166	$500	$300	$175	$166
Thermocouples	$95	$55	$40	$38	$95	$55	$40	$38
H_2 Leak Sensor	$132	$106	$97	$92	$132	$106	$97	$92
Anode/Cathode Pressure Sensor	$710	$638	$574	$556	$710	$638	$574	$556

5.4.3 Protection and Interconnects

The contactors and fuses used in this type of fuel cell application typically require high current ratings. The number of manufacturers that supply these types of devices is somewhat limited. The cost of these components is an average of the component costs obtained from the internet and quoted prices from authorized distributors of the products. The cost for the connectors and other interconnection cable was estimated to be 10% of the overall system electrical costs.

5.4.3.1 Batteries

Energy storage is required to provide critical load support and system start-up during grid outages. As outlined in Section 4, the batteries were sized to provide 100% of nominal power for 10 minutes or 200% of nominal power for 30 seconds.

Battery costs were obtained from battery manufacturers on the basis of the design for providing 100% of nominal power for 10 minutes. Table 5-21 shows the minimum requirements of the battery. We assumed that the batteries will experience no more than a 60% discharge (40% remaining charge) during a typical outage event while the fuel cell was starting up. Once the fuel cell is started up and reaches operating temperature the batteries are recharged. The battery cost per unit is shown in Table 5-22. The batteries selected are readily available gel lead-acid batteries rated at 12V, 58 ah at C/100 hr rate for the 5-kW system, and 12V, 137 ah at C/100 hr rate for the 10-kW system. Four batteries are connected in series to provide the nominal 48 VDC.

Table 5-21. Minimum Battery Requirements

System Power (kW)	Minimum Battery Rating		Battery Voltage (VDC)
	kW-hr for start-up	Amp-hr rating	
5	1.67	58	48 (4@12 VDC in series)
10	3.33	137	48 (4@12 VDC in series)

Table 5-22. Battery Cost

System Power (kW)	Cost per System ($)			
	100	1,000	10,000	50,000
5	$669	$643	$620	$595
10	$1,348	$1,329	$1,282	$1,231

5.4.4 Electrical Cost Summary

Table 5-23 provides a summary of the costs associated with the electrical power system and support components (including controls and sensors). Overall costs are dominated by the converter.

Table 5-23. Electrical Cost Summary

Component	Cost per System ($)							
	5-kW System (Annual Production)				10-kW System (Annual Production)			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
DC/DC converter	$3,735	$2,538	$2,209	$1,780	$5,070	$4,100	$3,350	$3,016
Batteries	$669	$643	$620	$595	$1,348	$1,329	$1,282	$1,231
Control Module	$500	$300	$175	$166	$500	$300	$175	$166
Thermocouples	$95	$55	$40	$38	$95	$55	$40	$38
H_2 Sensor	$132	$106	$97	$92	$132	$106	$97	$92
Anode/Cathode Pressure Sensor	$710	$638	$574	$556	$710	$638	$574	$556
Cathode Flow Meter	$128	$115	$103	$97	$128	$115	$103	$97
Voltage Sensors (2)	$100	$86	$78	$74	$100	$86	$78	$74
Contactors	$72	$64	$60	$54	$72	$64	$60	$54
Total Cost	$6,141	$4,544	$3,956	$3,453	$8,191	$6,793	$5,760	$5,324

6. Limitations of the Analysis

The analytical approach 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 and 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 less than 12% of the overall cost with the other notable component being the DC/DC converter. In no case considered in this study did stack cost exceed 49% of the overall system cost. This stresses the importance of the BOP design and component selection. Battelle made reasonable choices regarding the overall system design based on past experience and industry input: 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 include catalyst deposition, decal transfer and hot pressing. Individual MEA stack components are die cut following hot pressing. The assumption 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 be available and minimum purchase quantities for roll-to-roll materials would not be justified for small production volumes.

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 the bipolar plates, for which some manufacturers use compression molded graphite composite material and others use stamped and coated metal material. For this analysis, the graphite composite bipolar plates were chosen. Table 6-1 summarizes the manufacturing processes that were evaluated.

The cost analysis assumed that membrane and 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.[11] Consequently, in-house production may not be justified until yearly volumes reach the largest 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.

[11] 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

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
	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	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	Die casting	Stamping, welding
	Sand casting + final machining (not chosen)	
	Machine from block (not chosen)	

6.1.2 PEM BOP Hardware Costs

BOP costs are strongly influenced by the cost of the electrical equipment—the DC/DC converter primarily. The costs included here reflect quotes adjusted to different volumes and sizes using typical scaling and volume production factors. We did not evaluate the core costs associated with the power electronics and controls to determine if significant cost savings might be available. Power electronics in this analysis were assumed to be air cooled and able to operate within a reasonable range of ambient temperatures. Depending on the size of the power electronics, cooling requirements may dictate the addition of an air or liquid cooling system, which was not included as part of this analysis. Power electronics already existing on-site supporting telecom operations may already include a cooling system capable of integrating the fuel cell and power electronics cooling needs. However, as noted above, we have included a cooling system for the fuel cell on the assumption that the backup power system is independent of any existing cooling system. If the site were designed from its inception with integration of fuel cell backup power in mind, cooling systems for the site and the fuel cell system (including the fuel cell itself) may be integrated, leading to overall system cost reductions.

Further limitations of this analysis include items considered to be dependent on site- and end-user-specific requirements. Because these costs are extremely variable site to site, they are not included as part of this analysis. Among the site-specific costs not directly included is the cost of hydrogen storage. Operating at full power, the 5- and 10-kW fuel cell systems considered in this analysis will consume approximately 90 standard liters per minute (SLPM) and 180 SLPM of hydrogen, respectively. Individual operator requirements will dictate the desired system run time in the event of a power outage, driven by the criticality of continued operation and estimated duration of power outage. The most common approach for shorter outage scenarios is anticipated to be a series of K cylinders, containing compressed hydrogen nominally at 2,000 or 6,000 psi[12]. These cylinders would be swapped when low or empty, and refilled by a gas supplier at their facility. Cylinders would be rented, not purchased, by the end user.

[12] Cohen, M., Snow, G. ReliOn, Inc. 2008. *Hydrogen Delivery and Storage Options for Backup Power and Off-Grid Primary Power Fuel Cell Systems.*

Some fuel cell manufacturers have designed their own storage modules targeting sufficient hydrogen storage to support 48 to 72 hours of run time. ReliOn (now owned by Plug Power) has developed a hydrogen storage module based on 16-24 hydrogen cylinders capable of storing hydrogen at 3,000 psi[13]. Contained in a custom cabinet, the storage module would be refueled from a delivery vehicle in a similar fashion as a fuel cell powered car would be refueled at a filling station. This setup enables both sufficient storage for extended outage durations as well as rapid refueling of the storage module. Drawbacks of this approach include footprint considerations to allow a refueling vehicle to come in close proximity to the hydrogen storage module. In remote applications, this may not be a factor; however, in urban settings a large refueling vehicle may not be able to directly access the backup power unit.

Maintaining larger volumes of hydrogen on standby for extended power outage durations is costly, typically requiring either a hydrogen tube trailer or a dedicated hydrogen ground storage tube system that is refilled on-site by a vendor. In both of these scenarios, sufficient footprint must be available to locate the tube trailer or storage tubes within an appropriate secured boundary. Due to the infrequent and intermittent operational conditions of the backup power system, on-site generation of hydrogen is not cost effective due to the capital investment required for generation equipment. Table 6-2 shows a comparison of several different hydrogen storage scenarios and the anticipated associated run time for the 5- and 10-kW systems.

Table 6-2. Estimated Run Durations—5- and 10-kW Fuel Cell Systems for Several Common Storage Options

Hydrogen Storage Method	Estimated Run Time (hrs)	
	5-kW System	10-kW System
(2) 2,000 psi K-Cylinders	1.9	1.0
(6) 2,000 psi K-Cylinders	5.8	2.9
(2) 6,000 psi K-Cylinders	4.4	2.2
(6) 6,000 psi K-Cylinders	13.2	6.6
Storage Module[14]	42.2/63.3	21.1/31.6
Storage Tank[15]	222	111
Tube Trailer (50,000 SCF Capacity)[16]	258	129

[13] Cohen, M., Kenny, K., ReliOn, Inc. 2010. *Hydrogen Deliver and Storage Options for Backup Power and Off-Grid Primary Power Fuel Cell Systems: Two Years Later.*
[14] Hydrogen storage module based on ReliOn (Plug Power) developed storage module, holding 8160/12240 SCF of hydrogen in 16/24 cylinder arrangements.
[15] Assuming six 21-foot-long by 30-inch-diameter tubes as a typical, off-the-shelf, setup which may be chosen for this application. Ground storage tubes are able to be custom sized for given applications. Available at http://www.alliancegas.com/storagetubes.html.
[16] Tube trailer capacities vary, and different sized trailers are able to be sourced for different applications. The above is based on a typical 26-foot-long tube trailer.

7. Cost Analysis Results

In this section we provide an overall view of system costs. To provide insight into the cost drivers that may be unique to backup power, we have broken out system costs into four categories associated with different aspects of operation and production: Total Stack Manufacturing; Fuel Air, and Cooling Supply Components; Power Electronic, Control and Instrumentation Components; and Assembly Components and Additional Work Estimate. These categories allow comparison across system size and technology.

7.1 PEM Backup Power Systems

This section presents the results of the analyses of four manufacturing volumes for 5- and 10-kW backup power PEM fuel cell systems, including fuel cell stack, BOP, and overall system costs. Figures 7-1 and 7-2 show the distribution of costs for each of the sizes for a production volume of 1,000 units/year. The largest contributor to the overall cost for both the 5- and 10-kW systems is the power electronics and controls category. The primary cost item in the category, representing 55% to 61% of this category, is the DC/DC converter.

Since the fuel cell stack dictates much of the equipment and space capital costs, all capital costs are captured in the “Total Stack Manufacturing” category. Furthermore, the manufacturing capital cost (the investment required to produce the systems) is relatively small on a per-system basis even for limited numbers of units, accounting for 0.61% of the total system cost at the most. Capital costs are assumed to be amortized over the projected lifetime of the machine or 20 years, whichever is shorter. The number of stacks required for all but the lowest volume production rates considered for this report results in most fabrication work being done in house with the attendant capital expenditures necessary to obtain and commission the production machinery. Stack Testing and System Testing are incorporated into the Stack and Assembly categories, respectively. All systems and production volumes assume that stack and final system testing and evaluation will be done in-house as a quality control measure. The cost of dedicated test equipment is rolled into the capital investment.

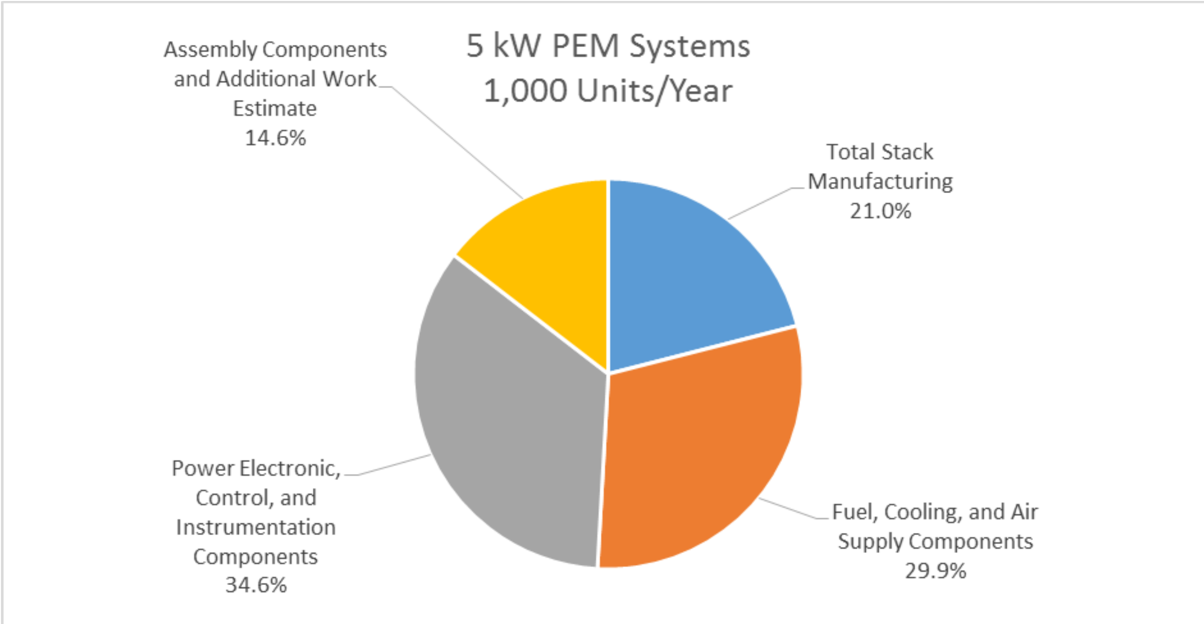


Figure 7-1. 5-kW PEM system costs at 1,000 units per year

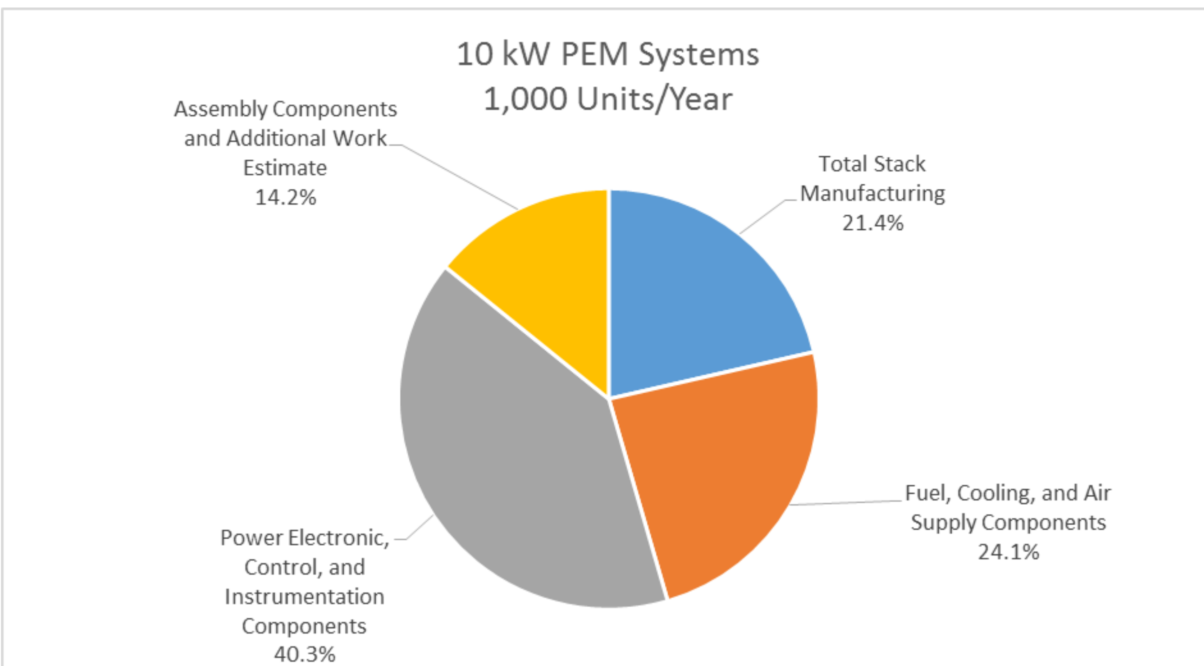


Figure 7-2. 10-kW PEM system costs at 1,000 units per year

Tables 7-1 and 7-2 provide the estimated costs for each size and production volume. Figures 7-3 and 7-4 illustrate the pre-markup cost trend with increasing manufacturing volume that is represented in Tables 7-1 and 7-2.

Table 7-1. Cost Summary—5-kW PEM Backup Power Fuel Cell System

Description	Estimated Costs (Units/Year)			
	100	1,000	10,000	50,000
Total Stack Manufacturing	$11,788	$2,765	$1,394	$1,101
Fuel, Cooling, and Air Supply Components	$4,503	$3,928	$3,418	$3,265
Power Electronic, Control, and Instrumentation Components	$6,141	$4,544	$3,956	$3,453
Assembly Components and Additional Work Estimate	$2,105	$1,915	$1,730	$1,560
Total System Cost, Pre-Markup	$24,537	$13,153	$10,499	$9,379
System Cost per kW_{net}, Pre-Markup	$4,907	$2,631	$2,100	$1,876
Sales Markup	50%	50%	50%	50%
Total System Cost, with Markup	$36,805	$19,729	$15,748	$14,069
System Cost per kW_{net}, with Markup	$7,361	$3,946	$3,150	$2,814

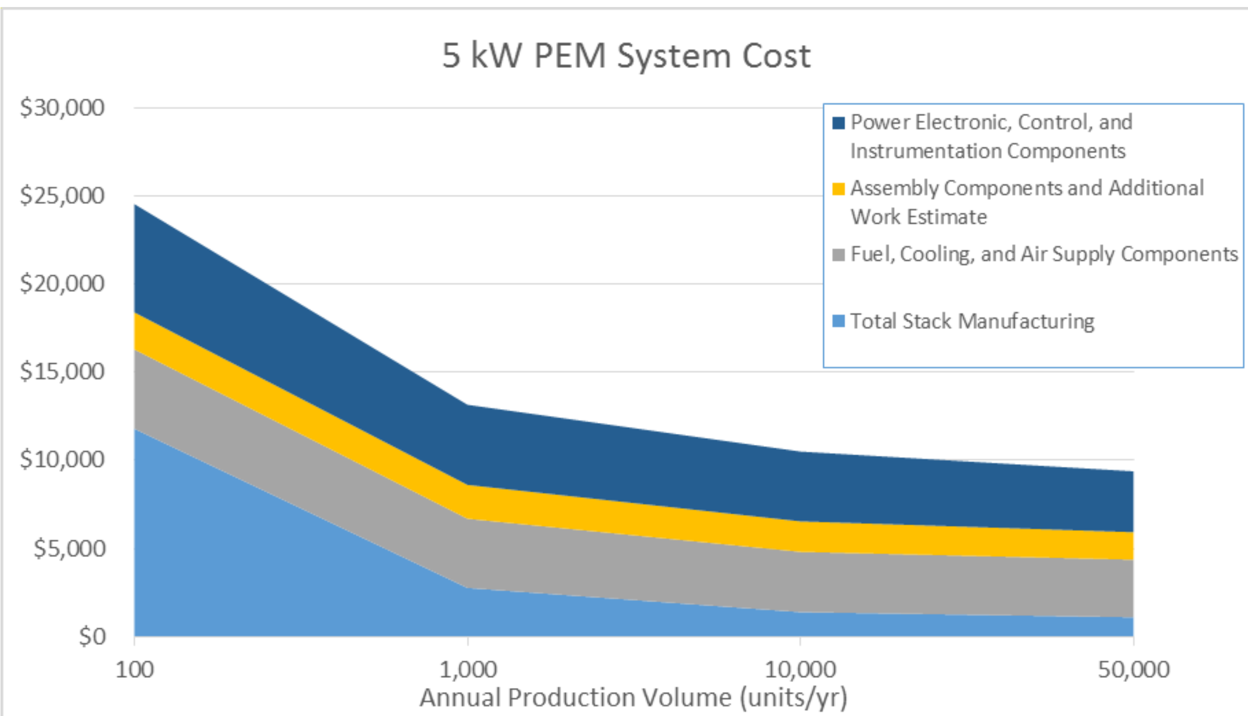


Figure 7-3. 5-kW PEM cost volume trends

Table 7-2. Cost Summary—10-kW PEM Backup Power Fuel Cell System

Description	Cost Summary (Units/Year)			
	100	1,000	10,000	50,000
Total Stack Manufacturing	$13,581	$3,607	$1,924	$1,593
Fuel, Cooling, and Air Supply Components	$ 4,802	$4,057	$3,481	$3,300
Power Electronic, Control, and Instrumentation Components	$8,191	$6,793	$5,760	$5,324
Assembly Components and Additional Work Estimate	$2,630	$2,390	$2,150	$1,935
Total System Cost, Pre-Markup	$29,204	$16,847	$13,315	$12,153
System Cost per kW_{net}, Pre-Markup	$2,920	$1,685	$1,331	$1,215
Sales Markup	50%	50%	50%	50%
Total System Cost, with Markup	$43,806	$25,271	$19,972	$18,230
System Cost per kW_{net}, with Markup	$4,381	$2,527	$1,997	$1,823

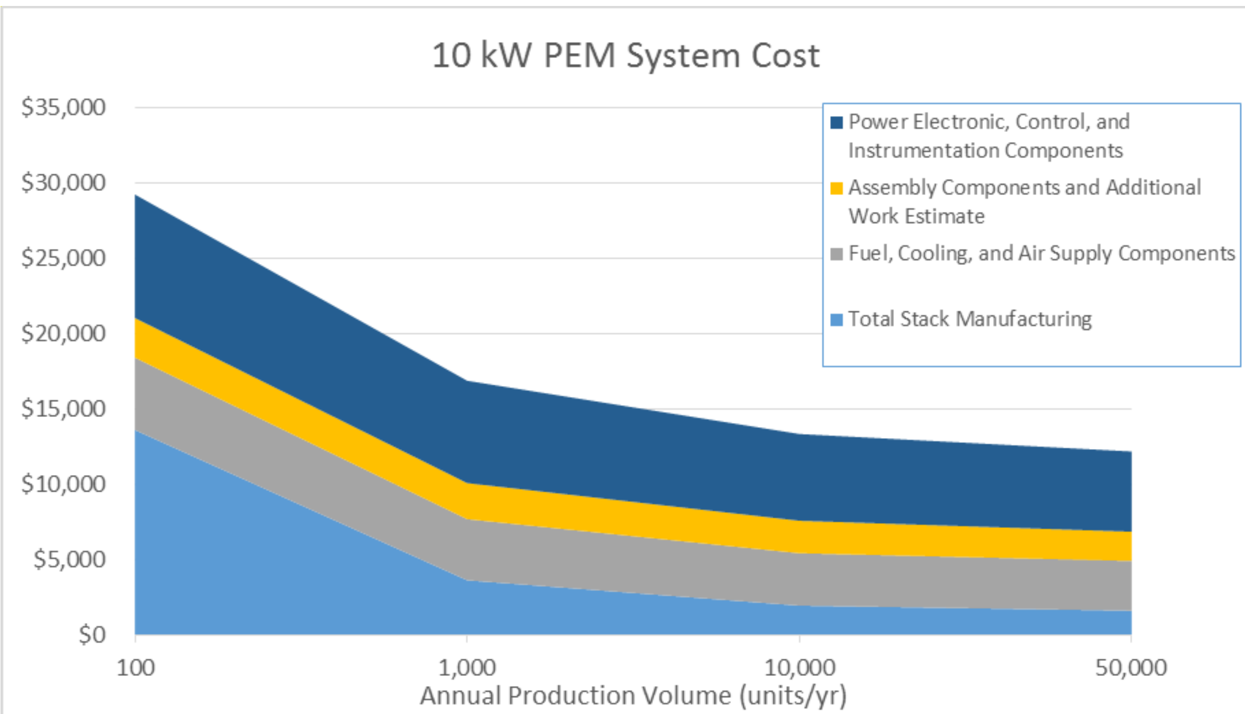


Figure 7-4. 10-kW PEM cost volume trends

Figure 7-5 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 net kilowatt. The trends in Figure 7-5 influence the life cycle cost analysis of Section 9.

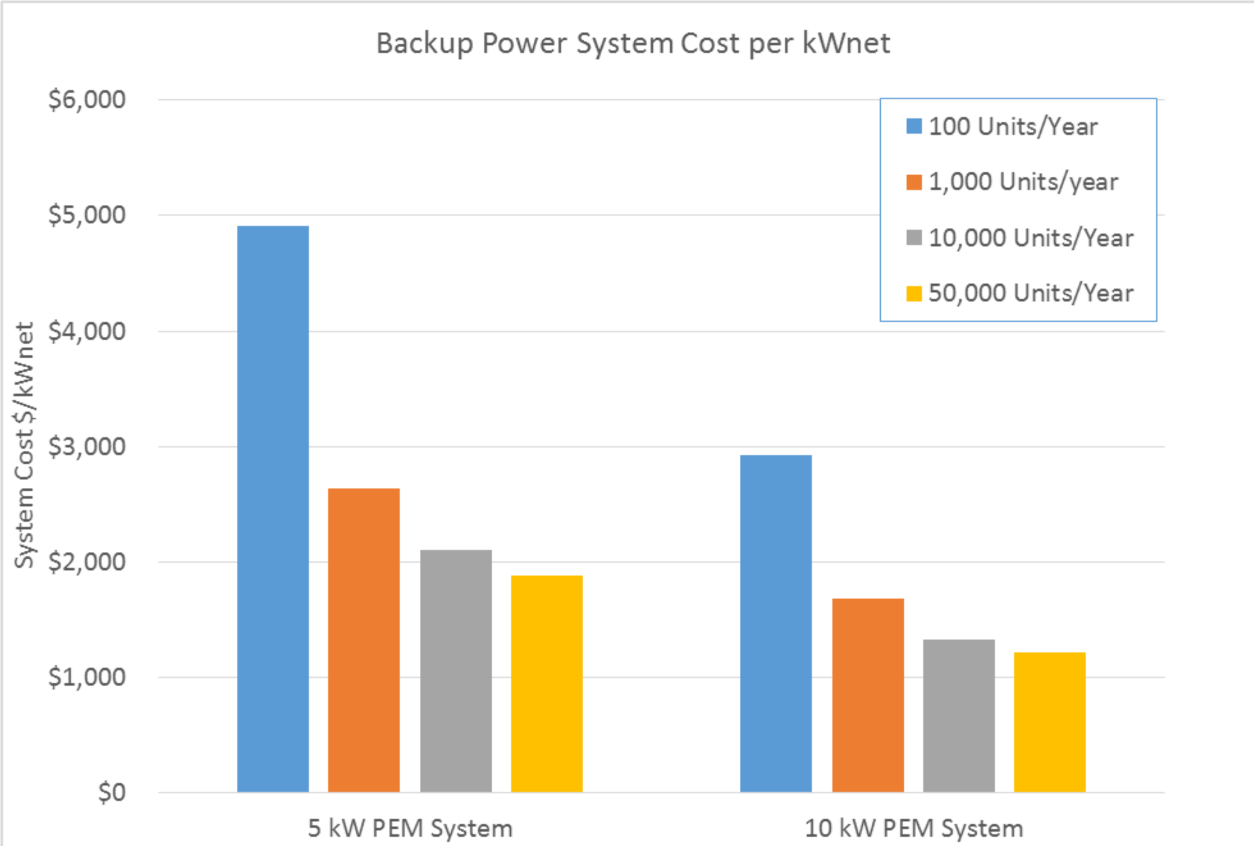


Figure 7-5. Pre-markup cost per kilowatt for 5- and 10-kW systems

7.2 Future Cost Reduction

The items below are potential areas for product or manufacturing improvement. Additional work and discussion is provided in Section 8 (Sensitivity Analysis). Because of the strong influence of the BOP on overall system costs, BOP hardware is clearly a topic of interest for cost reduction.

Before considering specific cost reduction areas, it is appropriate to note that the selected PEM system design has been optimized for cost. BOP equipment consists of COTS items not necessarily designed for fuel cell use; therefore, further cost savings may be realized through use of components designed with fuel cell system requirements in mind. Further, specific applications or installations will apply different constraints and afford different opportunities in system design. A significant opportunity for cost reduction likely exists in modifications to the system schematics to eliminate components by integration with other hardware or by advances in technology that eliminate the need for some hardware. The first place to look for cost improvement is in the details of the system configuration giving attention to potential simplification and function integration.

A review of the cost tables (Section 5) and sensitivity analysis (Section 8) shows that power electronics are major contributors to the overall cost, specifically the DC/DC converter. Costs associated with the DC/DC converter may decrease as the renewable energy market further develops and is integrated into an increasing number of applications. The remainder of the BOP is comprised of relatively mature equipment which is less likely to experience decreases in costs attributed to market growth.

A final comment is appropriate on the manufacturing process. The scrap and reject rates assumed here are those recommended by our industry contacts as representative of the state of the art. Five percent failure for the stack and three percent failure rate of the system at final test are unacceptable failure rates for mass produced hardware. It is essential to develop effective quality control measures and robust fabrication process to reduce those rates to less than 0.5%.

8. Sensitivity Analysis

8.1 PEM System

The sensitivity analysis of the costs for the 5-kW PEM fuel cell system at production volumes of 1,000 and 10,000 units per year explores the impact of specific 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 for the difficult nature of precisely assessing their magnitude, such as the cost of platinum. The analysis demonstrates the effect on the overall cost of the system based on reasonable variations in each factor. The cost variances are not independent. For example, a decrease in current density increases the total amount of membrane, GDL, catalyst, and other materials. The charts below show that a 50% decrease in GDL cost could offset most of the cost increase associated with a 50% decrease in current density. The results of the sensitivity analyses are shown in the following charts (Figures 8-1 and 8-2), which show the relative importance of the major cost drivers. Note that due to the similarity of the 5- and 10-kW systems, only the 5-kW system was considered as part of this analysis.

For the 5-kW PEM fuel cell system sensitivity analysis, the cost factors that were varied along with their basis and effect include:

- GDL Cost
    - Assumed to be $56/m^2
    - GDL cost greatly affects MEA cost
    - Varied by -50% to observe effect
    - Up to ~5% change in system cost

- DC/DC Converter
    - Assumed to be $2,538 at 1,000 units/year
    - Assumed to be $2,209 at 10,000 units/year
    - Varied by ±20%
    - Up to +/- ~4% impact to overall system cost

- Current Density
    - Assumed to be 1.5 A/cm^2
    - Adjusted to 1.0 A/cm^2 to see effect
    - The current density of 1.5 A/cm^2 was chosen due to minimal amount of expected run hours over system lifetime (compared to a primary power fuel cell system)
    - Up to ~4% change to overall system cost

- Membrane Thickness
    - Assumed to be 50 micrometers (μm)
    - Adjusted to 25 μm and 100 μm to see effect
    - There is only a minor impact on overall system cost

- Platinum Loading
    - Assumed to be 0.15 milligrams (mg)/cm^2
    - Varied to 0.12 mg/cm^2 and 0.3 mg/cm^2
    - There is only a minor impact on overall system cost

- Platinum Cost
    - Assumed to be $1,294/troy ounce
    - Varied by ±40%
    - The cost of platinum is highly variable, ranging from ~$800 to over $2,000 per troy ounce
    - Platinum is currently trading at roughly $1,000/troy ounce
    - For past system studies on lower power systems, platinum cost has shown a significant cost impact
    - There is only a minor impact on overall system cost for this system

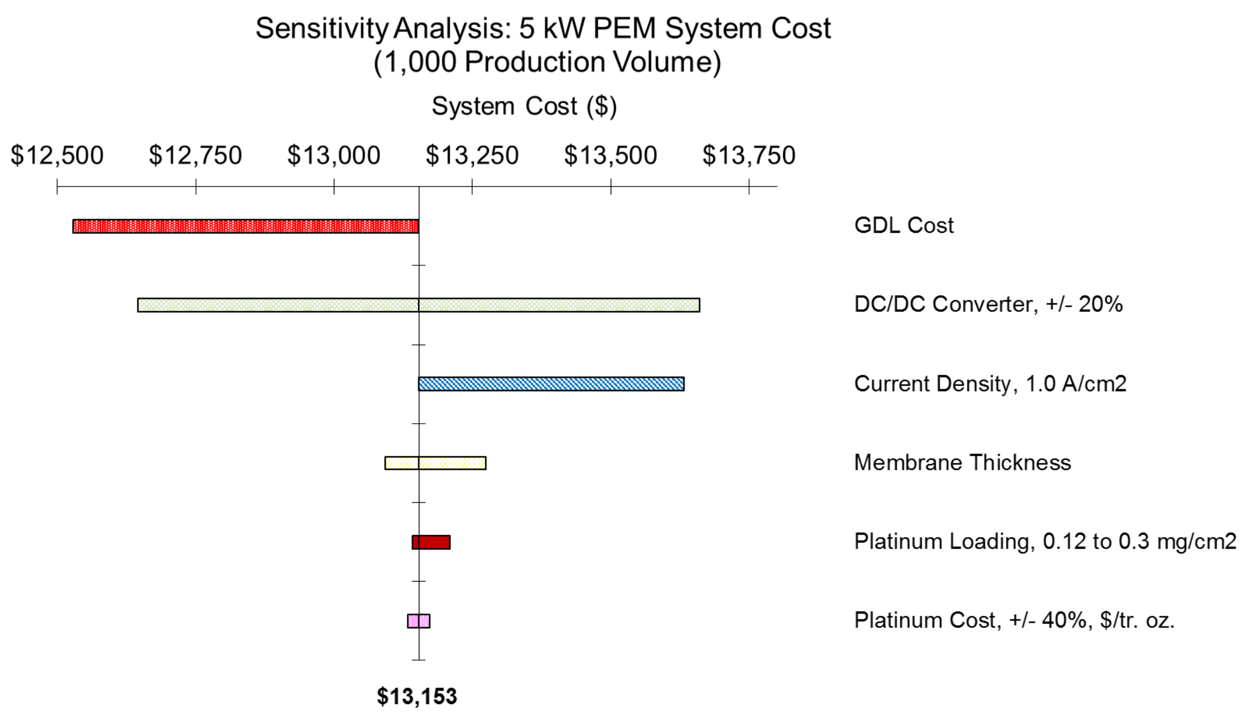


Figure 8-1. PEM sensitivity analysis: 5-kW system cost – 1,000 production volume

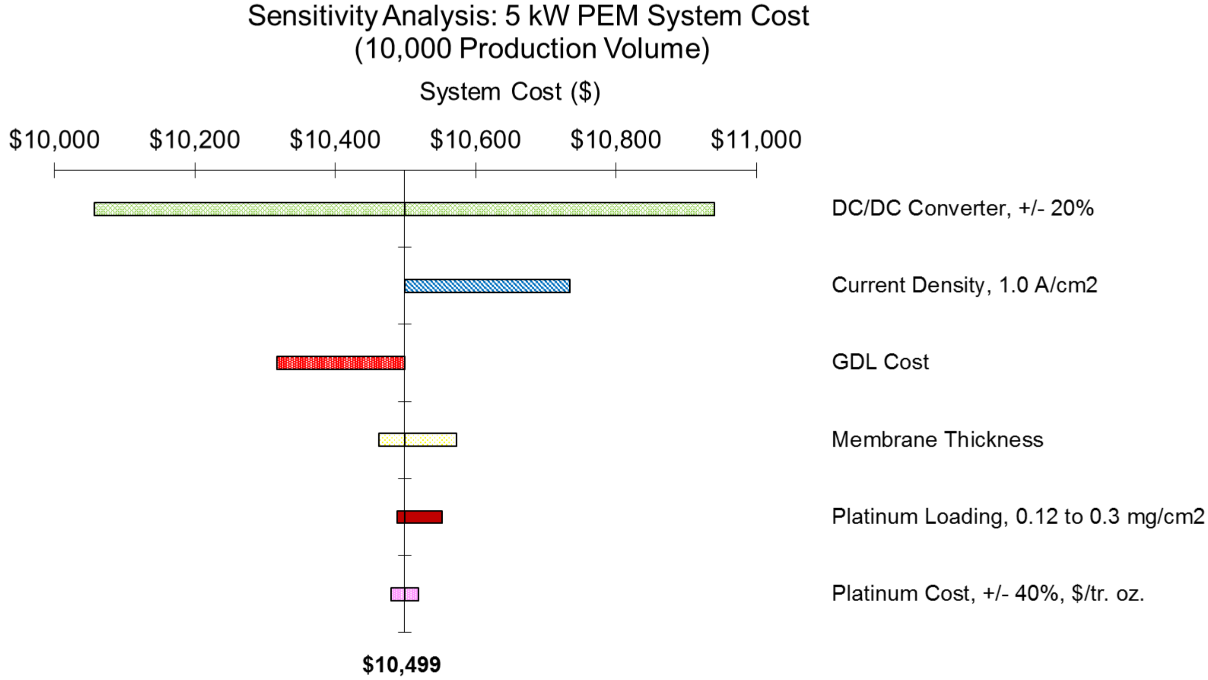


Figure 8-2. PEM sensitivity analysis: 5-kW system cost – 10,000 production volume

9. Life Cycle Analyses of Fuel Cells

Backup power systems are installed to address the costs and risks associated with loss of production, loss of business, or increase in likelihood of injury associated with an electric power grid outage. The costs associated with a power outage can be significant[17] and in some cases (e.g., hospitals), the personal health impacts may be extreme. These costs are independent of the backup power technology installed so long as the backup power system starts quickly, performs reliably and lasts for the full duration of the grid (or other primary power) outage. To assure quick and reliable starts, backup power systems typically start up once each month to confirmation operation. In this context, a fuel cell system must compete directly with battery pack systems, natural gas engines, diesel engines, and possibly other energy storage and conversion technologies, including solar/wind-assisted battery systems.

In the United States, the average power outage lasts less than 1 hour[17]. However, recent storms and grid failures (e.g., Superstorm Sandy, October 2012; Northeast blackout August 2003)[18] have exposed the potential for widespread, extended grid outages that may last for multiple days or even multiple weeks. During an extended outage, the normal repair/maintenance/support infrastructure for backup power systems may be ineffective or completely inoperative. Preparation for terrorist attacks that may intentionally disrupt more than one utility (e.g., natural gas and electric distribution) adds another set of

[17] Power Outage Annual Report, Eaton 2015. Available at http://images.electricalsector.eaton.com/Web/EatonElectrical/%7Bde3f8139-7d99-4324-9166-22262683e51d%7D_US_BlackoutTracker_2015_Final.pdf

[18] Jacobs, Mike. "13 of the Largest Power Outages in History – and What They Tell Us About the 2013 Northeast Blackout." *Union of Concerned Scientists*. August 8, 2013. Accessed May 2016. Available at http://blog.ucsusa.org/mike-jacobs/2003-northeast-blackout-and-13-of-the-largest-power-outages-in-history-199

requirements to the plan. In that context, the energy density, reliability, and shelf-life of on-site storage becomes a significant factor in backup power system selection. Further, a grid outage plan addressing longer durations will incorporate a greater variety of operations and electrical loads than a plan intended to provide just for safe shutdown of operations during a short outage, thereby increasing the net energy requirement and power levels to be provided.

Our analysis suggests that fuel cell systems must achieve significant reductions in cost to compete directly with the available alternatives on a first-cost basis. The situation is further complicated by a possible perception on the part of staff responsible for backup power selection that fuel cells are a new and unproven technology—a decided deterrent to their installation where reliability is essential. Despite these drawbacks, we believe there are opportunities for fuel cell backup power systems when all aspects of the installation are considered. Experience with the reliability and maintenance requirements of alternative technologies (e.g., diesel) should yield an advantage to fuel cells once their true capabilities are understood by decision makers.

Compressed hydrogen has essentially infinite shelf-life as compared to gasoline or diesel fuel, which degrade over time—a phenomenon that discourages large on-site storage. Diesel fuel is valuable and relatively easy to steal, thus requiring additional security measures for remote locations in particular. Hydrogen is not a commodity fuel with commonplace uses; therefore, the potential for theft is reduced. Further, compressed hydrogen cylinders may be stored outside in any weather while other on-site stored fuels, and batteries in particular, must be appropriately housed in temperature-managed conditions. Moreover, any mechanical prime mover (e.g., diesel or gasoline reciprocating engine or natural gas turbine) may experience bearing wear during the monthly short-duration test runs, as lubrication films may not fully develop after a few weeks of non-use. Additionally, environmental regulations may limit the total number of hours an engine-type backup power system may run during a year. Even without environmental regulation, the odor of diesel exhaust in particular may not align with good-neighbor objectives. Noise and vibration are additional aspects of engine operation which may preclude or at least discourage their use in some locales and for some installations, particularly in urban areas.

It is difficult to place a generic monetary value on many of the aspects where fuel cells are clearly superior. For any potential application, the responsible staff will need to weigh these factors against the additional cost of the fuel cell system. Installations to address the high cost of infrequent but long-term outages are likely to find that fuel cells offer an attractive alternative to more conventional backup power technologies when the costs of additional housing and space conditioning are included along with any good-neighbor equipment (additional noise buffers, exhaust dilution systems, etc.). When fuel cells are compared against the historic choice of batteries for 10-kW and smaller telecom applications, operational costs of fuel cells may be lower. For example, batteries require replacement every couple of years even if they are not used, while degradation of a fuel cell is based on operating hours.

10. Conclusions

This section summarizes the backup power fuel cell system costs and resulting conclusions.

10.1 System Cost Summary

The summary pie charts for 1,000 units per year, repeated from Section 7, emphasize that the BOP costs dominate the final cost for both 5- and 10-kW systems. For production quantities of 1,000/year or higher the stack represents a maximum of 21.4% of the total system cost. This applies for both the 5- and 10-kW systems. Within the BOP costs, the major contributor for all systems is the power electronic hardware dominated by the DC/DC converter. This category alone represents up to 25% of the overall system cost as shown in Figure 10-1. The relationships among subsystem costs are substantially different than for systems using natural gas or other fuels due to the simplified system design afforded by direct hydrogen fuel systems.

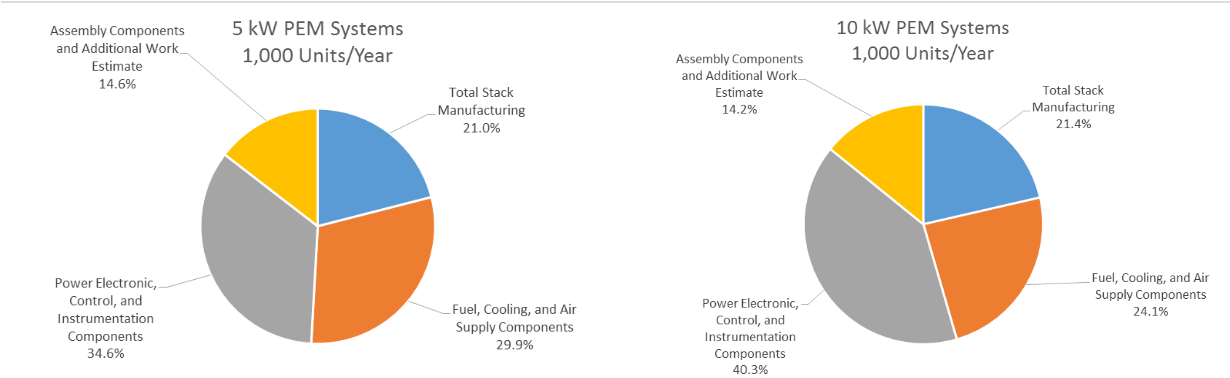


Figure 10-1. PEM system costs at 1,000 units per year

The total cost for each size system at two representative production volumes is shown in Table 10-1. A sales markup of 50% was integrated into the overall cost and is called out separately. The table emphasizes the system cost difference between each size system on an installed cost-per-kilowatt basis. Figure 10-2 shows the installed cost (including markup) per kilowatt for both the 5- and 10-kW systems at the various annual production volumes analyzed.

Table 10-1. PEM System Cost

Description	5-kW		10-kW	
	1,000 Units/year	10,000 Units/year	1,000 Units/year	10,000 Units/year
Total Stack Manufacturing	$2,765	$1,394	$3,607	$1,924
Fuel, Cooling, and Air Supply Components	$3,928	$3,418	$4,057	$3,481
Power Electronic, Control, and Instrumentation Components	$4,544	$3,956	$6,793	$5,760
Assembly Components and Additional Work Estimate	$1,915	$1,730	$2,390	$2,150
Total System Cost, Pre-Markup	$13,153	$10,499	$16,847	$13,315
System Cost per kW_{net}, Pre-Markup	$2,631	$2,100	$1,685	$1,331
Sales Markup	50%	50%	50%	50%
Total System Cost, with Markup	$19,729	$15,748	$25,271	$19,972
System Cost per kW_{net}, with Markup	$3,946	$3,150	$2,527	$1,997

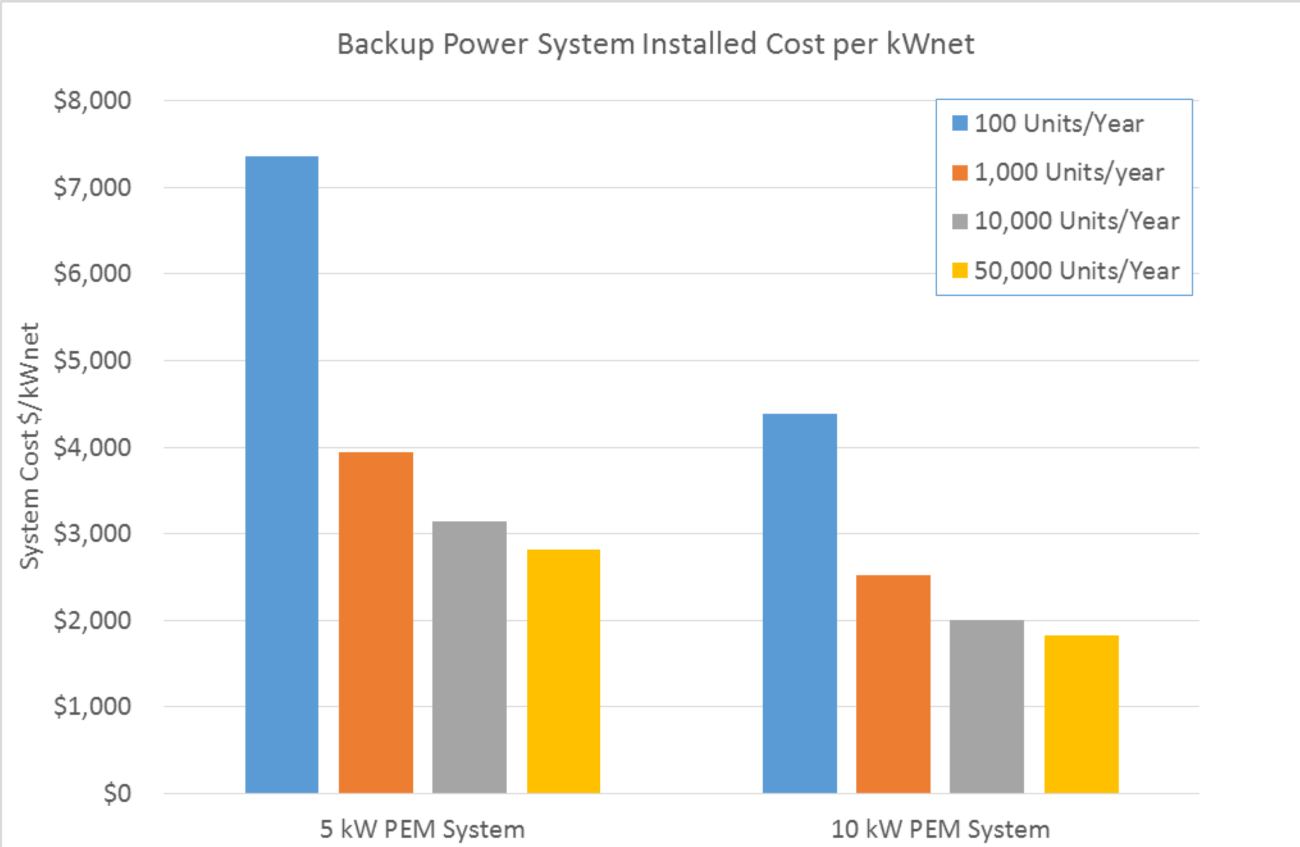


Figure 10-2. Net system installed cost (after mark-up)

10.2 Value Proposition

The overall value proposition for a PEM backup power system depends on the projected economic losses and safety hazards posed by an outage. Fuel cell backup power systems may not yet be competitive with conventional generator or battery-based systems on a cost alone basis, but they do offer benefits over these incumbent technologies including increased reliability, near-infinite fuel storage shelf life, benign exhaust streams, and quiet operation. The latter two factors become increasingly important in dense urban settings, such as installations on the roofs of city buildings. It is difficult to place a generic monetary value on many of the aspects where fuel cells offer superior benefits over conventional backup power systems. End users will need to weigh these factors against the additional cost of the fuel cell system to determine the appropriate system for each application. Fuel cells are likely to offer an attractive alternative to more conventional backup power technologies when the costs of additional housing and space conditioning are included along with any good-neighbor equipment (additional noise buffers, exhaust dilution systems, etc.) required of conventional backup power sources.

10.3 Sensitivity and Future Market Impact

The sensitivity analysis suggests that changes of +/-40% in the cost of platinum impact PEM system by only 0.15%. Section 8 indicates that some factors such as current density and power electronics maturity that are likely to improve in the future will have greater overall cost benefits. Both system sizes show significant sensitivity to power electronics cost, specifically the DC/DC converter, suggesting that additional, more detailed analysis of the core costs of power electronics would be beneficial. Changes of +/- 20% in the cost of the DC/DC converter alone influence the overall system cost by 4%.

As fuel-cell-powered material handling equipment (MHE) increases market penetration and as automotive use of fuel cells increases, we expect that the direct hydrogen-fueled backup power market will continue to develop, initially for areas with needs specific to those areas where fuel cell backup power systems offer significant secondary advantages (lower noise, environmental impact, fuel theft) over incumbent technology. Power electronics developments for MHE and automotive systems assist in reducing fuel cell system cost, noted here as the largest cost contributor to a backup power system. Development of power electronics for the solar power industry may also provide future cost savings for fuel cell systems.

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

Machine Rate Calculations

The basic machine rate equation from James (2014)[1] is:

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

where:

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

To calculate a baseline production line cost, we assume that the line 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 *Journal of Manufacturing Science and Engineering* (JMSE) paper 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:

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

[1] 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, 024503.

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

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

where: n = unique pieces of equipment making up production line
N_i = number of item i required for production line
C_i = capital cost of item i
L_i = expected life of item i

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

Bipolar Plate Compression Molding		**Cost**	**Units Per Line**	**Expected Life (yrs)**
1,000-ton fast-acting press	Wabash 1000H-48	$650,000	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	$650,000	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 line are a function of the power required to operate each piece of equipment. For cost-estimating purposes, the total power draw of the production line 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 line
N_i = number of item i required for production line
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:

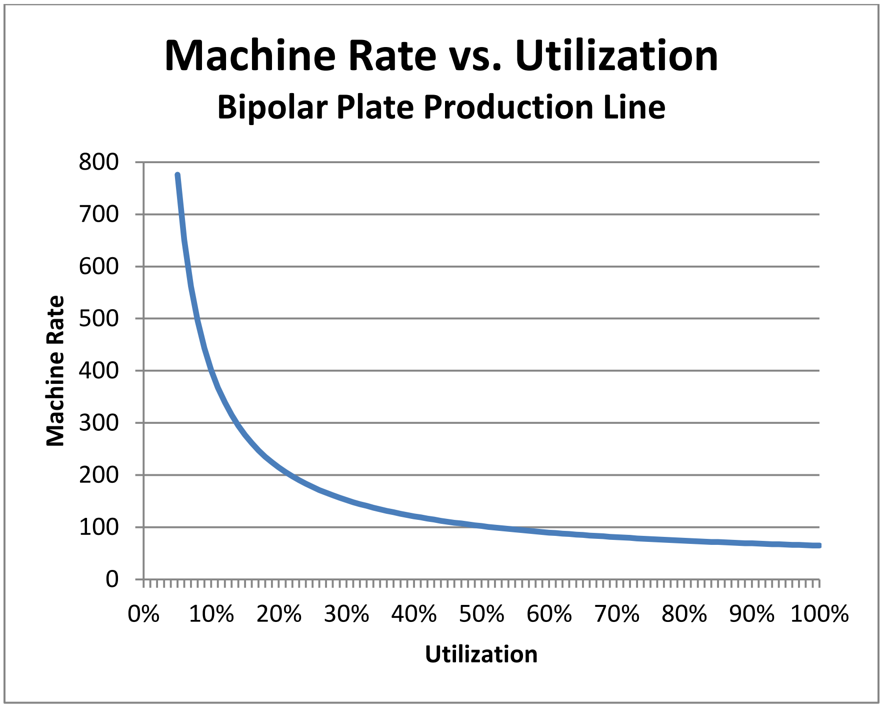
Bipolar Plate Compression Molding	**N_i**	**V_i**	**A_i**	**D_i**	**P**
1,000-ton fast-acting press	1	460	150	96%	66.24
Heated platens, 15"x12", 4.5 kW, controller	1	230	25	25%	1.44
Arbor or hand-operated hydraulic pre-mold press	1	0	0	10%	0.00
Electronic scale, industrial, gram resolution	1	120	1	100%	0.12
Small industrial oven	1	230	20	20%	0.92
Total					**68.72**

The machine rate is calculated as:

$$R_M = \$638{,}400 * \frac{(1.4 * 0.122656 + 0.06 + 0.12)}{6000 * U} + (0.07 * 68.72) + (45.00 * 0.5) = \frac{\frac{\$37.42}{hour}}{U} + 27.31$$

where: U > 0

Graphically:



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

LTPEM Production Line	Baseline Cost	Cost per Hour		100% Utilization Machine Rate
		Power	Labor	
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	$40.24
Die Cutting	$125,000	$0.32	$22.50	$30.15
Gasket Injection Molding	$48,000	$0.72	$45.00	$26.04
End Plates	$416,000	$6.50	$90.00	$120.89
Stack Assembly	$1,310	$0.00	$45.00	$45.08
Testing and Conditioning	$300,000	$2.42	$14.85	$34.85

Make vs Buy Decision

As indicated in James (2014)[2], 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 inspection. Assuming a 65% minimum machine utilization and 40% markup for profit plus overhead, the job shop maximum machine rate becomes:

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

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

$$R_{Mjsmax} = 1.4 * \left[\frac{\frac{\$37.42}{hour}}{0.65} + \$27.31 \right] = \$118.83$$

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

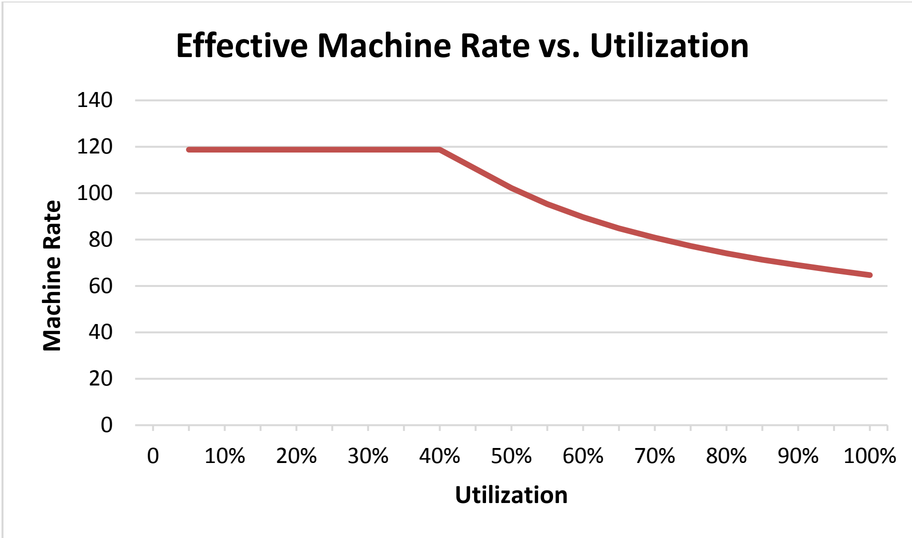
$$R_{Mih} = \left[\frac{\frac{\$37.42}{hour}}{U} + \$27.31 \right] = \$118.83$$

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

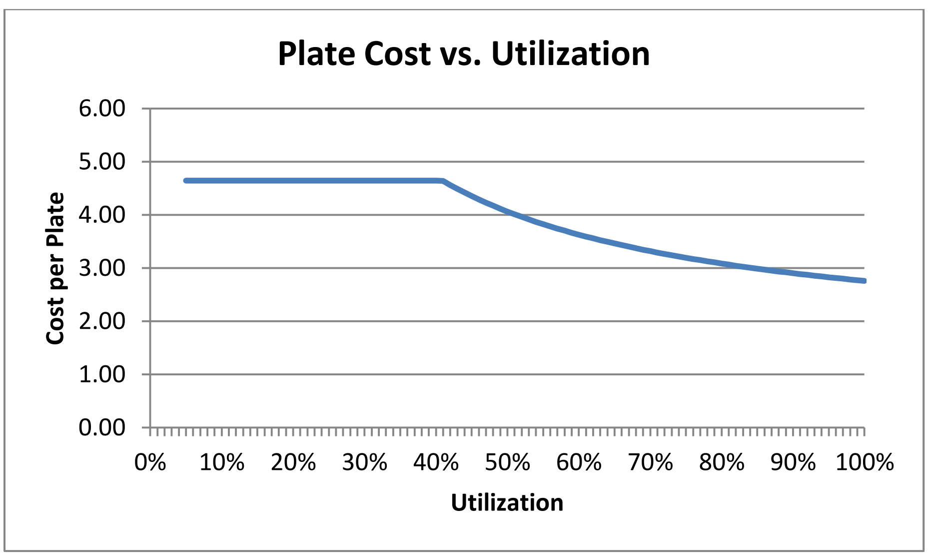
In other words, for utilization rates of less than 40.9%, bipolar plate manufacturing should be subcontracted to a job shop instead of incurring the costs of manufacturing the plates in-house.

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.

[2] Ibid.



This can be further illustrated by estimating the production per unit for bipolar plates. Each anode bipolar plate for a 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-hours per machine hour. Using the above equations, the bipolar plate unit cost as a function of line 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

Material Cost Learning Curve Calculations

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*, Stewart, R.M., et al, 2^{nd} Ed., Wiley-Interscience, 1995, 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 $10{,}000^{th}$ unit.

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:

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

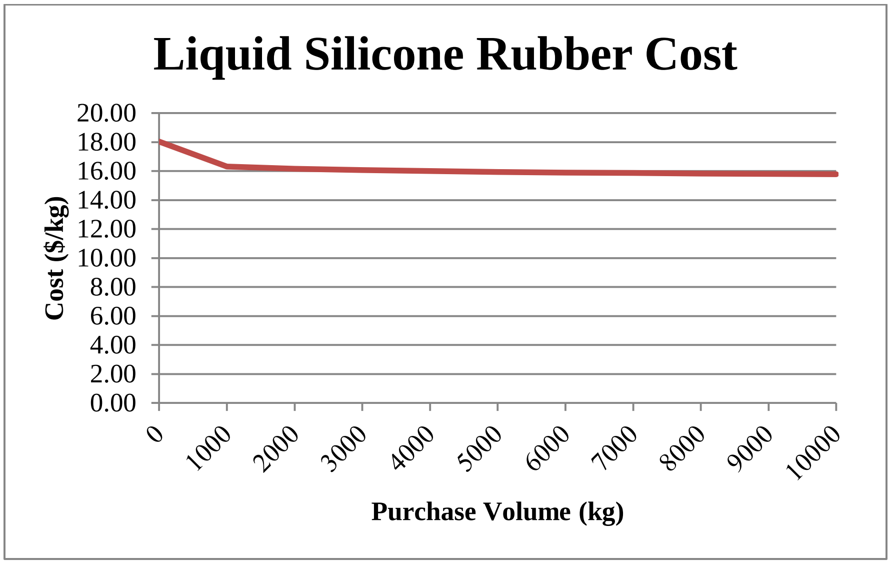
Using a learned cost of $15.40/kg for a volume of 55,000 kg, then the cost of the first unit is:

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

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 gas diffusion layer (GDL) in the low-temperature polymer electrolyte membrane (LTPEM) stack, the cost curve is steeper. One supplier provided low-volume quotes of $535.63/m² for 3 m², and $313.13/m² for 45 m². Estimates obtained from previous fuel cell manufacturing cost analyses estimated high-volume costs to be in the range of $56.00/m² for volumes up to 100,000 m². Iteration using the costs above led to a value of m=0.86, which results in:

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

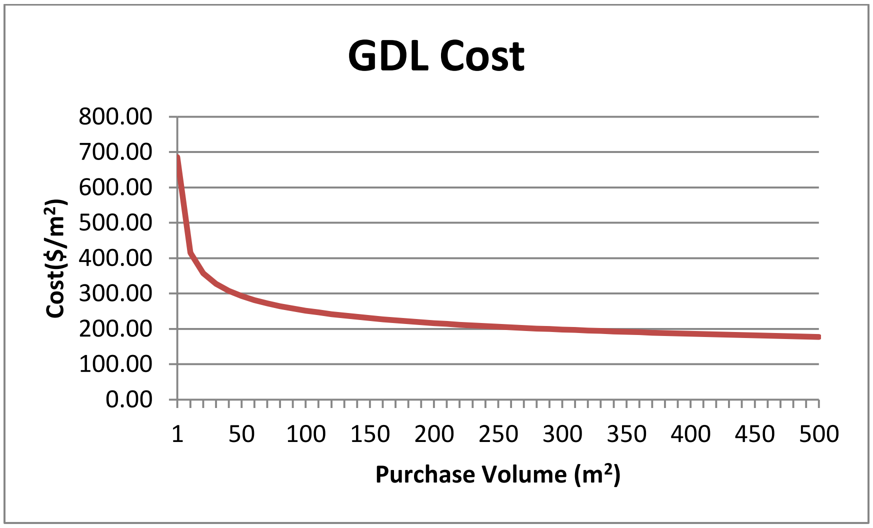
Using a learned cost of $56.00/m² for a volume of 100,000 m², then the cost of the first unit is:

$$A = Y / X^b = 56.00 / 100{,}000^{(-0.21759)} = \$685.72$$

For a purchase of 40 and 100 m² of material, the calculated cost per unit is:

$$Y_{40} = A \times X^b = 685.72 \times 3^{(-0.21759)} = \$539.92$$
$$Y_{100} = A \times X^b = 685.72 \times 45^{(-0.21759)} = \$299.52$$

The corresponding cost chart would appear as:



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

LTPEM Material	Unit	Y	X	m	b	A
Platinum	kg	$48,226.50	1	1.00	0.0000	$48,226.50
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	$28.76	150,000	0.86	-0.2176	$384.65
Polyester Film	m^2	$0.32	30,000	0.55	-0.8625	$2,326.22
GDL	m^2	$22.00	500,000	0.69	-0.5353	$24,732.17
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

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 30-kilowatt (kW) stacks requires more than 4,000 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:

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

For the bipolar plate material, the equation above yields:

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

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.

High-volume purchase costs of DE-521 were very difficult to obtain. Because the cost of DE-521 is driven primarily by the cost of DuPont’s Nafion polymer, the cost was calculated based on learning curve analysis of the primary cost driver, and assumed values associated with manufacturing and supplier markup.

Appendix A-3: LTPEM Platinum Catalyst Coating Process

Platinum Catalyst Membrane Coating Process

Model Approach

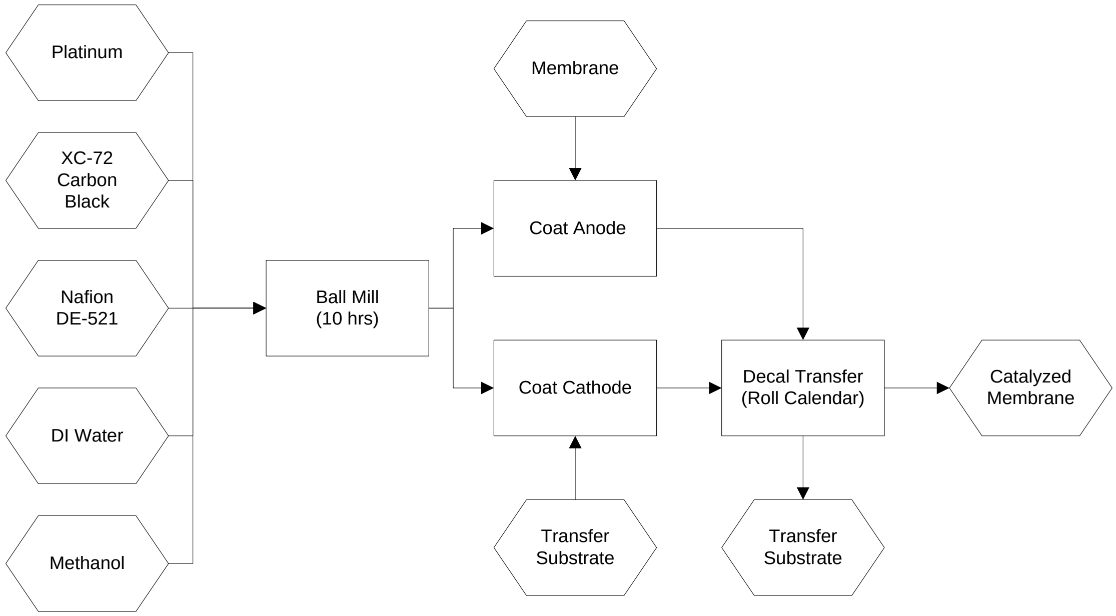
- Catalyst ink preparation operation
    - Compute machine setup labor time based on user input
    - Compute required batch size based on part batch size and catalyst loading
    - Compute catalyst ink material unit cost based on usage
    - Compute catalyst ink processing time and machine utilization

- 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

Process Flow



Background

In its March 2009 report, Directed Technologies, Inc. (DTI) reported that the wet platinum (Pt) catalyst composition as specified in U.S. patent no. 7,141,270 consists 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

DTI also reported that, 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

While DTI assumed that the ink slurry was mixed using ultrasonic processing, 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. 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).

All of the above methods pay a material cost penalty by applying catalyst to the entire MEA surface, including the non-active areas. A more economical approach may involve 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.

Preliminary Analysis

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:

$$142.0\text{-millimeter (mm) width} \times 142.0\text{-mm length} = 201.6 \text{ square centimeters } (\text{cm}^2)$$

Material densities for the catalyst components are as follows:

- ρ(Pt) = 21.45 grams per cubic centimeter (g/cm^3)
- ρ(XC-72) = 0.264 g/cm^3
- ρ(Nafion DE-521) = 1.05 g/cm^3
- ρ(DI water) = 1.0 g/cm^3
- ρ(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:

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

Yielding a wet catalyst density of:

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

The Pt content of the wet catalyst is:

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

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

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

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:

$$\mathrm{v} = (32.3/21.45) + (48.4/0.264) + (19.4/2.05) = 194.3\ \mathrm{cm}^3$$

Yielding a dry catalyst density of:

$$\rho(\text{dry catalyst}) = (100/194.3) = 0.515\ \mathrm{g/cm}^3$$

The Pt content of the dry catalyst is:

$$\mathrm{m(Pt)/v(dry\ catalyst)} = 32.3/194.3 = 0.166\ \mathrm{g/cm}^3 = 166\ \mathrm{mg/cm}^3$$

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

$$\mathrm{d(dry\ catalyst)} = 1/166 = 0.006\ \mathrm{cm} = 60\ \mathrm{microns}$$

The total Pt loading for this design is 0.15 milligrams per square centimeter (mg/cm^2) with cathode loading in a 2:1 ratio relative to anode loading, making the loadings 0.10 mg/cm^2 and 0.05 mg/cm^2 for the cathode and anode, respectively. This will require wet deposition to depths of 20 and 10 microns, respectively, resulting in dry layer depths of 6 and 3 microns. Therefore, to coat both sides of the membrane with a total loading 0.15 mg/cm^2 will require a total coated depth of 30 microns (0.003 cm):

$$\text{Wet catalyst weight} = 0.85\ \mathrm{g/cm}^3 \times (201.6 \times 0.003)\ \mathrm{cm}^3 = 0.514\ \mathrm{g/part}$$

The 6-kilowatt (kW) stack requires 36 cells. Based on producing 1,000 stacks per year, the required annual production before scrap is:

$$\text{Annual production} = 36\ \text{parts/stack} \times 1{,}000\ \text{stacks} = 36{,}000\ \text{parts}$$
$$\text{Catalyst batch size} = 36{,}000\ \text{parts} \times 0.514\ \text{g/part} \times 0.001\ \text{kg/g} = 18.51\ \text{kg}$$

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/troy ounce (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) for April 2016 delivery. 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 Methenex and others at around $630/MT ($0.63/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 × 18.51 kg = 1.11 kg
Nafion DE-521: 0.72 × 18.51 kg = 13.33 kg
Vulcan XC-72: 0.09 × 18.51 kg = 1.67 kg
Methanol: 0.065 × 18.51 kg = 1.20 kg
DI water: 0.065 × 18.51 kg = 1.20 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 = $724.90/kg
Vulcan XC-72 = $1.44/kg
Methanol = $1.07/kg
DI water = $0.31/kg

The cost of the ink is:

$$\text{Material cost} = (0.06 \times 41{,}602) + (0.72 \times 724.90) + (0.09 \times 1.44) + (0.065 \times 1.07) + (0.065 \times 0.31)$$
$$\text{Material cost} = \$3{,}018.28/\text{kg} = \$3.018/\text{g}$$

Total annual catalyst material cost before scrap is:

$$\$3{,}018.28/\text{kg} \times 18.51\ \text{kg} = \$57{,}301.33$$

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:

$$\text{Material prep time} = 5 \times 21.4\ \text{sec} = 107\ \text{sec} = 1.8\ \text{minutes}$$

The primary cost for operating the ball mill is the energy input to the motor running the mill. Some studies have looked into 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. 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:

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

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:

$$V = 0.079 \times \pi \times (1.067)^2 \times 1.219 = 295\ \text{kg}$$
$$V = 0.079 \times \pi \times (1.219)^2 \times 1.524 = 482\ \text{kg}$$

We note that production levels of 1,000 stacks per year will require 18.51 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:

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

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:

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

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:

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

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

$$\text{Charge volume } (m^3) = 1.11 \times (\text{catalyst weight (kg)} / \text{catalyst density } (kg/\ m^3))$$
$$\text{Charge volume } (m^3) = 0.0013 \times \text{catalyst weight}$$

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

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

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

$$\text{Material removal time} = 8.1 \times 18.51 = 149.9 \text{ sec} = 2.5 \text{ minutes}$$

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 18.51 kg of catalyst:

$$\text{Process time} = 1 \text{ batch} \times (10 + 0.5 + (1.8 / 60) + (2 \times (2.5 / 60))) \text{ hrs} = 10.61 \text{ hrs}$$

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

$$\text{Roundup}(10.61 / 6{,}000) = 1 \text{ mill}$$

Machine utilization is:

$$10.61 / 6{,}000 = 0.18\%$$

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 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 202.0 mm × 202.0 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:

$$\text{Number of lengthwise parts} = \text{INT}(\text{Roll width} / \text{Part length})$$
$$\text{Lengthwise waste fraction} = (\text{Roll width} / \text{Part length}) - \text{Number of lengthwise parts}$$

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 meter. Common thin films (polyimide, polyethylene) used as transfer media tend to be either 0.4 or 0.8 meter, 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 widths and is the most expensive, so it will be used to determine the maximum coating width with minimum scrap. Because the 6-kW cells are square, orientation is not an issue, as it would be for rectangular cells. Three cells will take up 606 mm of membrane width, leaving a 4.0-mm edge margin on a 610-mm roll width for the membrane. The material length required will be:

$$\text{Material length} = (36{,}000 \text{ parts} / 3 \text{ part widths/part length}) \times 202.0 \text{ mm part length} / 1{,}000 = 2{,}424.0 \text{ meters}$$

The total material area required before scrap is:

$$\text{Membrane area} = 2{,}424.0 \text{ meters (m)} \times 0.610 \text{ m} = 1{,}478.64 \text{ m}^2$$
$$\text{Transfer substrate area} = 2{,}424.0 \text{ m} \times 0.8 \text{ m} = 1{,}939.2 \text{ m}^2$$

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

$$\text{Membrane cost} = \$78.15/\text{m}^3$$
$$\text{Transfer substrate cost} = \$3.27/\text{m}^3$$

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 46,000 parts is:

$$\text{Number of setups} = \text{Roundup}(\text{Carrier length (m)} / \text{Roll length (m)})$$
$$\text{Membrane: Number of setups} = \text{Roundup } (2{,}424.0 / 100) = 25$$
$$\text{Transfer substrate: Number of setups} = \text{Roundup } (2{,}424.0 / 1{,}000) = 3$$

Slot Die Coating

Slot die coating is capable of very thin coating thicknesses. The coated material passes 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:

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

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 0.15 mg/cm^2 of platinum, the anode will be coated to a depth of 10 microns, while the cathode will be coated to a depth of 20 microns, making the maximum coating speeds:

$$\text{Anode maximum coating speed} = 157.18 \times 0.987^{10} = 137.9\ \text{mm/sec} = 8.27\ \text{meters per minute (m/min)}$$

$$\text{Cathode maximum coating speed} = 157.18 \times 0.987^{20} = 120.99\ \text{mm/sec} = 7.26\ \text{m/min}$$

Part throughput is calculated as:

$$\text{Throughput (parts/hour)} = \text{Coating speed (m/min)} \times \text{Parts per part length (parts)} / \text{Part length (m)} \times 60\ \text{min/hour}$$

$$\text{Anode: Throughput} = 8.27 \times 3 / (202.0 / 1{,}000) \times 60 = 7{,}369.3\ \text{parts/hour}$$

$$\text{Cathode: Throughput} = 7.26 \times 3 / (202.0 / 1{,}000) \times 60 = 6{,}469.3\ \text{parts/hour}$$

Total machine time to set up and produce 36,000 parts is:

$$\text{Anode machine time} = (25\ \text{setups} \times 0.5\ \text{hour/setup}) + (36{,}000\ \text{parts} / 7{,}369.3\ \text{parts/hour}) = 17.39\ \text{hours}$$

$$\text{Cathode machine time} = (3\ \text{setups} \times 0.5\ \text{hour/setup}) + (36{,}000\ \text{parts} / 6{,}469.3\ \text{parts/hour}) = 7.06\ \text{hours}$$

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

$$\text{Roundup}((17.39 + 7.06) / 6{,}000) = 1\ \text{coater}$$

Machine utilization is:

$$(21.74 + 9.11) / 6{,}000 = 0.41\%$$

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 and is capable of delivering approximately 100,000 parts before refurbishment at a cost of 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

$$\text{Anode annual tooling cost} = \frac{1}{5}((\$14{,}000 + (4 \times \$3{,}500)) \times \text{Roundup}((36{,}000\ \text{parts/year} \times 5\ \text{years}) / 500{,}000\ \text{parts/tool})) = \$5{,}600$$

$$\text{Cathode annual tooling cost} = \frac{1}{5}((\$14{,}000 + (4 \times \$3{,}500)) \times \text{Roundup}((36{,}000\ \text{parts/year} \times 5\ \text{years}) / 500{,}000\ \text{parts/tool})) = \$5{,}600$$

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 (Tape casting of ceramics, *Ceramic Processing Before Firing*, 1978) 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:

$$\text{Anode liquid removed per area} = 0.335\ \text{g/cm}^3 \times 0.001\ \text{cm} = 0.0003\ \text{g/cm}^2$$
$$\text{Cathode liquid removed per area} = 0.335\ \text{g/cm}^3 \times 0.002\ \text{cm} = 0.0007\ \text{g/cm}^2$$

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.

$$\text{Heater area} = \text{Drying time (min)} \times \text{Substrate speed (m/min)} \times (\text{Part width (mm)} / 1{,}000) \times \text{Parts across width}$$

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

$$\text{Anode drying time} = 0.0003\ \text{g/cm}^2 / 2.0\times10^{-5}\ \text{g/cm}^2\text{-sec} = 15\ \text{sec} = 0.25\ \text{min}$$
$$\text{Cathode drying time} = 0.0007\ \text{g/cm}^2 / 2.0\times10^{-5}\ \text{g/cm}^2\text{-sec} = 35\ \text{sec} = 0.58\ \text{min}$$

The required dryer length is:

$$\text{Anode dryer length} = 0.25\ \text{min} \times 8.27\ \text{m/min} = 2.07\ \text{m}$$
$$\text{Cathode dryer length} = 0.58\ \text{min} \times 7.26\ \text{m/min} = 4.21\ \text{m}$$

Sizing for the maximum dryer length, and assuming 12-inch × 36-inch panels fitted two across the drying conveyor, we require 10 total IR panels.

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 DTI, Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications: 2010 Update, Section 4.4.6.1), or a calendaring process, where the material is preheated and passed through heated rollers. For the preliminary analysis, we will assume a calendaring process.

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 the required setups to run 36,000 parts is the same as the number of setups for the anode slot die coating:

$$\text{Number of setups} = 25$$

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. Assuming that 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:

$$\text{Oven dwell time} = \text{Part weight (g)} \times \text{Part specific heat (J/g-°C)} \times \text{Temperature rise (°C)} \, / \, \text{Energy input (W)}$$

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

$$\text{Energy input} = \text{Heater watt density (W/cm}^2\text{)} \times \text{Part area (cm}^2\text{)} \times \text{Energy transfer efficiency}$$
$$\text{Energy input} = 2.3 \text{ W/cm}^2 \times 201.6 \text{ cm}^2 \times 0.80 = 371 \text{ W/part}$$

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:

$$\text{Catalyst specific heat} = (0.194 \times 4.2) + (0.323 \times 0.13) + (0.484 \times 4.18) = 2.88 \text{ J/g-°C}$$

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

$$\text{Anode dry catalyst volume} = 201.6 \text{ cm}^2 \times 0.0003 \text{ cm} = 0.060 \text{ cm}^3$$
$$\text{Cathode dry catalyst volume} = 201.6 \text{ cm}^2 \times 0.0006 \text{ cm} = 0.121 \text{ cm}^3$$

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

$$\text{Membrane volume} = 201.6 \text{ cm}^2 \times 0.0075 \text{ cm} = 1.512 \text{ cm}^3$$

The heating dwell time for each is then (dry catalyst density = 0.515 g/cm^3):

$$\text{Anode oven dwell time} = ((2.2\ \text{g/cm}^3 \times 0.504\ \text{cm}^3 \times 1.2\ \text{J/g-°C}) + (0.515\ \text{g/cm}^3 \times 0.060\ \text{cm}^3 \times 2.88\ \text{J/g-°C})) \times 75\text{°C} / 371\ \text{W} = 0.825\ \text{sec/part}$$

$$\text{Cathode oven dwell time} = ((2.2\ \text{g/cm}^3 \times 0.504\ \text{cm}^3 \times 1.2\ \text{J/g-°C}) + (0.515\ \text{g/cm}^3 \times 0.121\ \text{cm}^3 \times 2.88\ \text{J/g-°C})) \times 75\text{°C} / 371\ \text{W} = 0.305\ \text{sec/part}$$

For the calendaring process, the layers will be moving together, so the worst-case heating time of 0.825 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 0.069 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:

$$\text{Parts per hour} = 300\ \text{m/hour} / 0.202\ \text{m} \times 3\ \text{parts per width} = 4{,}455.4\ \text{parts/hour}$$

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 400,000 parts is:

$$\text{Anode machine time} = (25\ \text{setups} \times 0.5\ \text{hour/setup}) + (36{,}000\ \text{parts} / 4{,}455.4\ \text{parts/hour}) = 20.58\ \text{hours}$$

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

$$\text{Roundup}(20.58 / 6{,}000) = 1\ \text{calendar machine}$$

Machine utilization is:

$$20.58 / 6{,}000 = 0.34\%$$

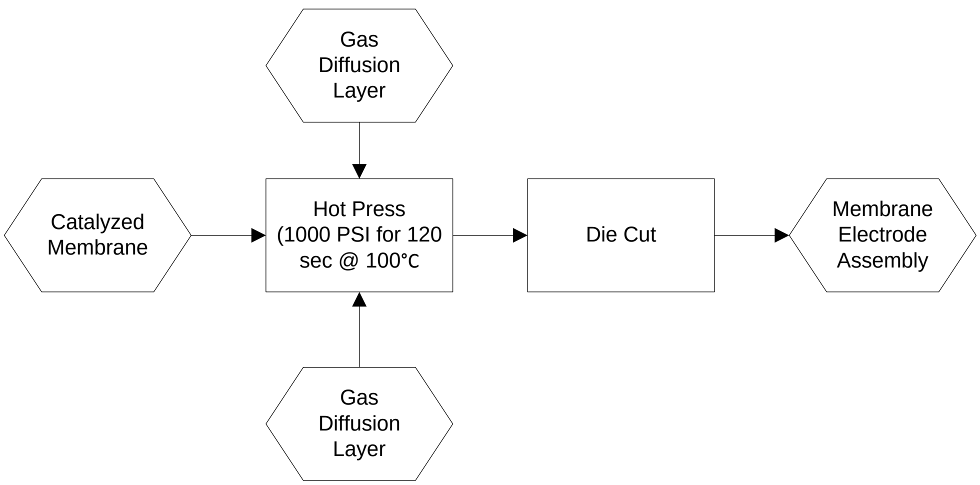
Appendix A-4: LTPEM MEA Hot Pressing Process Documentation

Membrane Electrode Assembly (MEA) Hot Pressing Process

Model Approach

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

Process Flow



Background

In "Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications: 2010 Update," Directed Technologies, Inc. (DTI) reported hot pressing conditions for membrane electrode assembly (MEA) fabrication as 160°C for 90 seconds using heated platens of 0.5 meter wide by 1.5 meters long for processing 0.5-meter wide roll materials. DTI estimated a reset period of 3 seconds to open the press, index the materials, and reclose the press.

In "Investigation of membrane electrode assembly (MEA) hot-pressing parameters for proton exchange membrane fuel cell," (Energy 32(12): 2401–2411, December 2007), Therdthianwong et al. found the most suitable hot pressing conditions for MEA fabrication to be 100°C and 1,000 psi (70 kilograms per square centimeter [kg/cm^2]) for 2 minutes, stating that these conditions "…provided the highest 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."

Preliminary Analysis

The 6-kilowatt (kW) stack cells for this analysis will have a total size of:

$$202.0\text{-millimeter (mm) width} \times 202.0\text{-mm length} = 408.0\ \text{cm}^2$$

The parts for this analysis were coated three across the 202-mm width for a total width of 606 mm.

Hot Press

Setup

Gas diffusion layer (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. However, the total number of setup operations will be dictated by the length of the shortest roll being processed, which is the membrane at 100 meters. In Appendix A-7 on the platinum coating process, the number of roll setups is shown to be:

$$\text{Number of setups} = 25$$

Tooling

Tooling consists of the heated platens, which generally consist of 2- 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. (www.customeng.com/platens/) for heated platens used for compression molding of bipolar plates. The quote estimated the cost at approximately $13,500 per square meter (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. An array of 15 cells arranged 3 width-wise by 5 length-wise take up 106 cm of length, which fits 14 heaters.

An engineering estimate for tool life based on heater life would be around 100,000 cycles. Using $15,600 per square meter [m^2] as a basis, 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

$$\text{Annual tooling cost} = \frac{1}{5}\left((\$15{,}600/\text{m}^2 \times 1.06\ \text{m}^2) \times \text{Roundup}(((36{,}000\ \text{parts/year} / 15\ \text{parts/cycle}) \times 5\ \text{years}) / 100{,}000\ \text{cycles/tool})\right) = \$3{,}307.20$$

Material

GDL material is typically sold in either 0.4- or 0.8- meter widths. The cost of the membrane is accounted for in a previous process step and is not included as part of the hot pressing operation. Assuming two GDL layers per MEA, the GDL material usage is calculated as:

$$\text{Material usage} = 0.8 \text{ m} \times 2{,}424.0 \text{ m} \times 2 = 3{,}878.4 \text{ m}^2$$

Material cost is computed in accordance with Appendix A-2 as:

$$\text{Material cost} = \$318.10/\text{m}^2$$

Hot Press Operation

The hot press time is broken up into two parts: material movement into and out of 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. (BDI) for automated handling with 2.8-second minimum as follows:

$$\text{Handling time} = \text{Max}((0.012 \times (\text{Platen length (cm)} + \text{Platen width (cm)}) + 1.6), 2.8)$$
$$\text{Handling time} = \text{Max}((0.012 \times (101 + 100) + 1.6), 2.8) = 4.0 \text{ sec}$$

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:

$$\text{Platen power input} = \text{Number of heaters} \times (\text{Platen width (cm)} \times 20 \text{ (W/cm)})$$
$$\text{Platen power input} = 14 \text{ heaters} \times (100 \text{ cm} \times 20 \text{ W/cm}) = 28 \text{ kW}$$

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:

$$\text{Parts/hour} = 15 \text{ parts/cycle} \ / \ ((124 + 4.0) \ / \ 3{,}600) \text{ hours/cycle} = 421.9 \text{ parts/hour}$$

The total machine time for processing and setup is:

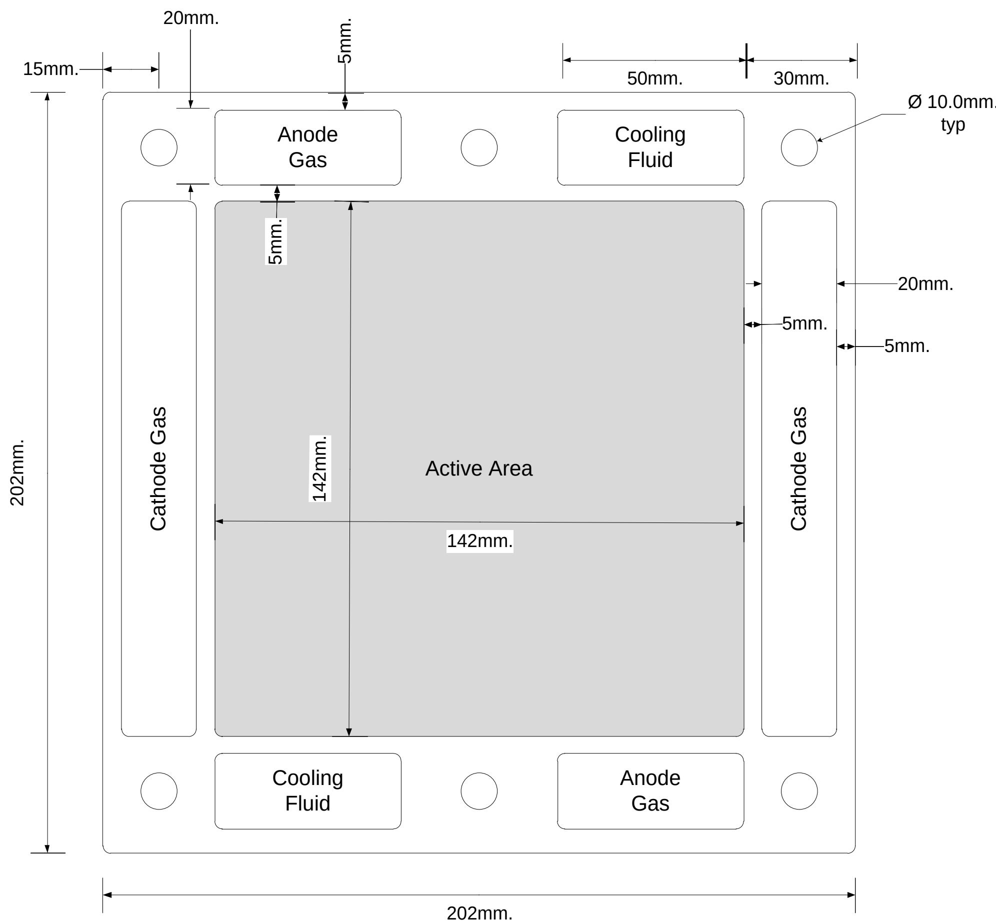
$$\text{Machine processing time} = (36{,}000 \text{ parts} \ / \ 421.9 \text{ parts/hour}) + (25 \text{ setups} \times 0.5 \text{ hr/setup}) = 97.8 \text{ hours}$$

Total machine labor time for processing and setup:

$$\text{Machine labor time} = 1 \text{ operator/machine} \times 97.8 \text{ hours} = 97.8 \text{ hours}$$

Die Cutting

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



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 width-wise by 5 length-wise). The outer cell perimeters will require a total length of :

$$\text{Outer perimeter length} = 2 \times (3 \times 202) + 2 \times (5 \times 202) = 3{,}232.0 \text{ mm}$$

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

$$\text{Inner perimeter length} = 4 \times (3 \times 202) + 2 \times (5 \times 202) = 4{,}444.0 \text{ mm}$$

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

$$\text{Feature length} = 4 \times (2 \times (50 + 20)) + 2 \times (2 \times (142 + 20)) + 6 \times (\pi \times 10) = 1{,}396.5 \text{ mm}$$

Therefore, the total die cutting length is:

$$\text{Die cutting length (mm)} = 3{,}232.0 + 4{,}444.0 + (15 \times 1{,}396.5) = 28{,}623.4 \text{ mm}$$

A rough quote of approximately $230 was obtained (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:

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

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

$$\text{Annual tooling cost} = (28{,}623.4 \text{ mm/die} \times \$0.04/\text{mm}) \ / \ 5 \text{ years}) \times \text{Roundup}(((46{,}000 \text{ parts/year} \ / \ 15 \text{ parts/cycle}) \times 5 \text{ years}) \ / \ 30{,}000 \text{ cycles/tool}) = \$228.99$$

Setup

The total number of setup operations will be dictated by the length of the shortest roll being processed, which is the membrane at 100 meters. As shown above, the number of roll setups is 25. Assuming 0.5-hour per setup, the total setup time is:

$$\text{Setup time} = 25 \times 0.5 \text{ hr} = 12.5 \text{ hrs}$$

Die Cutting Operation

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:

$$\text{Press force} = \text{Die cutting length (mm)} \times \text{Material thickness (mm)} \times \text{Shear strength } (\text{N/mm}^2)$$
$$\text{Press force} = 28{,}623.4 \text{ mm/die} \times 0.7 \text{ mm} \times 76 \text{ N/mm}^2 = 1{,}523 \text{ kilonewtons (kN)}$$

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:

$$\text{Press energy} = 1{,}523 \text{ kN} \times 1.5 \times 0.025 \text{ kW/kN} = 57 \text{ kW}$$

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

$$\text{Processing time} = 36{,}000\ \text{parts} / 15\ \text{parts/cycle} / 1{,}800\ \text{cycles/hour} = 1.3\ \text{hours}$$

The total machine time for processing and setup is:

$$\text{Machine processing time} = 12.5 + 1.3 = 13.8\ \text{hours}$$

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

$$\text{Roundup}(13.8 / 6{,}000) = 1\ \text{machines}$$

Machine utilization is:

$$13.8 / 6{,}000 = 0.23\%$$

Total machine labor time for processing and setup:

$$\text{Machine labor time} = 1\ \text{operator/machine} \times 13.8\ \text{hours} = 13.8\ \text{hours}$$

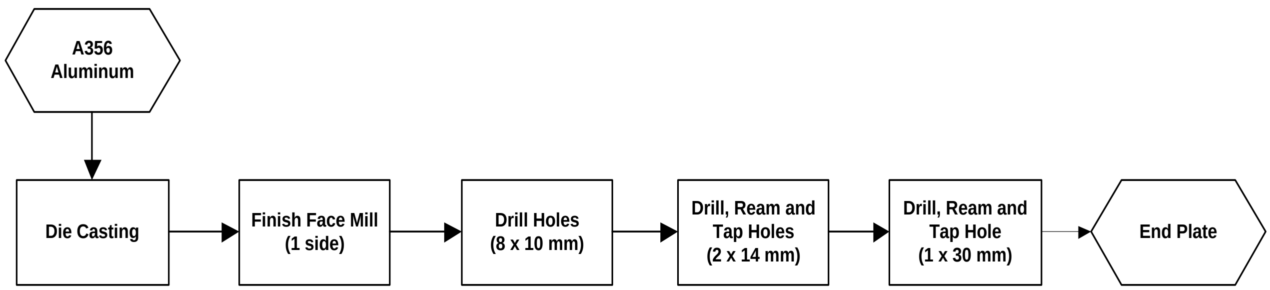
Appendix A-5: LTPEM End Plate Manufacturing Process Documentation

PEM End Plate Manufacturing Process

Model Approach

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

Process Flow

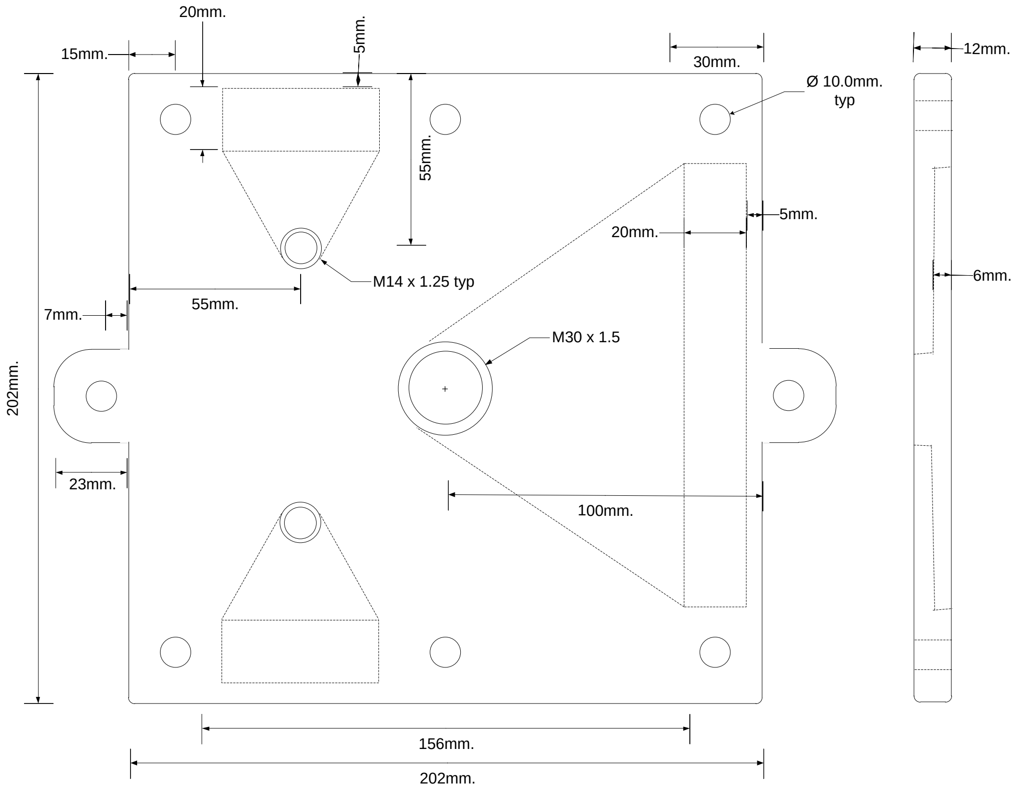


Background

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 in order to apply even pressure across the face of the stack. The process selection for the low temperature polymer electrolyte membrane (LTPEM) end plate was die 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.

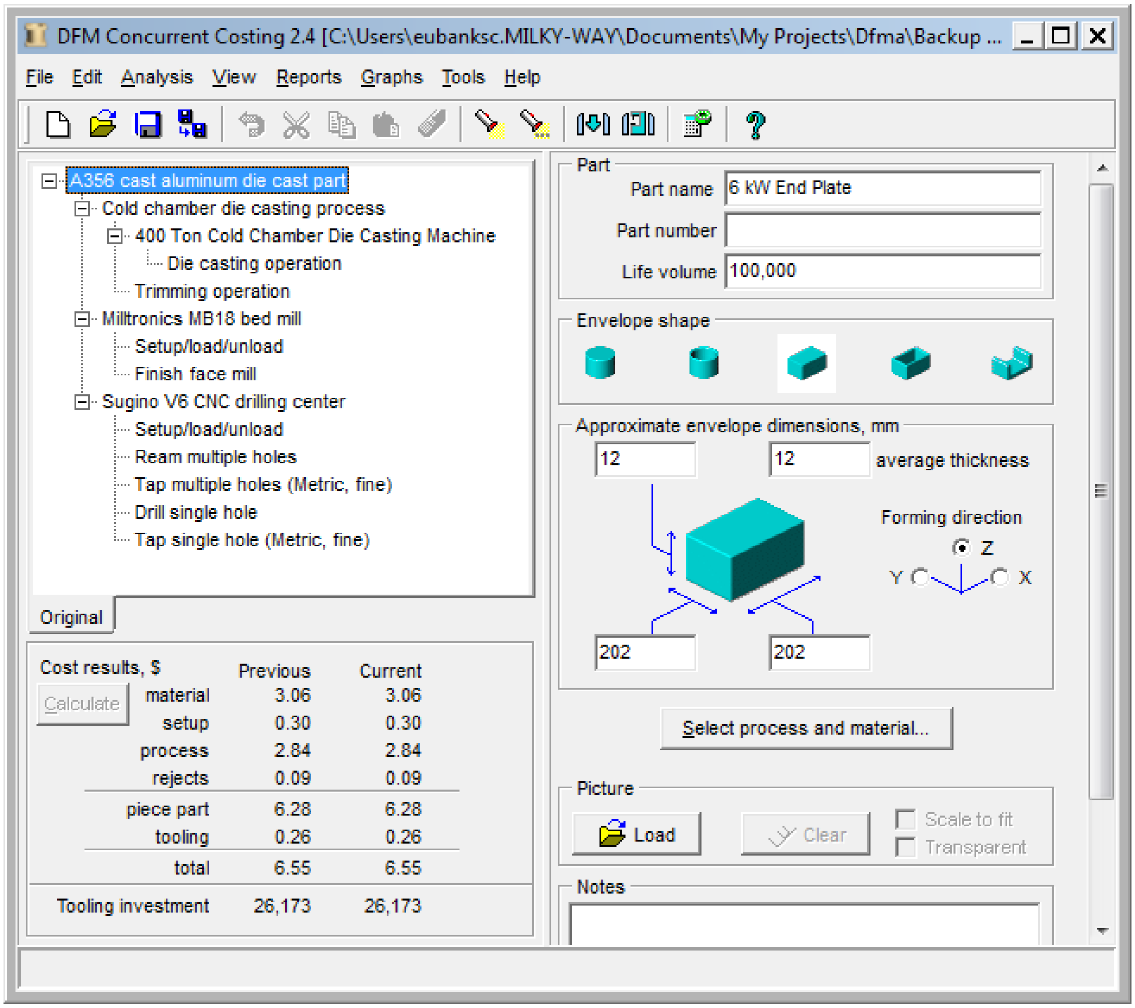
Preliminary Analysis

The 6-kW stack end plate features and dimensions are shown below for reference:



DFMA® Software Analysis

End Plate



The DFMA® software estimates a 7.65-hour machine setup time, and calculates the total manufacturing time for the end plates as 192 seconds (sec), making the total machine time for annual production of 1,000 6-kW stacks:

$$\text{Machine time} = (192 \text{ sec/part} / 3{,}600) \times 2{,}000 \text{ parts} + 7.65 = 114.3 \text{ hours}$$

Machine utilization is:

$$\text{Utilization} = 114.3 / 6{,}000 = 1.9\%$$

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 = 228.6 hours.

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

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

Tooling cost is $26,173 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: Number of tools purchased = Roundup(Total production / Tool life)
Total production = Annual production × 5

$$\text{Annual tooling cost} = (\$26{,}173\ /\ 5\ \text{years}) \times \text{Roundup}((2{,}000\ \text{parts/year} \times 5\ \text{years})\ /\ 100{,}000\ \text{parts/tool}) = \$5{,}235$$

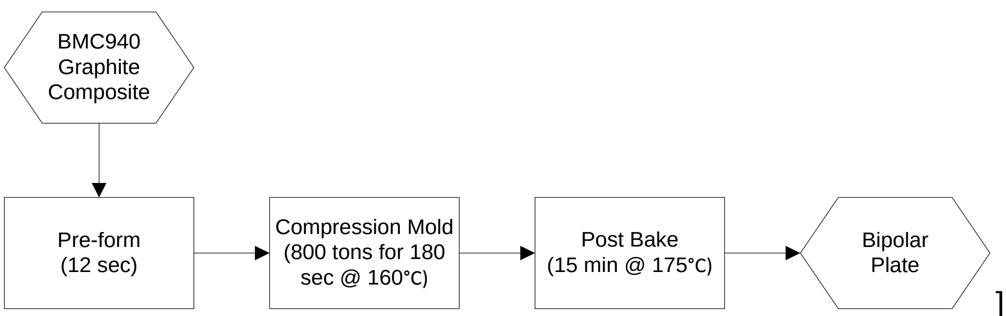
Appendix A-6: LTPEM Bipolar Plate Compression Molding Process Documentation

Bipolar Plate Compression Molding Process

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 Manufacture 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

Process Flow



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

Preliminary Analysis

Unlike injection molding, compression molding requires that a pre-measured, usually pre-formed, and generally pre-heated 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:

$$202 \text{ millimeter (mm) width} \times 202 \text{ mm length} = 408 \text{ square centimeters (cm}^2\text{)}$$

Process values will be calculated based on annual production of 1,000 6-kilowatt (kW) stacks per year. The 6-kW stack requires 37 anode bipolar plates and 37 cathode bipolar plates, requiring annual production of 37,000 of each type of plate.

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.

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/cm³) (BMC940 spec sheet) and 5% overage allowance, the total annual material required before scrap is:

$$\text{Cathode plate material required} = 1.9\ \text{g/ cm}^3 \times 0.001 \text{ kilograms per gram (kg/g)} \times (408 \times 0.2)\ \text{cm}^3 \times 1.05 \times 37{,}000 \text{ parts} = 6{,}023.3 \text{ kg}$$

$$\text{Anode plate material required} = 1.9\ \text{g/ cm}^3 \times 0.001 \text{ kg/g} \times (408 \times 0.3)\ \text{cm}^3 \times 1.05 \times 37{,}000 \text{ parts} = 9{,}035.0 \text{ kg}$$

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

$$\text{Material cost} = \$2.066/\text{kg}$$

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:

$$\text{Tonnage} = 0.4\ \text{ton/cm}^2 \times 408\ \text{cm}^2 = 163.2\ \text{tons}$$

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 (979 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 (in.) diameter. To move a 30-inch diameter cylinder at 30 ips requires a pump delivery of:

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

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-in. cylinder requires a delivery pressure of:

$$\text{Pressure} = 1{,}000\ \text{tons} \times 2{,}240\ \text{lbs/long ton}\ /\ ((30\ \text{in.})^2 \times (\pi\ /\ 4)) = 3{,}169\ \text{psi}$$

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 408-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:

$$\text{Part girth} = \text{Part length} + \text{Part width} + \text{part depth}$$
$$\text{Handling time} = \text{Max}((0.60714 \times (\text{Part girth}\ /\ 25.4) - 4.57143), 4)$$
$$\text{Cathode plate handling time} = \text{Max}((0.60714 \times ((202 + 202 + 2)\ /\ 25.4) - 4.57143), 4) = 5.13\ \text{sec}$$
$$\text{Anode plate handling time} = \text{Max}((0.60714 \times ((202 + 202 + 3)\ /\ 25.4) - 4.57143), 4) = 5.16\ \text{sec}$$

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

$$\text{Cathode plate cycle time} = ((6 \times 5.13) + 230 + 10) = 270.8 \text{ sec/cycle} = 0.0752 \text{ hour/cycle}$$
$$\text{Anode plate cycle time} = ((6 \times 5.16) + 230 + 10) = 270.9 \text{ sec/cycle} = 0.0752 \text{ hour/cycle}$$

Throughput is calculated as:

$$\text{Parts per hour} = 6 \text{ parts/cycle} \ / \ 0.0752 \text{ hour/cycle} = 79.8 \text{ parts/hour}$$

Since throughput for each type of plate is essentially the same, we can calculate the total time required to process both sets of plates (74,000 parts) as:

$$\text{Press machine time} = 74{,}000 \text{ parts} \ / \ 79.8 \text{ parts/hour} + (2 \times 4) \text{ hour setup} = 935.3 \text{ hours}$$

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

$$\text{Roundup}(935.3 \ / \ 6{,}000) = 1 \text{ machine}$$

Machine utilization is:

$$935.3 \ / \ 6{,}000 = 15.6\%$$

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- to -2.5-in. thick aluminum plates loaded with electric cartridge heaters spaced 3 in. (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:

$$\text{Platen width} = ((2 \times 202 \text{ mm}) + (3 \times 50 \text{ mm})) = 554 \text{ mm}$$
$$\text{Platen length} = ((3 \times 202 \text{ mm}) + (4 \times 50 \text{ mm})) = 806 \text{ mm}$$
$$\text{Platen area} = 554 \text{ mm} \times 806 \text{ mm} = 4{,}465 \text{ cm}^2$$
$$\text{Platen cost} = (4{,}465 \text{ cm}^2 \times \$1.333/\text{ cm}^2) + \$3500 = \$9{,}451$$

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:

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

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

$$\text{Annual insert tooling cost} = \frac{1}{5}((\$24.50 \times 408 \times 6) \times \text{Roundup}((94{,}000 \text{ parts/year} / 6 \text{ parts/cycle} \times 5 \text{ years}) / 100{,}000 \text{ parts/tool})) = \$11{,}995$$

$$\text{Annual platen tooling cost} = \frac{1}{5}((\$9{,}451) \times \text{Roundup}((94{,}000 \text{ parts/year} / 6 \text{ parts/cycle} \times 5 \text{ years}) / 500{,}000 \text{ parts/tool})) = \$1{,}890$$

Heated Platen Energy

Omega (http://www.omega.com/prodinfo/cartridgeheaters.html) estimates 0.5-in. 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-in. (7.6-cm) heater spacing:

$$\text{Number of heaters} = \text{Ceiling(Platen width (cm) / 7.6}$$
$$\text{Platen power input} = \text{Number of heaters} \times (\text{Platen length (cm)} \times 20 \text{ (W/cm)})$$
$$\text{Number of heaters} = \text{Ceiling } (55.4 \text{ cm} / 7.6 \text{ cm}) = 8$$
$$\text{Platen power input} = 8 \text{ heaters} \times (80.6 \text{ cm} \times 20 \text{ W/cm}) = 12.9 \text{ kW}$$

The mold insert will be attached to heated platens that are capable of maintaining 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.

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:

$$\text{Parts per bake cycle} = (79.8 \text{ parts/hr} \times 0.25 \text{ hr}) = 19.95 \text{ parts per bake cycle} \cong 20 \text{ parts/rack}$$

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 in. × 24 in. × 18 in. (0.2 m^3) working volume with seven-shelf capacity, and 2-in. (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:

$$\text{Rack girth} = (\text{Parts per rack} \times (\text{Part width (mm)} + 50)) + (\text{Part length (mm)} + 50) + 10$$
$$\text{Rack girth} = (6 \times (202 + 50)) + (202 + 50) + 10 = 1{,}774$$
$$\text{Rack handling time} = \text{Max}((0.60714 \times ((1{,}774) / 25.4) - 4.57143), 4) = 37.8 \text{ sec}$$

Given that the rack handling time is about 15% 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.

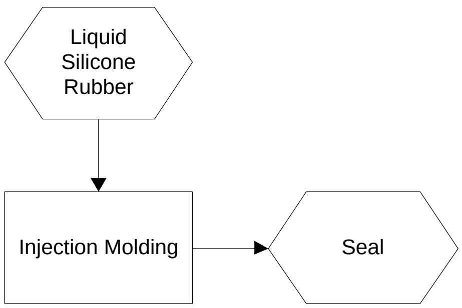
Appendix A-7: LTPEM Seal Injection Molding Process Documentation

Seal Injection Molding Process

Model Approach

- Use standard Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA®) injection molding cost analysis

Process Flow



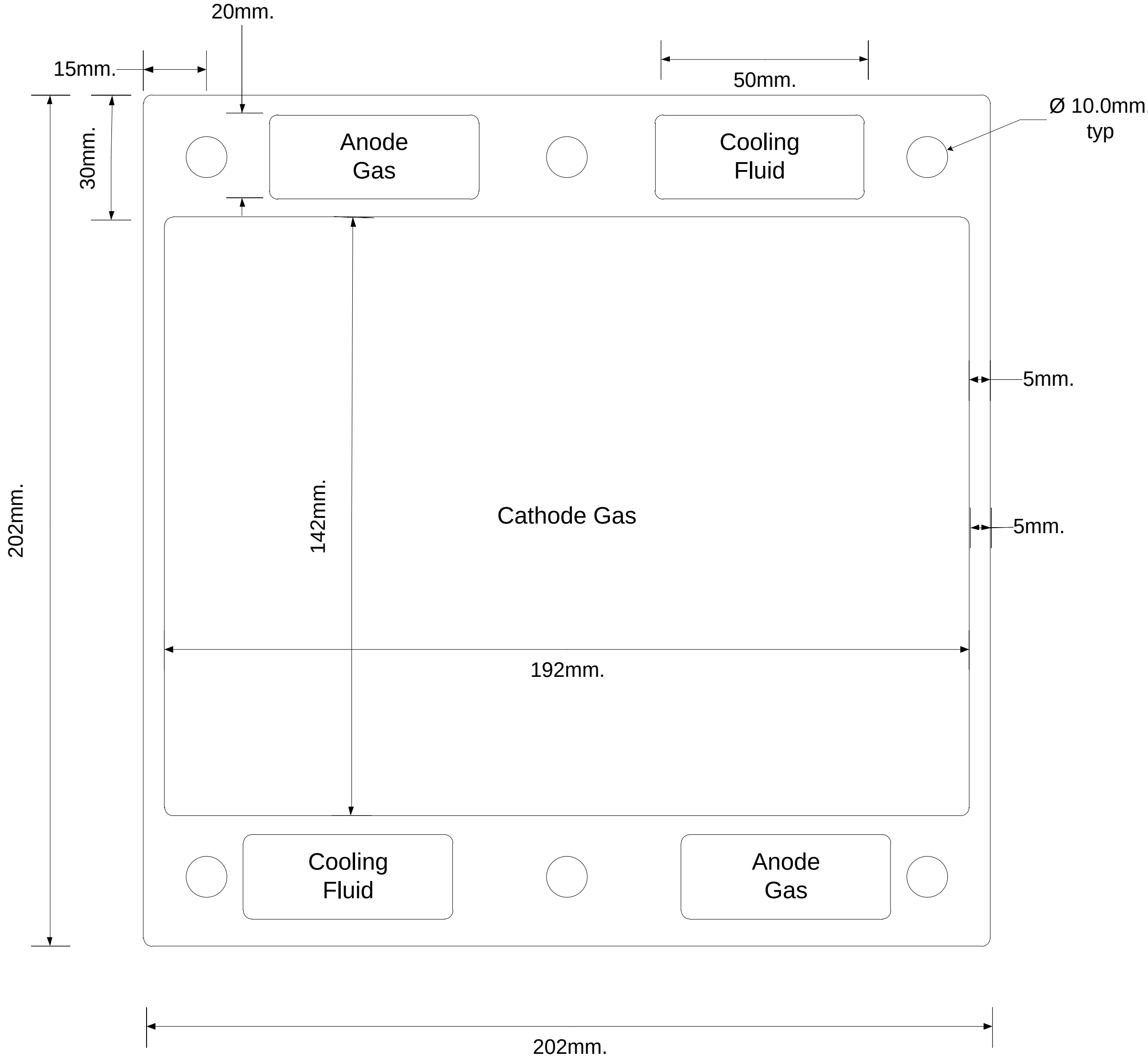
Background

The BDI DFMA® 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.

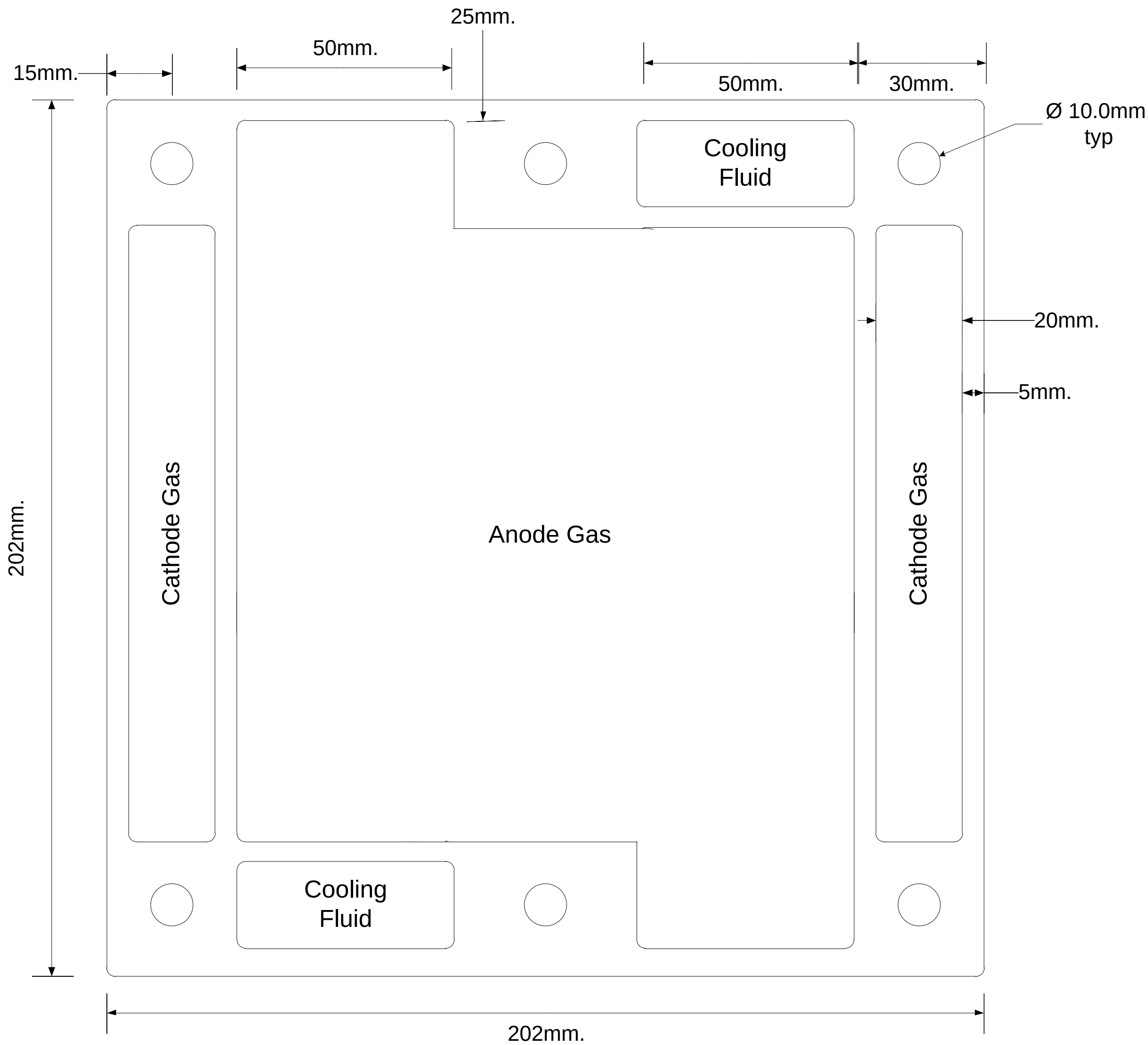
Preliminary Analysis

The stack requires three seals (cathode, anode, and cooling) per cell plus two cathode seals, one on each end of the stack. To manufacture 1,000 6-kilowatt (kW) stacks consisting of 36 cells each requires a total of 72,000 each anode and cooling seals, and 38,000 cathode seals. The seal features and dimensions are shown below for reference.

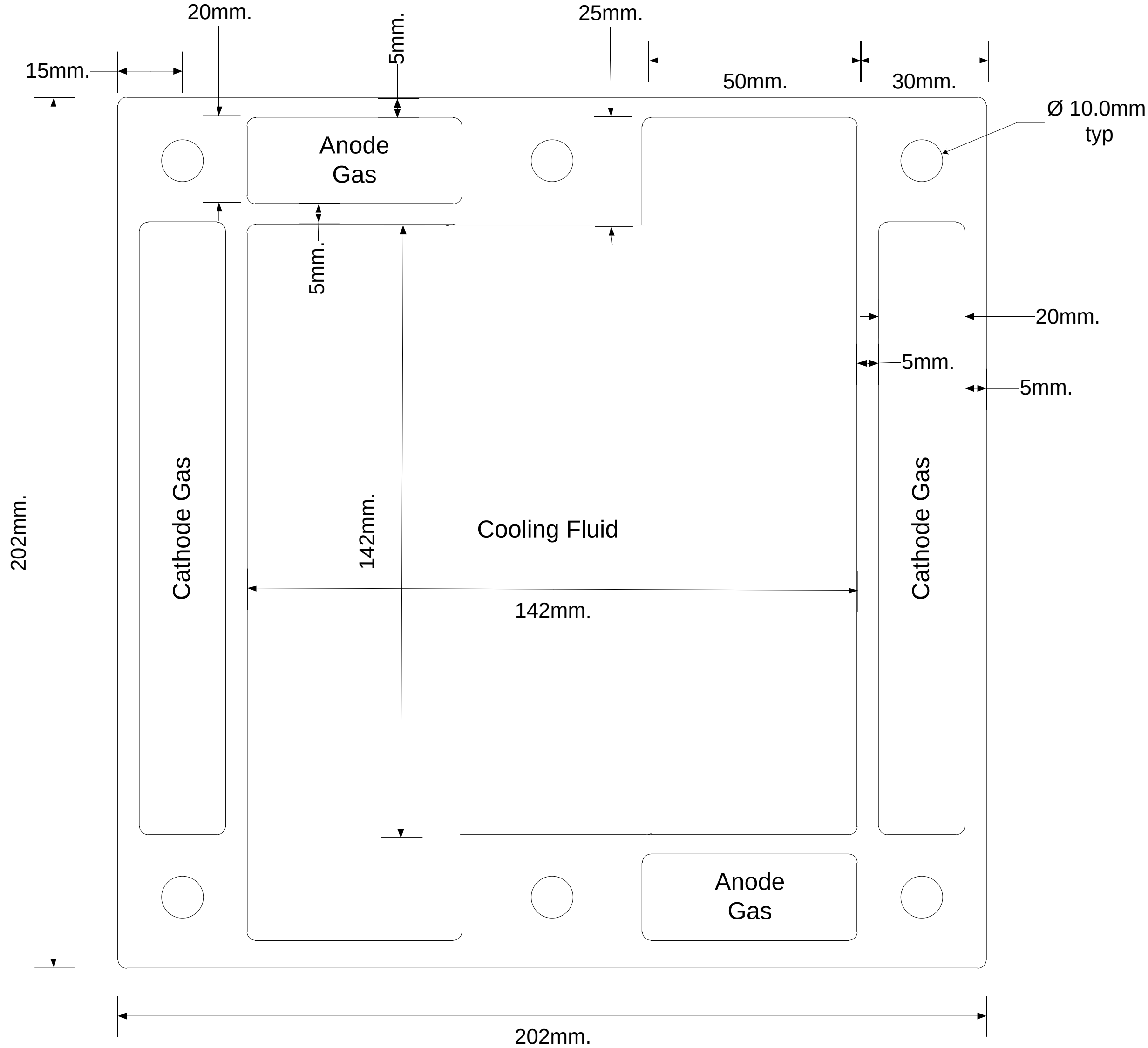
Cathode Seal



Anode Seal

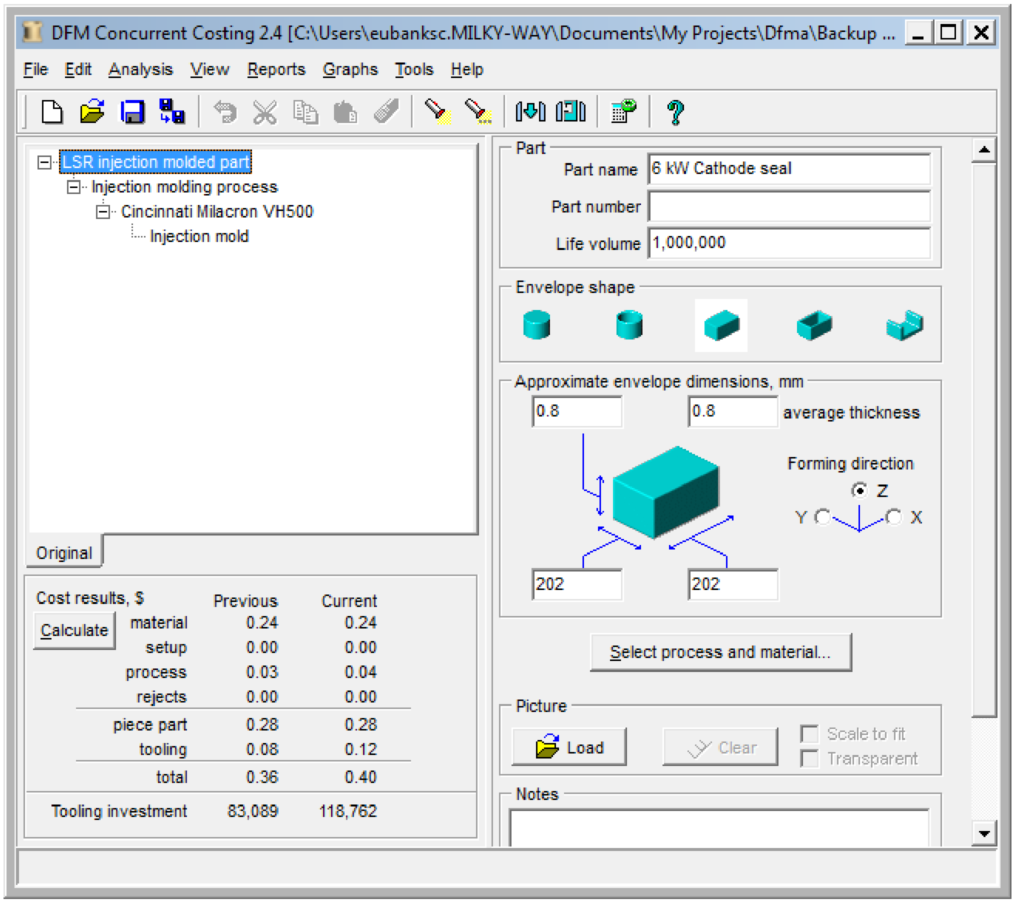

25mm.
50mm.
15mm.
50mm.
30mm.
Ø 10.0mm.
typ
Cooling
Fluid
20mm.
5mm.
202mm.
Cathode Gas
Anode Gas
Cathode Gas
Cooling
Fluid
202mm.

Cooling Seal



DFMA® Software Analysis

Cathode Seal



The DFMA® software estimate for the 6-kW cathode seal is a 1.5-hour machine setup time, and calculates the total manufacturing cycle time as 9.07 seconds (sec) for a four-cavity mold, making the total machine time for annual production of 1,000 stacks:

$$\text{Machine time} = (9.07 \text{ sec/cycle} \;/\; 4 \text{ parts/cycle} \;/\; 3{,}600) \times 38{,}000 \text{ parts} + 1.5 = 25.4 \text{ hours}$$

Machine utilization is:

$$\text{Utilization} = 25.4 \;/\; 6{,}000 = 0.42\%$$

Assuming one full-time operator per two molding machines, the total machine labor time is equal to half the machine time = 12.6 hours.

The DFMA® software estimate for material weight per part is 0.010 kilogram (kg), making total annual material usage:

$$\text{Material usage} = 0.010 \text{ kg/part} \times 38{,}000 \text{ parts} = 380 \text{ kg}$$

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

$$\text{Material cost} = \$16.28/\text{kg}$$

Tooling cost is $50,127. The tool is assumed to be capable of producing 1 million parts. Amortizing over a 5-year production life, the total annual tooling cost is:

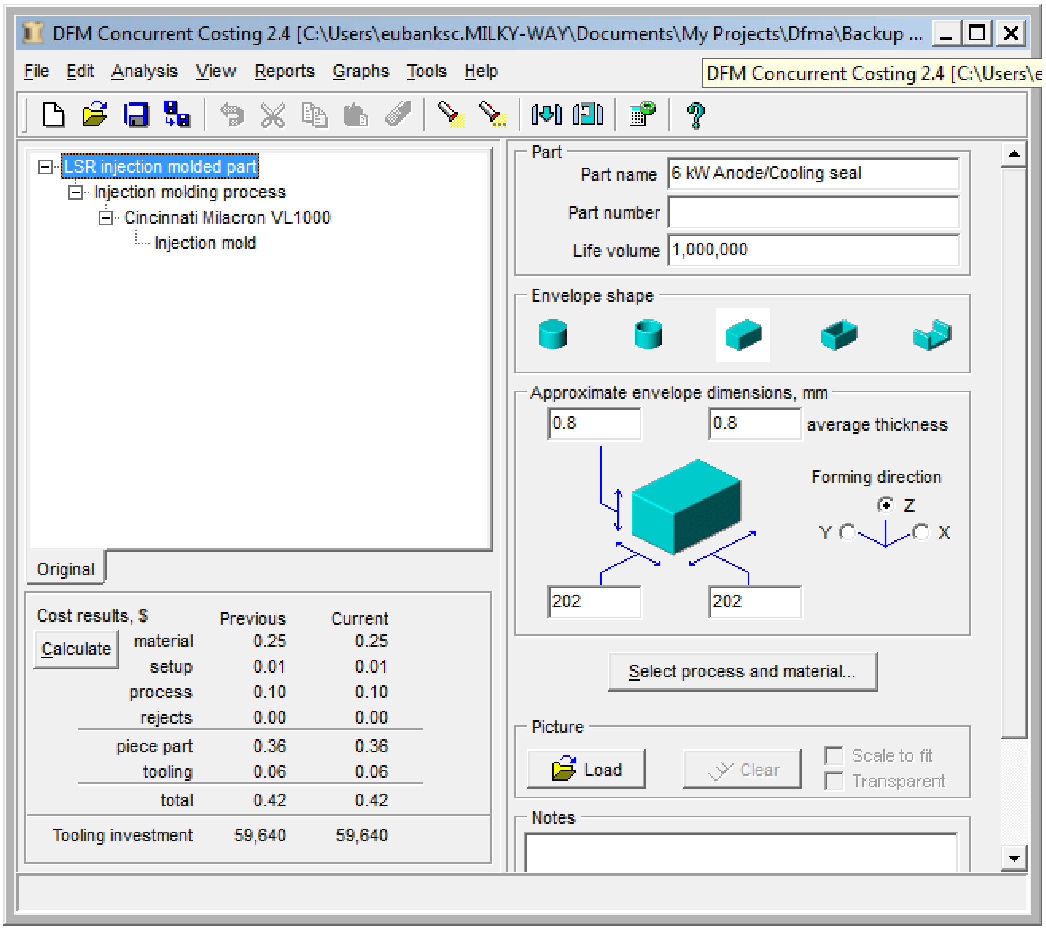
$$\text{Annual tooling cost} = \frac{1}{5}(\text{Tooling cost} \times \text{Number of tools purchased})$$

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

$$\text{Annual tooling cost} = \frac{1}{5}\,(\$50{,}127 \times \text{Roundup}((38{,}000 \text{ parts/year} \times 5 \text{ years}) \;/\; 1{,}000{,}000 \text{ parts/tool})) = \$10{,}025.40$$

Anode/Cooling Seal

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



The DFMA® software estimate for the anode/cooling seal is a 1.5-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:

$$\text{Machine time} = (9.66 \text{ sec/cycle} \ / \ 4 \text{ parts/cycle} \ / \ 3600) \times 72{,}000 \text{ parts} + 1.5 = 48.3 \text{ hours}$$

Machine utilization is:

$$\text{Utilization} = 48.3 \ / \ 6000 = 0.81\%$$

Assuming one full-time operator per two molding machines, the total machine labor time is equal to half the machine time = 24.15 hours.

The DFMA® software estimate for material weight per part is 0.011 kg, making total annual material usage:

$$\text{Material usage} = 0.011\ \text{kg/part} \times 72{,}000\ \text{parts} = 792\ \text{kg}$$

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

$$\text{Material cost} = \$16.28/\text{kg}$$

Tooling cost is $59,640. The tool is assumed to be capable of producing 1 million 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: Number of tools purchased = Roundup(Total production / Tool life)
Total production = Annual production × 5

$$\text{Annual tooling cost} = \frac{1}{5}\left((\$59{,}640) \times \text{Roundup}((72{,}000\ \text{parts/year} \times 5\ \text{years})\ / \ 1{,}000{,}000\ \text{parts/tool})\right) = \$11{,}928.00$$

Appendix A-8: Assembly Cost Learning Curve Calculations Documentation

Assembly Cost Learning Curve Calculations

Background

The Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA®) software produces assembly times based on hand assembly at its most efficient. Using the 6-kilowatt (kW) polymer electrolyte membrane (PEM) stack as an example, the assembly time was estimated to be 0.518 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*, Stewart, R.M., et al, 2nd Ed., Wiley-Interscience, 1995, 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

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:

$$A = Y / X^{b} = 0.518 / 100^{(-0.23447)} = 1.524 \text{ hrs}$$

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

$$\bar{C}_{100} = \frac{\left(\sum_{i=1}^{100} 1.524 * \mathrm{i}^{(-0.23447)}\right)}{100} = 0.667\ hrs$$

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

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

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

1st Year Average Stack Assembly Time (hrs)				
Type of stack	**No. of stacks per year**			
	100	**1,000**	**10,000**	**50,000**
6-kW PEM Stack	0.667	0.533	0.519	0.518
12-kW PEM Stack	0.672	0.537	0.524	0.522

The average system assembly times are:

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

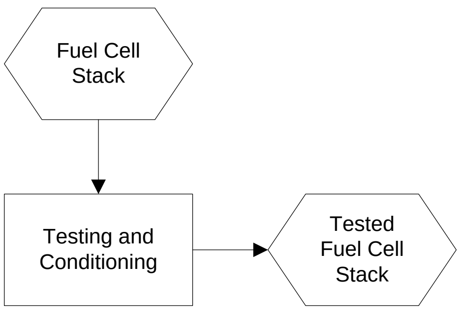
Appendix A-9: LTPEM Stack Testing and Conditioning Process

Testing and Conditioning Process

Model Approach

- Test and condition fuel cell stack

Process Flow



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:

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

For a 6-kilowatt (kW) stack current of 200 amperes (A) and cell count of 36 cells, we have:

$$\mathrm{H_2\ consumption\ grams\ per\ second\ (g/sec)} = 200\ \mathrm{A} \times 36\ \mathrm{cells}\ /\ (2 \times 96{,}485\ \mathrm{cal/mol}) = 0.0373\ \mathrm{mol/sec}$$

Converting to liters per minute (L/min):

$$\mathrm{H_2\ consumption\ L/min} = 1.2 \times 0.0373\ \mathrm{mol/sec} \times 60 \times 2.016\ /\ 0.0899 = 60.2\ \mathrm{L/min}$$

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

$$\mathrm{Air\ flow\ L/min:}\ (2\ /\ 1.2) \times 60.2\ \mathrm{L/min} = 100.3\ \mathrm{L/min}$$

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:

$$\text{Setup labor time} = 0.5 \text{ hour/stack} \times 1{,}000 \text{ stacks} = 500 \text{ hrs}$$

The Fuel Cell and Hydrogen Energy Association placed the 2010 nation-wide 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).

$$1 \text{ kg of } H_2 = (1{,}000 \ / \ 2) \times 22.4 \text{ L} = 11{,}200 \text{ L} = 11.2 \text{ cubic meters } (\text{m}^3)$$

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

$$\text{Full power material usage} = ((60.2 \text{ L/min} \ / \ 1{,}000 \text{ l/m}^3) \ / \ 11.2 \text{ m}^3\text{/kg}) \times 60 \text{ min/hr} = 0.323 \text{ kg/hr}$$

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:

$$H_2 \text{ usage} = 0.323 \text{ kg/hr} \times ((0.25 \times 1.0 \text{ hr}) + (1.0 \times 0.5 \text{ hr}) + (0.25 \times 1.0 \text{ hr})) \times 1{,}000 \text{ stacks} = 323 \text{ kg}$$

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

$$\text{Material cost} = \$22.02\text{/kg}$$

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:

$$\text{Testing machine time} = ((2.5 \text{ hrs/stack} \ / \ 2) + (0.5 \text{ hrs/stack})) \times 1{,}000 \text{ stacks} = 1{,}750 \text{ hrs}$$

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

$$\text{Testing labor time} = (2.5 \text{ hrs/stack} \ / \ 3) \times 1{,}000 \text{ stacks} = 833.3 \text{ hrs}$$

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 Manufacture and Assembly (DFMA®) software, the 6-kW stack assembly labor time was estimated to be 0.53 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:

$$\text{Scrap value} = (\text{Unit value} / (1 - \text{Scrap rate})) - \text{Unit value}$$

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

$$\text{Scrap labor time} = (((2 \times 0.53 \text{ hrs/stack}) / (1\text{-}0.05)) - (2 \times 0.53 \text{ hrs/stack})) \times 1{,}000 \text{ stacks} = 55.78 \text{ hours}$$

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

$$\text{Scrap value (\$)} = ((\$40.92/\text{stack} / (1\text{-}0.05)) - \$40.92/\text{stack}) \times 1{,}000 \text{ stacks} = \$2{,}153.68$$

Appendix A-10: LTPEM Production Facility Estimation

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 Penn State University, and were downloaded from http://www.personal.psu.edu/jav1/ on 10/18/2013.

Equipment Footprint

Line utilization calculations provide the equipment count for a particular production line. Using the bipolar plate production as an example, each station consists of two pieces of equipment: the 1,000-ton fast acting press, and the post-bake oven, which have the following footprint dimensions in inches (in.):

Press: 60 in. x 70 in.
Oven: 40 in. x 40 in.

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

$$\text{Press: } (60 + (2 \times 36)) \times (70 + (2 \times 36)) \,/\, 144 \text{ in}^2/\text{ft}^2 = 130 \text{ ft}^2$$
$$\text{Oven: } (40 + (2 \times 36)) \times (40 + (2 \times 36)) \,/\, 144 \text{ in}^2/\text{ft}^2 = 87 \text{ ft}^2$$

Three additional space allowances are made for each line 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-in. by 48-in. pallet for receiving and pickup, adding to the required area by:

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

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:

$$\text{Personnel allowance} = 1 \times 20 \text{ ft}^2 = 20 \text{ ft}^2$$

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:

$$\text{Aisle allowance: } (130 + 87 + 27 + 20) \times 0.35 = 92 \text{ ft}^2$$

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

$$\text{Floor space allocation} = 130 + 87 + 27 + 20 + 92 = 356 \text{ ft}^2$$

The polymer electrolyte membrane (PEM) 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	296
Decal transfer	258
Hot press	426
Die cutting	178
Bipolar plate	357
End plate	1,236
Seal injection molding	233
Stack assembly	258
Stack test and conditioning	245
System assembly	258
System test	245

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 Manufacture 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	11,051	0	0	1.00	1.00

PEM Production Station	a (sec)	b (sec)	t (sec)	n′	1/n′
Stack test and conditioning	1,800	600	9,000	4.50	0.22
System assembly	11,051	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 is capable of operating a maximum of three machines in a cell arrangement. We also assume that lines 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 a particular annual volume and the line utilization (assuming a single operator is trained to perform multiple tasks). Using the line utilization numbers for 10,000 6-kilowatt (kW) stacks per year, we have:

PEM Production Station	Stations	Utilization	Operators per line	Operators per shift
Catalyst	1	0.002	0.20	0.01
Slot die coating	1	0.040	0.50	0.02
Decal transfer	1	0.034	0.50	0.02
Hot press	1	0.163	0.50	0.08
Die cutting	1	0.023	1.00	0.02
Bipolar plate	2	0.774	0.50	0.77
End Plate	1	0.242	2.00	0.48
Seal injection molding	1	0.866	0.50	0.43
Stack assembly	1	0.855	1.00	0.86
Stack test and conditioning	3	0.972	0.33	0.96
System assembly	2	0.919	1.00	1.84
System test	7	0.952	0.33	2.20
Total				**7.69**

Rounding up to eight machine operators per shift, and assuming approximately 1one support staff per four line operators for purchasing, quality control, and maintenance, the facility needs to support a total of 10 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	120
Restrooms	100
Parking	2,208
Office	144

Total factory building floor space can be estimated as:

$$\text{Equipment} + \text{Food service} + \text{Restrooms} + \text{Office} = 7{,}191\ \text{ft}^2$$

Assuming a construction cost of \$250/ft^2, the estimated cost of factory construction is approximately \$1,797,750.

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

$$((\text{Factory space} + \text{Parking space})^{1/2} + 60)^2 = 32{,}454\ \text{ft}^2 = 0.57\ \text{acre}$$

Assuming a real estate cost of \$125,000/acre, the estimated total real estate cost is approximately \$70,700.